WILEY-VCH

Jean-Claude Diels • Ladan Arissian

Lasers

The Power and Precision of Light

Jean-Claude Diels and Ladan Arissian

Lasers

Related Titles

Paschotta, R.
Encyclopedia of Laser Physics and Technology
2008
ISBN: 978-3-527-40828-3

Hecht, J.
Understanding Lasers
An Entry-Level Guide
2008
ISBN: 978-0-470-08890-6

Smith, F. G., King, T. A., Wilkins, D.
Optics and Photonics
An Introduction
2007
ISBN: 978-0-470-01784-5

Meschede, D.
Optics, Light and Lasers
The Practical Approach to Modern Aspects of Photonics and Laser Physics
2007
ISBN: 978-3-527-40628-9

Quimby, R. S.
Photonics and Lasers
An Introduction
2006
ISBN: 978-0-471-71974-8

Jean-Claude Diels and Ladan Arissian

Lasers

The Power and Precision of Light

WILEY-VCH

WILEY-VCH Verlag GmbH & Co. KGaA

The Authors

Prof. Jean-Claude Diels
University of New Mexico
Dept. of Physics & Astronomy
1919 Lomas Blvd
Albuquerque, NM 87131
USA

Dr. Ladan Arissian
University of New Mexico
Department of Electrical and Computer Engineering
Center for High Tech Materials
1313 Goddard SE
Albuquerque, NM 87106
USA

Typesetting le-tex publishing services GmbH, Leipzig
Printing and Binding Ebner & Spiegel GmbH, Ulm
Cover Design Bluesea Design, McLeese Lake, Canada

Library of Congress Card No.: applied for

British Library Cataloguing-in-Publication Data: A catalogue record for this book is available from the British Library.

Bibliographic information published by the Deutsche Nationalbibliothek
The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available on the Internet at http://dnb.d-nb.de.

Printed in the Federal Republic of Germany
Printed on acid-free paper

ISBN Print 978-3-527-41039-2

ISBN ePDF 978-3-527-64005-8
ISBN oBook 978-3-527-64003-4
ISBN ePub 978-3-527-64004-1

To my mother Maryam and my daughter Vida.

Ladan Arissian

To my daughter Natacha, who taught me that music and lasers can live in harmony and my wife Marlies, for having patiently endured the clickety-clack of a keyboard as evening conversation.

Jean-Claude Diels

Contents

Preface *IX*
References *XII*

1 A Scenic Route through the Laser *1*
1.1 The Meaning of »Laser« *1*
1.2 Radiation from an Atom *9*
1.3 The Anatomy of a Laser *15*
1.4 Some Examples of Lasers *20*
1.5 Pulsed Lasers *34*
1.6 Properties of a Laser Beam *41*
1.7 How to Make the Shortest Laser Pulse *45*
1.8 Ultrashort Ultraintense Laser Pulses *61*
1.9 Ultrashort Ultraprecise Laser Pulses *66*
1.10 Ultrashort Ultrasensitive Laser Pulses *69*
1.11 The Nonlinear Wizard: Juggling with Frequencies *70*
References *79*

2 Laser Coherence at Home *81*
2.1 The Laser Printer *81*
2.2 The Laser Scanner *83*
2.3 The Laser in Data Storage *87*
2.4 Miscellaneous Applications *90*

3 The Laser in Medicine *93*
3.1 Introduction *93*
3.2 The Laser in Dentistry *94*
3.3 The Laser and Vision *96*
3.4 Lasers and the Neural Network *102*
3.5 Lasers for the Skin and Cosmetics *104*
3.6 Lasers in Surgery *110*
3.7 Biostimulation Lasers for Ulcer Treatment *113*

3.8 Lasers in Diagnostics *113*
3.9 Ultrafast Peeking *125*
References *131*

4 **Lasers in Industry** *133*
4.1 Laser Machining *133*
4.2 Laser Cutting/Drilling *134*
4.3 Cutting the Forest *136*
4.4 Nanostructure with Lasers *137*
References *140*

5 **Laser Time Capsule** *141*
5.1 Introduction *141*
5.2 Ultrashort Pulses in Microscopy *142*
5.3 Communication *144*
5.4 Frequency Combs *149*
References *158*

6 **Light in Matter** *159*
6.1 Attosecond Science *161*
6.2 Lasers in Nuclear Physics and Accelerators *170*
6.3 Laser Cooling *177*
References *179*

7 **High Power Lasers (Tazer/Teaser)** *181*
7.1 Filaments *181*
7.2 Laser-Induced Lightning *191*
7.3 Laser Tazer–Teaser *198*
References *199*

8 **Laser Sensors** *203*
8.1 Passive Sensors *203*
8.2 Active Sensors *217*
References *224*

9 **Future Perspectives** *227*
References *231*

Index *232*

Color Plates *237*

Preface

There is no need to convince anyone of the importance of lasers. The growth of this technology and its presence in our daily lives cannot be overemphasized. It can be felt as simply as flipping a switch, like using a laser pointer or a scanner, but there are times that its use is mysterious and glorified, such as in the case of the laser gun, Star Wars and laser induced lightning. The aim of this book is to provide a better intuition about this technology and its applications. We felt that knowing about lasers should not be restricted to scientists and engineers in the field, or to those who are direct users of lasers. It can and has to be shared with everybody. We hope this book will inspire the reader to have meaningful dreams about the future of this technology and its applications, and to alleviate confusion and misuse of science in public media.

We do not believe that science should be boring, or be the prerogative of strange people with unbrushed hair, big glasses, and torn t-shirts. Science is for everyone's benefit. When a baby rolls a ball or throws a stone she/he starts learning mechanics. With a simple activity, a lot of intuition is established about *mass*, *velocity*, and *gravity*. This is why even in a scientific community a common method to understand a subject is via mechanical analogies. Any physics student has a tough experience at his/her first exposure to quantum mechanics; only a carefree baby can easily assimilate new concepts. We thought that a way to gain a better understanding about optics and in particular about lasers, is to discuss them in an informal way. Some details are kept, some are missed, which is the nature of an imperfect work.

Who cares about lasers? Of course we do, because they are at the center of our job and lives, and we think that others should care as well. Lasers play an important role in the evolution of technology. A *wheel*, which is a symbol of the mechanical era, served to move objects around, and facilitated transportation. With mechanical technology came another leap in human power and mobility. In scientific aspects it helped us understand the mechanics of the universe, and planetary motions in the sky. In biology it gave a better picture of the mechanics of motion and bone structure. Then came the finer technology of *electricity*, enabling the transport of energy through electrons in wires. Understanding electricity is not so straightforward, and the experience of an electric shock is not commonly sensed as a knife cut.

Having had electricity around for more than a century, we have gained some intuition about *voltage* and *current*, although they are not as clear concepts as *speed* and *position*. At the start of the twentieth century *quantum mechanics* appeared and puzzled scientists for a long time. It brought with it all new concepts, but it was accepted, in the same manner as we have become used to talking to someone over the phone, or meeting a friend on a computer screen, rather than the traditional face to face interaction. We extend our experience and senses with technology. Just like the caveman who lived in bare nature might not have known all the trees and bushes, we may not know all the scientific reasons and backgrounds of the technologies we have at hand.

There is a notion that, after the mechanic and electric eras it is time for a photonic era, and that the *laser* is the greatest manifestation of it. The laser is not a stand alone subject: it could not have been realized without fine machining, precision optics, and controlled electrical power. It is a magnifying box for photons, not by collecting photons in one position like a lens, but by putting them *in phase* in a stimulation process. With the power of a laser we can mimic the sun in a laboratory, tame electrons inside molecules and atoms, tatoo a biological cell, have faster and more precise clocks, and eventually guide lightning towards our mean neighbor's house.

Chapter 1 is a scenic route to the laser. It is an overview of the radiation of light, the properties of the laser, the different types of lasers, properties of the beams and of pulses, the generation of ultrashort pulses, ultra-high intensities, and so on. We have dropped many details and concepts to make this chapter as short as possible. Our purist colleagues may not appreciate our shortcuts and analogies, but this book is not intended for them. We intentionally omitted naming any of the great scientists who have contributed to the birth and growth of the laser. Doing otherwise would have been an unfair selection among the tens of thousands of scientists who have been involved in materializing the dream of creating and understanding laser sources and their applications.

The rest of the book is organized in seven chapters to cover some industrial, medical, military, and scientific applications of the laser, with many important application having been left out in the interest of brevity. The laser has surreptitiously entered so many aspects of our lives, that a comprehensive listing of all its uses may become as boring as reading a dictionary. The history of the discovery of the laser, and anecdotes about ensuing competition in patent recognition, has already been published [1–5]. Instead, we present an informal conversation about lasers, rather than an explanation of their technical and scientific aspects, which has been published by others [6].

In view of all the other contributions, why did we dare to write this book? Because we thought that our »cartoon« approach to science is unique and might reach a different audience than existing textbooks. This book was started as a celebration of the 50th anniversary of the discovery of the laser. For that occasion, we intended to make an overview of all the applications and how they relate to the exceptional properties of the laser.

If you expect to have acquired a textbook, please return this book as fast as possible to the source. Physics is very often explained with simple analogies (which would make a rigorous mind cringe).

No self-respecting science book could be published without exhaustive references. This *is not a self-respecting* science book. If we had to give credit to all the scientists in the world who have contributed to the field, the content would dwarf the phone directory of New York city. We have purposely omitted citing *any* names.

This book was started on the initiative of Ladan Arissian, a poet and physicist, as you will clearly sense from the style of various chapters. She has a broad educational background in various disciplines of physics (nuclear, condensed matter, and optical science). In addition to being a research physicist, she dreams of being a teacher and strives to present science in new ways.

This book would not have been published if it had not been ornamented with the name of Professor Jean-Claude Diels, who was willing to sacrifice his reputation as a serious science writer of »ultrafast laser pulse phenomena« [7]. He has decades of experience in tweaking and building impossible lasers and trying to understand the effect of each optical component on the optical pulse. He has never closed the laser box and refused to reduce it to a rectangle in a diagram. He only agreed to coauthor this book if he could insert his cartoons in the text.

Our enthusiasm about lasers and their applications is just a minute reflection of the work of men and women in science, bearing all the frustration and obstacles of conducting research. We are in debt to all scientists, engineers, technicians, and students whose persistence and patience have introduced the laser in all fields of science as well as in our daily lives.

Albuquerque, March 2011

Jean-Claude Diels
Ladan Arissian

References

1 Hecht, J. (2005) *Beam: The Race to Make the Laser*, Oxford University Press, New York.
2 Hecht, J. (1992) *Laser Pioneers*, Academic Press, Boston.
3 Taylor, N. (2000) *Laser: The Inventor, the Nobel Laureate, and the Thirty-Year Patent War*, Simon & Schuster, New York.
4 Bertolloti, M. (2005) *The History of the Laser*, Institute of Physics Publications, Bristol, Philadelphia.
5 Townes, C.H. (1999) *How the Laser Happened: Adventures of a Scientist*, Oxford University Press, New York.
6 Hecht, J. (2008) *Understanding Lasers*, 3rd edn, IEEE press, John Wiley & Sons.
7 Diels, J.C. and Rudolph, W. (2006) *Ultrashort Laser Pulse Phenomena*, 2nd edn, Elsevier, Boston.

1
A Scenic Route through the Laser

1.1 The Meaning of »Laser«

»Laser« is one of the rare acronyms whose meaning has not been lost over five decades. It stands for *L*ight *A*mplification by *S*timulated *E*mission *R*adiation. These words are not sufficient to clarify the meaning, unless we have a picture associated to each of them in our mind. The next few sections will be devoted to unraveling the meaning of each term.

1.1.1 Light (Photon) is a Wave

The first letter »L« tells us that »laser« is »light«. Light is an old known entity originating from the sun and the moon. Once it was associated with fire and thought to be the first essential element. In modern language we say that light actually consists of photons, just as matter is made of atoms. Our intuitive picture of atoms is that they can be nicely classified by their mass in a table – the Mendeleev table. Atoms themselves are boxes filled with electrons, protons and neutrons, and there is a mass associated with each component.

Atoms can combine to make molecules, the ultimate component we expect to arrive at when grinding to its finest constituent any piece of material, from a live leaf to a piece of paper. In a way molecules and atoms are what we deal with on a daily basis, but at such a fine scale that it escapes our direct perception. Photons are as ubiquitous, but quite different from atoms and their constituents. Ubiquitous, because they are associated not only with visible light, but also with invisible radiation (infrared and ultraviolet), x-rays, gamma rays, radio waves, and even the radiation from our electrical network at 50 or 60 Hz. They are quite different because there is no mass associated to

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

the photon. A wave is associated with the photon, which is an oscillation propagating at the speed of light.

What is a wave? There is always a pattern and motion associated to the wave; the ripples of a stone thrown in a pond or folds of a flag. One can imagine more and more examples that the word »wave« is applied to. As physicists we would like to pause and clarify some features of the wave with definitions that can be used to quantify similar observations. If you take a picture from the ripples on the pond you realize that there are regular patterns that repeat in water, and you can possibly count the number of peaks on the water surface, that are separated by a »wavelength«. You can also only consider a fixed point on the surface and monitor its motion as it goes up and down, or oscillates. It takes a »period« for each point on the pond to repeat its position. The pattern on the wave (for example, the peaks) have a certain »speed« or »wave velocity«, and the peaks that are created by the wave have an »amplitude«. It is reasonable to conclude that stronger waves have bigger amplitudes, but there is more to the strength or energy of a wave, as we will see in the following sections.

When a wave goes through a medium it does not mean that the medium is necessarily moving with it. In the case of a flag waving in the wind, there is a wave that goes through the flag, but the fabric itself is not carried away. The wave propagates for huge distances, while each particle responsible for the wave motion stays at the same average position, just inducing the motion of the next particle. In most cases, the wave starts from a local oscillation (Figure 1.1a), and propagates radially from there, like rings produced by a duck paddling on a pond (Figure 1.1b). In the case of light, it is the electric field produced by a charge oscillating up and down that starts off the wave. This is called *dipole* emission.

The velocity of a wave is a property of the medium in which the wave propagates. Sound waves propagate at 343 m/s (1125 ft/s) in dry air at room temperature and faster in denser media. The opposite holds for light waves that usually travel faster in air or vacuum. There are different types of waves. Mechanical waves like spring oscillations and sound waves are due to mechanical motion of particles. The oscillation of these waves is along the propagation direction. Light waves, however, are electromagnetic waves, which originate from the oscillation of charges (electrons, for example). This was the first dilemma in early attempts to interpret light waves: what is moving?

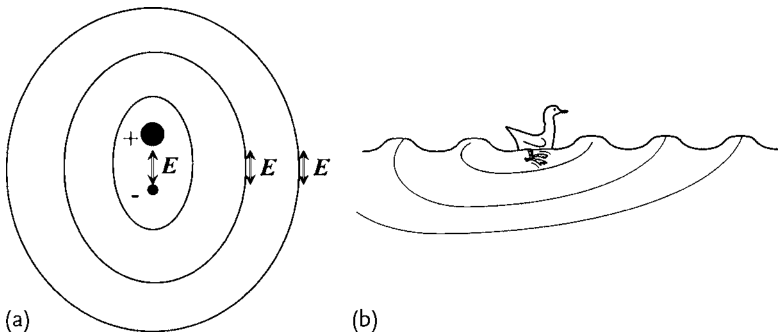


Figure 1.1 (a) An oscillating electric field is created by a pair of charges with a periodically varying distance (oscillating dipole). This periodically varying field creates an electromagnetic wave that propagates at the speed of light in vacuum, just as a wave is created in (b) by a duck paddling in a pond.

Our intuition is shaped by the observation of water waves in a pond, an oscillating spring, or the swing of a pendulum. These are all mechanical waves. Like sound waves, they require a medium; they need matter to exist. Hence was born the notion of the »ether«, a (fictitious?) medium to support the propagation of light waves. Today the »ether« has simply given way to vacuum, but it does not mean that the understanding of the nature of light has become simpler.

As will be explained in Section 1.1.2 below, quantum mechanics tells us that the amplitude of the positive–negative charge oscillation is restricted to discrete values. Consequently, the emitted oscillation also takes discrete values, to which is associated an energy: the photon energy $h\nu$, where ν the frequency of the oscillation, and h is called the »Planck constant« (see Eq. (1.1) in the next section). It is as if the duckling in Figure 1.1a had discrete gears to activate his webbed paws. What is more puzzling is that the »neutral« gear is missing. The minimum energy state of the quantum harmonic oscillator is not zero, but $(1/2)h\nu$. This is often referred to as *vacuum fluctuation* or zero point energy. The absence of vacuum (the ether concept) has been replaced by an absence of zero energy. Since, according to Einstein, there is an equivalence of matter and energy, the two concepts are not so far apart.

1.1.2 Photon Energy

Quantum mechanics tells us that a photon has dual characteristics, it acts both as a wave (Section 1.1.1) and as a particle. In a way, the photon is a wave that can be counted. This might be a bit hard to digest, since our common sense is restricted to our daily experience with objects that are not so delicate. What do we mean by acting like a particle? They can be counted. A photon is like a »currency«, and the light that we experience is like a sum of money, we never notice that tiny penny.

Let us take a closer look and see why we generally ignore single photons. A typical red laser pointer has an output power of 3 mW (3 mJ/s), which consists of individual photons having an energy of the order of 3×10^{-19} J. This means that every second there are 10 000 million million photons shooting out of a pointer. If we associate even a penny to each photon, in a second we get a sum of money that is more than the wealth of a country.

Just as not all currencies have the same value, photons have different energies. Here we need to use the wave aspect of the photon. The faster a wave oscillates, the more energy it possesses.

The longest (slower) electromagnetic wave that we encounter in our daily life is created by the 50 Hz electrical network covering the globe. As a result the earth radiates, making one oscillation over a distance of 6000 km. Radio waves are long too: it takes 3 m (3.3 yd) for a short wave (FM radio) to make an oscillation. For a long wave (AM) it takes about 300 m (330 yd) to complete one.

The visible light that we are used to also oscillates, but much faster. The green visible light consists of photons of 500 nm wavelength; meaning that over a thickness of a sheet of paper (which is 0.1 mm or 0.004 of an inch) it makes 200 oscillations. An x-ray with a wavelength of about 1 nm, oscillates 100 000 times over the same length. It thus appears that the following connection exists: photons that oscillate faster have a shorter wavelength, and more energy. Or in the simplified language of mathematics

$$E = h\nu = \frac{hc}{\lambda} , \tag{1.1}$$

where »E« stands for energy, »h« is the physical Planck's constant, »c« is the speed of light, »ν« is the number of oscillations of a pho-

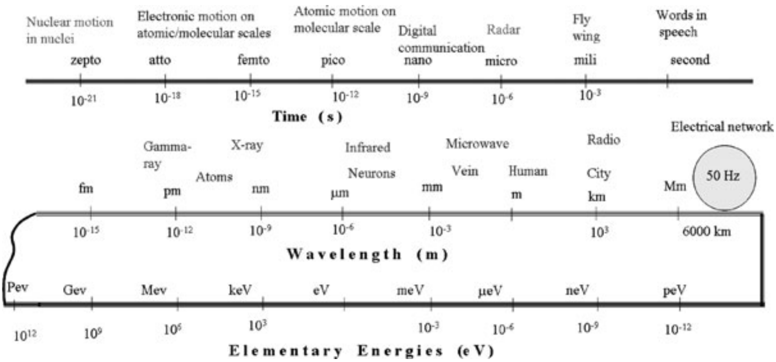
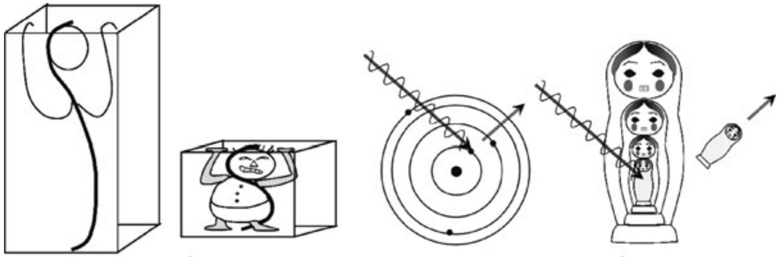


Figure 1.2 Different objects that radiate electromagnetic waves and the wavelength and elementary energy associated with them. Please find a color version of this figure on the color plates.

ton in a second, and »λ« is the wavelength, or the length in which a single oscillation takes place. For the photon associated with visible radiation, the elementary photon energy is too small to use the traditional energy unit of Joule. Instead, the energy unit used by physicists is the electronvolt (eV). 1 eV (1.602×10^{-19} J) is the energy acquired by an electron that is accelerated under the potential difference of 1 V. Infrared radiation at a wavelength of 1.24 μm has exactly the energy of 1 eV. As shown in Figure 1.2, our earth, due to the electric power network, radiates photons of 2.067×10^{-13} eV energy.

1.1.3 Energy and Size

Could »Spiderman« really have the strength of a spider, scaled up to his size? Is a cat that is 100 times more massive than a mouse 100 times stronger? In biology things will not scale linearly. Body mass increases linearly with volume in three dimensions, while muscle strength in arms and legs is proportional to cross-sections, and therefore increases only in two dimensions. If a human is a million times more massive than an ant, he is only 10 000 times stronger. In a way smaller animals are stronger relative to their masses. Physics scales in a simpler way than biology. In a musical instrument higher frequencies are generated by shorter strings, thus have more energy. Some physicists like to draw a box around the object that they study, and they know that as the box gets smaller they are dealing with higher



(a) (b) (c) (d)

Figure 1.3 Particle and wave in a box: the longer wavelength fits in the larger box (a). A shorter wavelength fits in the smaller box (b), corresponding also to a larger particle energy. Electrons (c) orbiting around the nucleus are analogous to nested Russian dolls (d). A photon of sufficient energy can knock off the electron of the outer shell, as one can easily remove the outer layer of the nested dolls. More problematic is the removal of an inner shell electron. While it would be an unresolvable »Chinese puzzle« to remove the inner doll, the possibility to eject an inner shell electron exists with high energy photons.

and higher energies. The speed and energy of the electrons oscillating in an atom are much bigger than the ones traveling in a long wire loop.

Using our wave picture and the equation of photon energy (1.1) we can look more closely at the size–energy relation. Consider fitting one full wave into two different size boxes. The wave that fits in the smaller box (Figure 1.3b) has a shorter wavelength than the one in the bigger box (Figure 1.3a). Using the photon energy equation (1.1), the wave with a smaller wavelength has higher energy. It seems that the more confined the wave, the stronger its elementary energy. This seems like an oppression force! Quantum mechanics tells us that the electrons around an atom are confined to well defined shells or electron levels like Russian nesting dolls (Figure 1.3c, d). The electrons in bigger shells have less energy and are loosely bound, which is why in most ionization processes the chance of knocking off an electron from an outer shell is the highest. This order is not as rigid as the order of taking out the Russian dolls: when dealing with higher energies photons, it is possible to scoop up the electron from an internal shell, leaving the external ones in place (not something you could to with the Russian dolls).

Looking at the waves in boxes, we only concentrated on the concepts of size, energy, and wavelength. There are other parallel manifestations of waves, such as in time and frequency. This means that in smaller boxes we are dealing with shorter time scales and faster frequencies. This is a very important fact for observing phenomena in nature: we need the proper time scale to watch an event. The speed that we take our data, or snapshots of an event, tells us what we can record and what we would miss. Imagine that we could only understand one word per minute. It would then be very difficult to get the meaning of sentences in a normal conversation. In cinematography 24 frames per second is sufficient to capture most daily events, but if we want to see faster events like a bullet passing through a target, we need to take more frames per second and then play it at a normal 24 frame per second rate. In Figure 1.2 the time scale of some events are shown. From this diagram one can see that in order to observe electron motion in atoms and molecules one should have a camera that takes picture every femtosecond. It is hard to imagine how fast a femtosecond is. If one could read the first Harry Potter book with 2.7 million words at the rate of one word per femtosecond, the whole book would be finished in a few nanosecond. Or, in other words, you could read Harry Potter a thousand million times in just 1 s. An attosecond is to the second, as a second is to the age of the Universe (0.4×10^{18} s). Figure 1.2 illustrates the various sources of radiation that affect our lives and how they are associated with energy, size, and time.

1.1.3.1 Light Energy

In the previous sections we talked about the energy of an individual photon; but only in a very sophisticated laboratory can one isolate a single photon. What we are exposed to usually consists of a large number of these photons. One can look at a light source as the wealth of a country and a photon as its currency unit. There is no country with a total wealth of only one unit of currency. For example, when we talk about wealth and debt of the United States of America, the numbers are in trillions, and it is quite easy not to mention a cent or two. That tiny cent which is the unit of currency is like a single photon. It exists, but is always lost in the total sum, just like a photon in a light source.

However, the analogy between currency and light stumbles at laser light. In our daily lives and economics there is only one way to add numbers. Luckily in science there are more. Let us assume not one duck as in Figure 1.1b, but two, paddling in synchronism as if competing in synchronized swimming. Along certain directions the wave will add »in phase«, along other directions they will cancel each other or »interfere destructively«. In the analogy of the coins, a large number N of photons of the same frequency will add up to N coins, for a total optical energy of $Nh\nu$. This is how daily white light of *incoherent light* adds up. In the case of laser light, or *coherent light*, N properly positioned and synchronized photons will produce a beam of $N^2 h\nu$. The reason is simple: it is the electric field of the waves that adds up coherently, which means overlapping the oscillations in phase (crest to crest and trough to trough). The total electric field is the sum of the electric field of each source element. However, the total *intensity* of the beam is proportional to the *square* of the total field and is thus proportional to the square of the number of emitters. When the waves are piled up randomly (incoherently) the phases do not match and only intensities are added linearly. Incoherent light is a crude summation over waves, it just adds the average intensity values and misses the phases. This property is being exploited by the US Air Force to create very high power lasers, by adding the beams of an array of fiber lasers.

One example of coherence can be found in the stock market. If we knew how to add coherently the phase fluctuations of the market, there would be no limit to our profit. It would take a financial wizard to buy stocks in a proper phase (exactly when they are at the lowest) and sell at the highest (peak). Such great wisdom is what fell upon physicists when they invented the laser; they found a way to add the photons coherently, stacking the waves on top of each other with equal phases.

How do we explain explain that incoherent »white light« adds up proportionally to the number of emitters N, rather than N^2? A similar addition takes place in daily life, at least for some of us. Suppose that, after having celebrated his graduation with numerous drinks, your inebriated friend starts heading for home, after hugging his favorite lamp post for the last time. The analogy of the photon field is his step. The total field is represented by the total distance from the lamp post to the end of the last step. How far will he have moved away from his starting point after $N = 100$ steps? The answer is: a distance of 10 steps away from the lamp post or $\sqrt{N}$ ft. If he had been sober, he would have moved 100 steps (N) straight towards his destination. Incoherent light fields add as incoherently as the steps of the drunkard: the sum of N elementary fields E of random direction adds up to a total field of magnitude $\sqrt{N}E$. An intensity I proportional to the square of the field is associated to each field E. The total intensity, in the incoherent sum, is $(\sqrt{N})^2 I = NI$. In the case of laser light or coherent light, the elementary fields line up, resulting in a total field NE and a total intensity $I_{\text{total}} = N^2 I$.

1.2 Radiation from an Atom

So far we have talked about photons as units of light energy that can be counted. They are not rigid; they act and move like waves. Now we want to know where they come from and how we can make them. In the following sections we learn how to add them properly (coherently) in a laser source. Photons are electromagnetic waves which are generated when charges oscillate. It is natural to turn our attention to atoms and molecules where there are as many electrons as the atomic number. Quantum mechanics tells us that not all the areas around the nucleus have the same chance of having electrons; electrons are stacked in shells just like the layers of Russian dolls. In the quantum mechanics world matter acts like waves, which means that it is hard to point at them as they are moving around. Electrons move around the atom nucleus in well defined shells. There are steps of energy and an electron can absorb a photon to change its energy status from one shell to another. Nothing gets lost in nature: if an electron goes from a lower energy shell to a higher energy one, it must have absorbed the energy difference. This is reversible: if an electron moves from a higher energy to a lower energy state, it must release the energy difference. That energy difference can be given entirely to a photon with an energy that satisfies the energy difference.

Just like the Brownian motion of particles, there is always fluctuations and excitements in the universe even in very remote places far from all galaxies. The electrons are just like children playing on slides in a playground as illustrated in Figure 1.4. Here, there are also clear energy levels; a lower energy on the ground and a higher energy up the slide. The children here use their muscle energy to go up the slide and they enjoy the release of energy when they slide down. This is similar to what happens around us, in all atoms. The electrons can pick up energy from photons around us, or even from thermal energy to climb the ladder and jump back down. That is how photons are absorbed and created.

(a) (b)

Figure 1.4 (a) A schematic of energy levels of an electron in an atom. (b) Children riding on slides; an analogy of electrons moving from one energy state to the other. We just have to imagine that the sound, momentum, and the joy of sliding down is the released photon energy. In the absence of coordination, this radiation is random or »spontaneous«.

The change in energy levels resulting in photon release is called »radiation«. This random radiation is everywhere and is »incoherent«. More than 40 years ahead of the realization of lasers, Albert Einstein formulated two types of radiation: »spontaneous« and »stimulated«. Spontaneous emission, like it sounds, is just the release of energy from higher to lower states without any coordination, just like the children in the playground of Figure 1.4. If the game is converted to a match by adding a referee on the ground giving the »start« signal, the motion of the children will be different. They will all wait at the top of the slide and start sliding at the gunshot. Here the radiation is stimulated. Another example of the comparison between stimulated and spontaneous emission can be found in shopping. Let us consider a number of people in the mall who are there with the intention of buying clothes and have the money in hand. They are all excited, just like our electrons in the upper state ready to emit. If there is a nice advertisement or a well dressed person walking by, our shoppers follow the signs and buy the same thing as they are being stimulated to. The stimulating advertisement or person puts their intentions in phase, inciting shoppers to walk in the same direction and simultaneously buy the same item. They are as hypnotized!

In the case of the emission from electrons in the excited states, a photon with similar energy difference in the vicinity of the atom causes the stimulated emission. One photon passing by one excited atom will stimulate the emission of another photon. Before the event, there was one photon and one excited atom. After the photon flew by, the atom energy has been reduced by the photon energy, and two identical photons are pursuing their course. The total energy of atom + radiation is the same before and after the interaction.

Having many atoms with electrons in the excited state, we need just a few passing by photons to make a cascade of photons with the same energy radiating at the same time, so well in phase. These photons also follow the path of the inciting photon and have the same direction. They have the same polarization, a concept that will be introduced in the following section.

1.2.1 Absorption and Dispersion

An electron can absorb a photon (or multiple photons in a nonlinear interaction) and move from one energy level to a higher level; it can also emit a photon and go to a lower level. The former is called *absorption* and the latter is associated to *gain*. The first one is like upgrading living standards by moving to a better house and putting down a sum of money; the second one is downgrading housing and releasing a sum of money for other causes. The house price is a fixed value and transition is only made when the money on the offer letter is provided. In the world of quantum mechanics, there is no fixed number and everything is described with *probabilities*. If the light frequency matches the separation the transition is more probable than when the frequency is off, but still even if the frequency is off, the transition in possible. The lines are not so sharp in quantum mechanics and there is always a shadow around them.

As seen in Figure 1.5, the absorption (which is the opposite of the gain) maximizes for the characteristic frequency »ν_0«. The absorption is not a delta function and has a characteristic *absorption width* in which the absorption is appreciated. Usually the absorption width is the range of frequencies over which the absorption is above half of its maximum value. In electromagnetism the *permittivity* »ϵ« is the resistance of the material to the light propagation, or how much it *permits* the light to go through. It is directly related to the electric *susceptibility* »χ,« which defines how easily the material is polarized by the electric field.

Absorption and index of refraction are two aspects of the complex function of light permittivity, the former being the imaginary part and the latter the real part. They are related mathematically through Kramers–Krönig relations. Using these relations, the index of refrac-

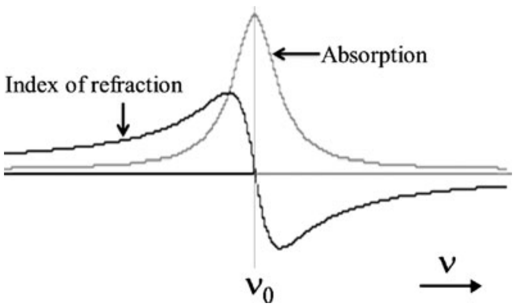


Figure 1.5 Absorption and index of refraction as a function of frequency ν. The absorption is maximized for the characteristic frequency ν_0. Any gain or absorption structure in the medium will effect the speed of light; as seen in the figure the light slows down for the frequencies less than the resonance and speeds up for the frequencies that are greater.

tion at a particular frequency can be calculated if the absorption at all frequencies is known, and vice versa.[1] The physical reason for this mathematical relation is »*causality*«; the fact that the material has a response time to the electric field. The response comes *after* applying the field. The speed of light »c/n« is directly related to the index of refraction »n«. No wonder the index of refraction curve in Figure 1.5 is known as the »*dispersion*« curve: the speed of light is lower for low frequencies and higher for frequencies higher than ν_0. A pulse covering all frequencies will be negatively chirped, with the frequency of the optical oscillation decreasing with time.

1.2.2 Polarization of Light

Polarization of light refers to the direction and path of the electromagnetic wave as it propagates. This property needs to be visualized in three dimensions. As for single photons, there is only one path for the wave: a circular path or »circular polarization«. A circular polarization propagates just like following the grooves of a screw, with one difference: most screws are tightened in a clockwise direction. They have only one helicity. A single photon has an equal chance of having either choices of helicity. Using the image of a screw, there are as many »left threaded« as »right threaded« screws. A ray of light con-

1) The opposite case, which is deriving the absorption from the measurement of the index of refraction at all frequencies, is mathematically possible but rarely practiced in reality.

sists of many such photons. By combining an equal number of photons with different helicity *in phase* one can get a linearly polarized light. A linear polarized light is a wave that oscillates perpendicular to the propagation direction and it can be visualized in two dimensions.

1.2.3 Beam Divergence and Resolution Criterion

Diffraction is a well known phenomenon in optics. When a wave passes through an aperture comparable to its wavelength, it gets distorted. When a bullet gets through a hole comparable to its size, it scratches the walls. For waves, the distortion is imprinted on the pattern as can be seen with water waves on a pond hitting a small obstacle. The reason for this distortion is wave addition or interference. The waves are generated at each point of the aperture. Looking at the two selected points at the edge of the aperture and at the center, we can add the wave amplitude coming from these two points on the observation screen. Since a wave completely changes its sign at half of its wavelength, if the difference in the path from the two beams is $\lambda/2$, there will be a shadow on a distant point on which the light transmitted by the aperture projected. The same difference is observed as we slide the two chosen points across the opening. They all result in the same path difference on a selected point on the screen.

Diffraction of a beam through an aperture is illustrated in Figure 1.6. The wave going through a circular opening is distorted. The black and white stripes of the beam are successive wavefronts, spaced by the wavelength. Being illuminated by a plane wave, all the points in the plane of the aperture are in the same phase of the oscillation (represented by the bright segment). As the wave from each point on the aperture propagates through different paths to the end screen, each one is in a different phase of its oscillation. The combination of all these rays, taking into account their interference, has an intensity distribution indicated by the red curve. This distribution depends on the shape and size of the hole that the wave has traversed. One can even follow the gray line that corresponds to the darkness on the right screen. The blue ray indicates a line corresponding to the first dark ring on the screen.

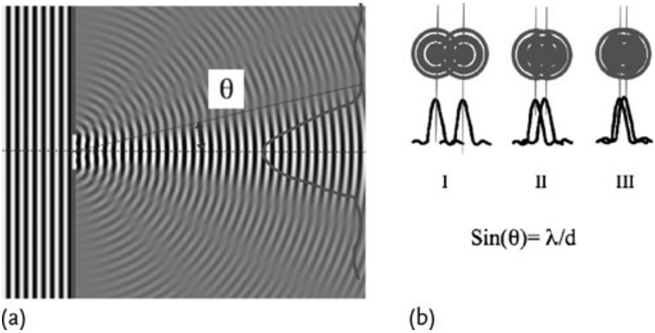


Figure 1.6 (a) Diffraction of a beam through an aperture. The path difference varies across the screen, showing more intensities where peaks from waves of different parts of the opening coincide and darker regions where peaks and valley coincide on the screen This results in an image (red pattern) of the aperture that is not so clear. (b) It is shown how far two points can be from each other in order to be distinguished. In order to resolve two images, the »Rayleigh criterion« defines the distance between the two points to be such that the first minimum ring overlaps the central maximum of the other image (case II). If the distance between the two points is larger (case I) the images are better resolved, while if the distance is smaller (case III) the resolution is lost. Please find a color version of this figure on the color plates.

For a plane wave[2] beam incident on a circular aperture, as shown in Figure 1.6, the angular observation of the dark rings on the screen follows the equation $D \sin(\theta_n) = n\lambda$, where $n = 1, 2, 3, \ldots$ is an integer, »D« is the size of the hole, and θ the angle of minimum brightness observed on the screen. For the first darkness »n« is 1.

A hole on the wave path is like a source emitting light through its extension, just like anything we want to observe by direct radiation or reflection. How close objects can be resolved is a major concern in all imaging techniques, from observing the stars to looking at tiny particles with a microscope. The resolution limit in imaging is called the Rayleigh criterion, which corresponds to having a minimum of one diffraction pattern overlap the maximum of the other one (II in Figure 1.6b). If the objects are closer (III in Figure 1.6b), the two peaks will merge, making it difficult to determine whether there are two objects. It is like having two people talking simultaneously. If there is a small delay between two words coming from the two persons, we might have a chance to catch the beginning of a one word and the

2) The plane wave is the simplest of all wave structures in space. It is an infinite sinusoidal wave with no transverse structure. It is represented as vertical, positive and negative stripes when the beam moves horizontally.

ending of the other one and record the two. However, when they speak within fractions of the second, it is not easy to distinguish both words clearly.

In imaging with lenses, from two objects, the Rayleigh criterion requires the distance between the two objects to be greater than $0.6\lambda/N_A$, N_A stands for numerical aperture. For imaging with a lens, $N_A = f/D$, where »*f*« is the focal length and, »*D*« is the diameter of the lens. Here the diameter of the lens corresponds to the hole size in the diffraction image. The Rayleigh criterion is a convenient concept used for any imaging technique from astronomy to microscopy.

1.3 The Anatomy of a Laser

Despite the simplicity of its acronym (*L*ight *A*mplification by *S*timulated *E*mission *R*adiation), the laser is more than just an optical amplifier. In general it has three main components: some »*pump*« mechanism to excite the radiation in a medium with optical »*gain*«, and a »*resonator*«, responsible for selecting the laser wavelength. The »pump« power can be electrical like a battery in a laser diode, or it can be another optical source. Its purpose is to excite the radiation. The »gain« medium can be a solid crystal or gas, prepared well to be excited and emit photons. We can use the photons radiated by the gain medium to induce »stimulated emission« by sending them back through the gain medium, provided it is still prepared in its excited state by the »pump«. A feedback mechanism is thus needed to return the waves, in phase, to the gain medium. This feedback is provided by a resonator, usually called the »laser cavity«. This resonator is not mentioned in the acronym, despite its essential role in the generation of laser light. There are some high gain pulsed lasers – such as the nitrogen laser or some excimer lasers, where the resonator is limited to one or no mirror. Because of the high gain, »lasing« occurs through the amplification of the spontaneous emission along the axis of the gain medium.

1.3.1 The Pump

The pump is the power plant for the laser and can take many different forms. It can be a source of incoherent light, like in many pulsed solid state lasers, it can be electrical, like in gas discharge lasers or in semiconductor lasers, it can be chemical energy, which is often the case in very high power infrared lasers used by the military, or it can even be another laser, which is the case for many crystal solid state lasers (the titanium sapphire laser, for instance) and dye lasers. It is often the pump that determines how efficient a laser system will be. There is a tremendous range of variation in the »wall plug efficiency« of laser systems. In a Ti:sapphire laser pumped by an argon laser, the argon laser will require over 30 kW of electrical power, to finally produce a Ti:sapphire laser beam of some 100 mW power! At the other extreme are the CO_2 laser and semiconductor lasers where the light output power is a sizable fraction of the electrical power input.

1.3.2 Gain

At the heart of a laser is a medium that has optical gain. It consists of an assembly of atoms or molecules that are in an excited energy state. In the analogy of the slides (see Figure 1.4) there are more children at the top than at the bottom of the slide. As a light pulse containing *n* photons[3] passes through such an excited medium, each photon will induce a certain number of stimulated emissions, resulting in an exponential increase of the number of photons with distance (in the medium). This is the reverse of the process of absorption, where the atoms are initially in the nonexcited state (»ground state«), and each photon will induce a certain number of upward transitions, resulting in an exponential decrease of the number of photons.

The higher the little girls stay on top of the slides before jumping, the more will be up on average. This is how a »population inversion«, necessary to achieve gain, is created. In laser jargon, an atom likely to be a good candidate as laser gain medium, is one where the upper level of the transition has a long lifetime. After each jump, the little child must quickly move away from the bottom of the slide, or there will be a traffic jam. Similarly, an essential condition for an efficient laser gain medium is that the lower energy state of the transition has a very short lifetime.

There is a process described in the next section by which atoms are put in the upper state: the »pump«. Given a constant rate of excita-

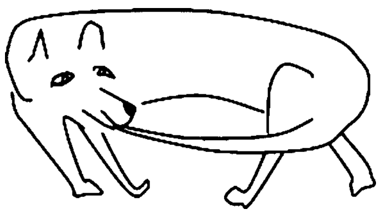
3) An optical pulse of a given energy in joules.
4) An optical beam of a given power in joules/s or watts.

tion into the upper state, in a continuous laser, n photons/s[4] passing through that medium will induce a certain number of stimulated emissions, resulting in an exponential increase of the photon flux (or beam power) with distance.

1.3.3 The Laser Body (Resonator)

Musical instruments are designed based on the fact that the size and geometry of the instrument defines what frequencies can be resonated in it (Section 1.1.3). However, it took a long time to apply this fact and combine it with all other elements to make a laser.

The analogy that we want to draw from in this section is that of an acoustic amplifier between microphone and speaker, when the microphone is put too close to the speaker. We have all heard the high pitched noise that drowns any other sound when the gain of the amplifier is turned up. Noise from the speaker enters the microphone, gets amplified, is blasted from the speaker into the microphone again, and so on. It is a case of a dog chasing its tail.



The same synergy exists between the optical gain medium and the optical resonator as between the oscillating amplifier and a musical resonance between microphone and speaker. The laser is a similar arrangement: an optical – rather than acoustic – amplifier where the output (i.e., the speaker) is fed back to the »input«. In the »acoustic amplifier«, the frequency, or pitch, of the oscillation can be set by any object with an acoustic resonance: a crystal vase, a glass, the string of a guitar, a tuning fork, a cymbal, a drum, ...

The closest analogy to the laser is that sketched in Figure 1.7a, where the microphone is inserted in a drum. It takes the least amount of energy to excite the note for which the drum is tuned. The noise from the speaker puts the membrane of the drum in vibration, result-

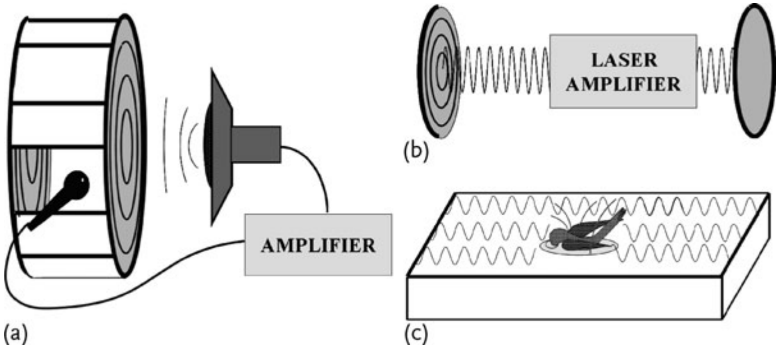


Figure 1.7 (a) An acoustic analogy of the laser: an amplifier with feedback. The pitch or wavelength of the sound produced is determined by the acoustic (mechanical) resonance of the drum. The laser is also an amplifier with feedback, where gain (Section 1.3.2) plays the role of an amplifier. A light beam that happens to be perpendicular to the two mirrors on either side of the optical gain medium is amplified. As the light wave makes a round trip from one mirror to the other and back to the initial point, it has to add upon itself, which imposes that the round trip length should contain an integer number of waves. The same situation occurs for the bird taking a bath: out of all the »noise waves« that it produces, the container is a resonator that will select the ones that add up upon themselves, hence have an integer number of crests between the walls.

ing in a plane compression wave of air propagating between the two faces of the drum, which is picked up by the microphone, amplifier, and fed back to the drum. A similar scenario takes place in the laser as sketched in Figure 1.7b. In the latter case, the resonance is provided by the mirrors guiding the light back and forth through the optical amplifier. Some of the sound is lost in going from the microphone to the amplifier. The gain has to be turned up to compensate for these losses. That minimum gain is called the threshold of oscillation, or the *lasing threshold* in the case of a laser.

An integer number of wavelengths has to fit in the »box« defined by the two mirrors of the laser resonator, otherwise the crest and the trough of successive waves will cancel each other. A similar situation occurs when a bird takes a bath in a perfectly rectangular container. No matter how wild it splashes in the water, it will produce standing waves that fit exactly the length of the box. This is a one-dimensional analogy – we should assume here that the transverse dimension of the box is infinite.

The role of the mirrors is twofold: they provide the wavelength selection, as well as the directionality of the laser beam. If the mirrors are perfectly plane, only the waves that are exactly, rigorously orthogonal to these two planes can provide the »feedback« to the optical amplifier. Only the first few lasers were built with flat mirrors. It was soon realized that curved mirrors made a laser considerably easier to align: a nonperfectly axial beam will still reflect back within a narrow cone, but it is no longer the »ideal resonator«.

The light amplifier and the resonator are not in perfect symbiosis, but thrive for different properties. As in acoustics, the resonator is there to provide purity of tone, eliminating any wavelength that does not fit as an exact integer fraction of the cavity length. Thus in a 0.5 m long laser cavity, there are $n_\lambda = 1\,000\,000$ wavelengths of 1 µm in a round trip (1 m). At a wavelength of 0.999 999 5 µm, the round trip corresponds to 1 000 000.5 wavelengths, meaning that, if the wave started with a crest at one mirror, it will come back with a trough and which will cancel the wave.

The most selective resonator will have mirrors of the highest reflectivity possible. In Figure 1.7b let us consider one end as a mirror with 100% reflectivity and the other mirror with a minor leakage (reflectivity 99.9%). A mirror designed for extraction of laser cavity power is called *output coupler*. If we were to turn off the amplifier and look at the evolution of stored energy in the resonator, we would see that after the first trip the light is reduced to 99.9% of its original value. In a second trip $(99.9 \times 99.9) = 99.8\%$ of the energy stays inside. How many trips does it take for the light to be reduced to half of its energy? After N_{RT} round trips, where $99.9^{N_{\mathrm{RT}}} = 0.5$ only half of the energy is stored in the resonator. With a help of a calculator in our example one finds this number to be 693 round trips. In other words, it takes 693 times the cavity length for the light to be reduced to half, and all the waves must perfectly overlap over this length. The effective length of the cavity is multiplied by 693. In the example of the 0.5 m cavity, even a wavelength off by $1/(693 \times 1\,000\,000)$ of a µm will be selected out, because it will interfere destructively with itself after N_{RT} round trips.

While a laser with a good resonator – called a »high Q« cavity,[5] provides a stringent wavelength selection, it does not produce large output power. Only a trickle (1.0%) of the power generated inside the resonator leaks out as useful output. In order to have large power out

5) The letter Q is used to designate a »quality factor« of a resonator – it is proportional to the number N_{RT} of round trips that survive in the cavity.

of a laser, one would need an end cavity mirror of large transmission, for instance 50%, requiring a gain of at least a factor of 2 per pass. Not only the wavelength selectivity is compromised by the large output coupling, but even the collimation of the beam. Indeed, since the lasing condition is achieved only after one round trip, any oblique ray that experiences two traversals of the gain volume will be part of the output beam.

It seems that lasers are not like a blast of energy as in a bomb, but rather a very conservative source of energy. Only a small percentage of the stored energy leaks out, similarly to the interest trickling out of a savings bank account.

It appears thus that, in order to create a laser of high output power, one has to compromise against the main qualities that characterize a laser beam: beam collimation and frequency selectivity. The solution to this dilemma is to inject the output of a low power, narrow band, and well collimated »seed« laser, into a high power »slave laser«. This is based on two types of radiation that we have already learnt.

We have seen that the stimulated photons are identical and undistinguishable from the stimulating photons. In general, a laser radiation is initiated by random spontaneous emission. The role of the seed photons is to overpower the spontaneous emission. As long as the seeded coherent radiation exceeds the spontaneous emission in the slave laser, the latter will clone the directionality, phase and frequency of the seeding radiation. This technique is also called »injection locking«.

1.4 Some Examples of Lasers

1.4.1 He-Ne Lasers

One of the first and most manufactured lasers has helium-neon as a gain medium. The first continuous He-Ne lasers were a technological challenge – in particular the ones built with a pair of flat mirrors for the cavity. Since the red He-Ne laser has a very low gain (of the order of 0.1% per pass), the radiation losses should be less than 0.1% in order for the laser to operate (or to reach the »lasing threshold«). The tolerances in flatness are incredibly difficult to meet … and maintain. In addition, the gain of the red He-Ne laser emission line is very small;

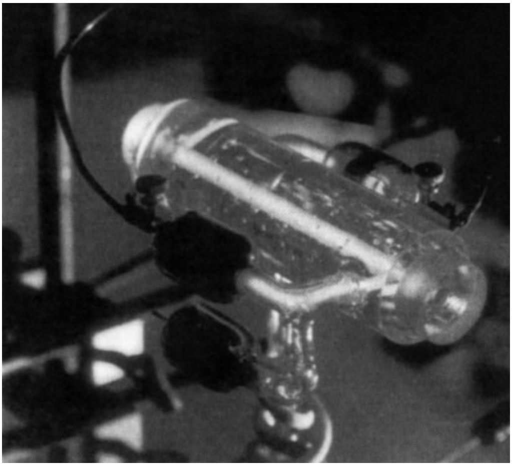


Figure 1.8 Short (12 cm) stable He-Ne laser with flat optical elements, directly bounded to the fused silica body (courtesy of Dr. Haisma, with permission from Koninklijke Philips Electronics N.V., Eindhoven from [1]). Please find a color version of this figure on the color plates.

it is not sufficient to compensate for the absorption of the best metallic mirrors. Good dielectric mirrors had to be developed for this laser. In the early 1960s, just after the first helium-neon laser was demonstrated, Philips Research Laboratories in Eindhoven (*Nat*uurkundige *Lab*oratorium) took up the challenge to make the perfect laser with a perfect flat resonator. The result was a thick wall cylinder of quartz, polished at both ends to better than 0.02 μm flatness, and a parallelism of better than 1 arcsec [2]. It thus required the development of polishing fused silica with extreme flatness and parallelism. In addition, coating techniques were developed to reach a reflectivity of 99.6%, a scattering of 0.1%, and a transmission of 0.3%. Mirrors and the polished quartz were of such perfect flatness and so polished that they formed a vacuum tight seal when put in contact – a technique still not very often used to this day because of the stringent finish requirements. There was no alignment possible and no room for error. The challenge was successfully met, leading to the laser sketched in Figure 1.8, probably the first and last He-Ne laser of its kind.

The perfectly cylindrically symmetric laser allowed putting some fundamental questions to test, such as the nature of the electric field produced by a laser. Is it always a linearly polarized beam and an electric field oscillating along a particular line perpendicular to the beam?

The answer was always yes, despite the fact that there was no preferential direction for the laser to oscillate.

1.4.2 Lasers for the Cavemen

Clearly, the He-Ne laser was not only a scientific innovation, but its construction required high vacuum technology, high quality dielectric coatings, and mirror polishing to a high degree of flatness. Other lasers, due to their high gain and/or long wavelength, did not pose such a technological challenge. For instance, the CO_2 infrared laser could have been built centuries ago, if only somebody had come across the recipe. Here the idea came far after the technology was available. Many »kitchen« versions of these lasers have been built and have probably cost their inventor a hefty electrical shock and a burned belly button. Lasers are typically more efficient at longer wavelength. Infrared lasers are easier to build and are more efficient than, for instance, ultraviolet lasers. One reason is that the mirror technology is simpler: the flatness only has to be comparable to the wavelength, which is considerably easier at 10 μm (10^{-5} m) than at 0.6 μm. Another reason is that inversion is easier to achieve, because there is less competition from spontaneous emission. Indeed, spontaneous emission rates are higher for more energetic transitions. As if the challenge of a higher slide in Figure 1.4 attracted children – a kind of reverse acrophobia?

1.4.2.1 The CO_2 Laser

An example of a continuous CO_2 laser is sketched in Figure 1.9. It is a tube of pyrex or quartz, typically 6–10 mm inner diameter, and 1–2 m long. Ideally, a second concentric tube is used for water cooling. An electric discharge requires a power supply of 15 to 25 kV, providing a current of 10–20 mA (current limiting resistances are essential, since the discharge has a negative resistance characteristic). A mixture of carbon dioxide (CO_2), nitrogen (N_2) and helium (He) is used, typically in the ratio 1 : 2 : 10, at a pressure of 10–30 torr.[6] Since CO_2 is the laser medium, one may wonder why the other gases are added. In fact, some gain exists in the discharge even with pure CO_2. However,

6) 1 torr is 1/760 of atmospheric pressure.

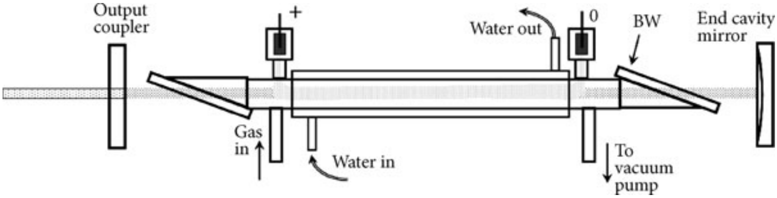


Figure 1.9 Typical low pressure CO_2 laser. The two windows (BW) can be made of germanium or salt (transparent to the wavelength of 10 μm emitted by the laser). They are at an angle such that there are no reflection losses for a beam polarized in the plane of the figure (called the Brewster angle). The electrodes can be small cylinders of nickel. The reflectivity of a flat plate of germanium (80%) is sufficient to achieve lasing action. The other reflector can be a flat metallic mirror (a concave mirror – typically 20 m radius of curvature – is generally used).Please find a color version of this figure on the color plates.

a marvel set of physical coincidences boost up the efficiency of that laser when the other gases are present.

The CO_2 laser is a *vibrational laser*. This means that the photon is emitted when the molecule switches from a higher energy mode of vibration to a different mode of lower energy. The CO_2 molecule is linear, with the carbon in the middle. Specifically, the upper state of that laser corresponds to the asymmetric motions of oxygen atoms with respect to the central carbon atom. To visualize this, one can picture an oxygen moving towards the carbon, while the oxygen at the other end is moving away from the carbon. The lower state is still an excited state, but corresponds to the »bending mode«, where the motion is that of a bird flapping its wings, with the carbon being the body, and the oxygen at the tips of the wings. When the electrons in the discharge collide with a CO_2 molecule, the latter gets excited somewhat preferentially in the asymmetric mode, the upper level of that laser. However, the electrons excite the vibration of a nitrogen molecule much more efficiently. Because the quantum vibrational energy of nitrogen is nearly equal to that of the CO_2 asymmetric stretching, that mode gets preferentially excited. Thus excited the CO_2 can emit a photon and in the process change to a bending mode or a bird flapping wing mode. How does the vibrating molecule come down to rest? Collisions with a helium atom are very effective in transferring the bending vibration energy of CO_2 into translation energy of the He, which is just heat. Helium is a very good heat conductor and will become cooled by collisions with the wall of the tube. Another approach for eliminating the heat is to replenish the medium quickly, in other words to increase the flow of gas.

The basic design of Figure 1.9 has evolved over the years to lead to multikilowatt lasers used for machining. The evolution towards higher power and efficiency has been quite straightforward.

One essential part of the efficient operation of a laser is the removal of the molecules in the lower state. For each photon created by stimulated emission in the beam, a CO_2 molecule is left in the bending excited state. When all the molecules have accumulated into that state, there can be no longer amplification. It is thus imperative to remove them. There are two methods: to remove them physically (high flow »gas dynamics« lasers) or to cool them more effectively. The latter approach involves increasing the (cooling) to surface ratio, which is the approach used in planar waveguide lasers, where the cooling surfaces are metallic plates also serving as electrodes. The other approach is to increase the energy of the laser, for a given size, is to increase the number of molecules participating in the gain, hence to increase the gas density. This has led to the atmospheric pressure pulsed CO_2 laser, where a strong electrical discharge is applied transversally across a tube containing a mixture of CO_2, He and N_2. These lasers are generally called TEA lasers (»transverse electrical discharge«). This type of laser produces nanosecond pulses of several joules of energy. High power – several kilowatts – CO_2 lasers are manufactured for industrial applications, welding, cutting, surface treatment, and so on ...

1.4.2.2 The Nitrogen Laser

The nitrogen laser is another example of a laser that was simple enough to appear in peoples's kitchen, following a recipe published in the Scientific American in 1974 [3]. Surprisingly, in view of the previous discussion in the introductory paragraph of Section 1.4.2 about the infrared lasers being easier to produce, it is a UV laser operating at 337 nm. As stated previously, there is more competition from spontaneous emission at short wavelength. Indeed, the energy level responsible for lasing in the nitrogen laser empties itself in a few nanoseconds. It is, however, relatively easy to produce a strong electrical discharge transverse to the lasing direction in a shorter time. The energy storage is electrical: a thin sheet of mylar or other dielectric sheet able to withstand very high voltage without breaking down is sandwiched between two copper plates to constitute the energy stor-

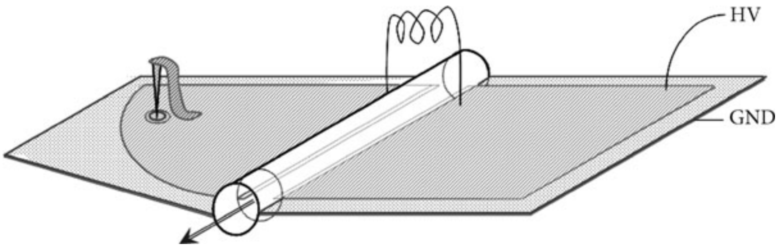


Figure 1.10 Sketch of a typical nitrogen laser. Copper foil is taped on both faces of a thin dielectric (circuit board, Kapton, or Mylar), creating a capacitive transmission line, which is charged via a resistance by a high voltage power supply (right side). The upper copper plates terminate as line electrodes in a discharge tube. The left capacitor/transmission line is connected to the right one via inductance of a resistance. On the far left: the spark gap that acts as a switch short-circuiting the capacitor (it can be a needle connected to the upper plate, pointing towards the ground plate, or a car spark plug). The short circuit propagates towards the right, brings the left electrode to ground potential, inducing a discharge across the tube, lasting until the complete capacitance is discharged (about 1 ns). The tube is closed by two windows, or one window and a mirror. Pure nitrogen at 25–50 torr pressure is pumped through the tube (air can also be used, but the performances are reduced). Please find a color version of this figure on the color plates.

age capacitor, as sketched in Figure 1.10. One of the plates is connected to a high voltage (in the order of 10–20 kV) and will also constitute the high voltage electrode of the laser. The other electrode is connected to a similar sandwich, terminated by a switch called the spark gap to the right of the figure. Some lasers have been built using just a car spark plug as a switch. Initially, the two capacitors are charged to the same voltage (they are connected by a resistance). As the spark gap (or spark plug) is fired, the short circuit established at that end propagates towards the left at a speed close to the speed of light, and a step function current of the order of a nanosecond in duration traverses the discharge tube. A little venturi pump can be used to flow the nitrogen at a low pressure (25–50 torr) through the tube. No mirror is needed: because of the laser spontaneous emission and very large gain, the geometry of the tube is sufficient to have light amplification by stimulated emission radiation without any mirror. Adding a mirror at one end increases the output energy, because the length of the amplifying medium is doubled. This simple technology grew in a small laboratory in Göttingen and led to one of the largest manufacturers of nitrogen lasers and excimer lasers. These lasers were extremely popular for three decades as a pump for visible dye lasers.

1.4.3 Semiconductor Lasers

Only two years after the birth of the first laser in 1960 (the ruby laser) IBM, GE, and the Lincoln labs of MIT simultaneously announced the realization of the semiconductor *p*-*n* junction laser. These first *diode lasers* (also called »injection lasers«) were made of gallium arsenide (GaAs). A semiconductor is characterized by having two energy bands instead of discrete energy levels as is the case for atoms and molecules. Photons are emitted by the transition of an electron from the higher energy band (the *conduction band*) to the lower energy band (the *valence band*). The two bands are separated by an energy difference called *band gap*. The laser consists of a small single crystal, with two halves of different physical properties, achieved by doping the crystal on either sides with different elements. The »*n*« region is doped with impurities labeled »donors« (for instance Se), because they tend to produce an excess of electrons giving this part of the crystal metallic like properties. The »*p*« region is doped with impurities labeled »acceptors« (for instance Zn), which tend to trap electrons, leaving no electron in the conduction band. The electrical properties of such a combination are asymmetric: the current will flow easily from the *p* side to the *n* side, while the junction will show a very high resistance if a positive voltage is applied to the *n* side and a negative one to the *p* side. Hence the label »diode« for these devices.

As voltage is applied to the diode, positive on the *p* side, negative on the *n* side, the electrons will cascade down from the high energy conduction band into the valence band at the location of the junction, where a population inversion (between the conduction band and the valence band) is created (Figure 1.11), provided that the current is sufficiently large. It is as if the electrons flow down a river, encountering a sudden drop at a waterfall. The radiation is thus emitted along a line that marks the junction between the *p* doped side and the *n* doped side of the semiconductor. While having a lot in common with standard lasers, a striking peculiarity of semiconductor lasers is their size. The *p*-*n* junction lasers are minuscule, with a size of about 0.1 mm. The junction thickness itself is of the order of 1 μm. The shorter the cavity, the less it will select a particular frequency, and the lesser its collimating properties. The gain of the junction laser can be very high. It is therefore not necessary to use a reflective coating on the facets of the

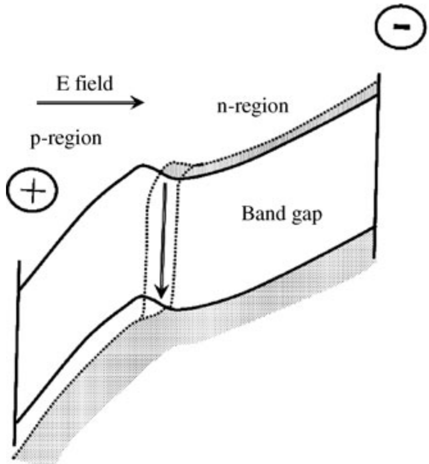


Figure 1.11 Energy band structure of a semiconductor laser. The occupation of electrons shown by the gray area extends in the conduction band in the *n* region and does not reach the top of the valence band in the *p* region. As a field is applied to the semiconductor, the electric potential adds to the electron energies, resulting in slanted bands (a). The current of electrons flows down the »river« of the conduction band to cascade down to the valence band at the junction just as a waterfall (b). Please find a color version of this figure on the color plates.

cube. Because the index of the refraction of GaAs is very high (3.34), the uncoated facets have a reflectivity of 30%, which is sufficient for lasing. If better performances are needed (single frequency or wavelength, better directionality), one may put an antireflection coating on the facets and place the semiconductor gain medium in a traditional cavity with mirrors.

Another limitation associated with the minuscule size of the *p-n* junction laser is the optical power that can be extracted. With a gain volume that is in the μm^3 range, the intensity can reach the damage threshold with only a few tens of milliwatt of optical power. The other limitation to the output power is saturation. It will be shown in Section 1.5.2 on »saturation« that the media that have a stronger gain and larger spontaneous emission, will see a drop in gain at lower intensities. Therefore, one would expect that semiconductor lasers do not have a future in high power applications. There is, however, a solution to the power limitations brought on by the microscopic emitting cross-section (a narrow line at the junction) of the semiconductor lasers: a total change in geometry leading to a large emitting area. These are the vertical-cavity surface-emitting lasers (VCSEL) and the vertical-external-cavity surface-emitting lasers (VECSEL). Instead of emitting in the plane of a junction, these lasers emit along the normal to the plane. Instead of being pumped by an electrical current, they are pumped optically (although electrically pumped devices are under development). With a large emitting area, one can expect to extract more power out of the semiconductor laser for the intensity corresponds to complete inversion. Most often the limiting factor is the optical pump power available.

1.4.4 Fiber Lasers

1.4.4.1 Introduction

The first few years following the discovery of the ruby laser were full of surprises. After 50 years, the ruby laser has nearly fallen into oblivion. As early as 1961, another laser was discovered, which was left largely ignored for the next three decades: the fiber laser [4, 5]. The gain medium was a fiber of barium crown glass, doped with the neodymium ion Nd^{3+}. This laser did not promise a bright future. Citing a review of the laser technology near the end of the first decade of laser development: »A number of fiber optics lasers have been constructed using Nd^{3+} in glass (wavelength 1.06 μm) as active medium in glass, but these devices have thus far not played a conspicuous role in the development of laser technology« [6]. Fiber lasers have started their comeback since the development of ultralow loss fibers for communication in the 1980s. Fibers are slowly extending their tentacles over areas where gas lasers or solid state lasers have been well entrenched. As a commercial ultrashort pulse laser, the fiber laser has even taken a big chunk of the market from the Ti:sapphire laser. It is now considered to be one of the most promising weapons for the Air Force, having replaced the development of chemical lasers.

Two main breakthroughs in fiber technology (i) the manufacturing of near lossless fibers and (ii) speciality fibers dubbed »Holey fibers«, »photonic crystal fibers«, or »photonic band gap fibers«, are contributing to progress in fiber lasers. The first is a material technological advance, the manufacturing of ultrapure silica, which has enabled the production of silica fibers with such a low loss that, after propagation through 1 km of fiber, 1 W of optical power would only be attenuated to 0.96 W.[7] The second advancement results from progress in manufacturing, which has made it possible to produce fibers where the inner core consists of a complex pattern of hollow and filled structures.

1.4.4.2 Optical Fibers

An optical fiber has very much the appearance and size of a hair. In fact, after a long haired graduate student had completed a complex fiber laser system, it became very difficult to disentangle hair from fibers. Optical fiber in fact exists in nature: the hair of polar bears not only provides insulation, but conducts the sunlight to the skin. A polar bear might even get a suntan under his white coat! The principle of light conduction in fibers is total internal reflection, as sketched in Figure 1.12a. If a light ray is incident on an interface between a medium of a high index of refraction n_{core} and a lower index n_{cladding} there will be a critical angle of incidence α_{cr} beyond which no light is transmitted, and all light is reflected by the interface (hence the name »total internal reflection«). The critical angle is given by $\sin\alpha_{\text{cr}} = n_{\text{cladding}}/n_{\text{core}}$. An optical fiber consists essentially of a filled spaghetti where the core would be denser than the outer part. The material of the core has a higher index of refraction n_{core} than that of the surrounding called cladding (n_{cladding}). Rays that are incident on the interface at an angle larger than α_{cr}, – or that make an angle with the axis of the fiber smaller than θ – are trapped in the core. Of course, the light energy will propagate at a different velocity for all the rays that zigzag through the fiber core at a different angle. This effect is called *modal dispersion* (the larger the angle, the smaller the light energy traveling along the fiber). We have seen in Section 1.2.3 that a beam of diameter D spreads (diffracts) with a half angle $\theta = \lambda/D$. If the diameter of the core is large, a large number of rays with different angles can be trapped by total internal reflection. If the diameter of the fiber is reduced, the value of λ/D increases until that angle reaches the critical value. There is at that point only one ray that can be trapped: the fiber is said to be *single mode* for that wavelength. Fibers with a larger core diameter are called *multimode fibers*. A single mode fiber at a given wavelength can be a multimode fiber at a short-

7) The fiber manufacturers express the fiber loss in dB/km, where the decibel is defined as 10× the logarithm in base 10 of the ratio of the transmitted power to the input power. The Corning fiber SMF 28 ULL has a loss of 0.17 dB/km.

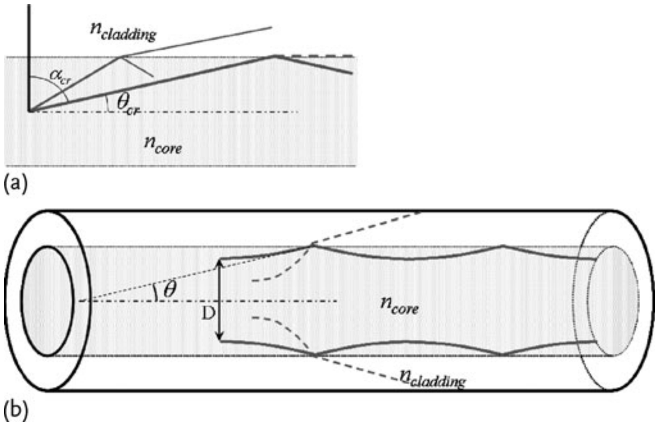


Figure 1.12 (a) Beam incident from the bottom on the interface between two glasses of different index of refraction $n_{\text{core}} > n_{\text{cladding}}$. Rays incident at an angle larger than or equal to α_{cr} are totally reflected, without any loss in the medium of index n_{cladding}. (b) Total internal reflection takes place between the core of an optical fiber and the cladding, provided that the rays make an angle with the axis of the fiber smaller than the critical value $\theta = 90° - \alpha_{\text{cr}}$. The smallest beam diameter *D* that can be trapped is the one for which the diffraction angle λ/D (see Section 1.2.3) corresponds to the critical θ. If the core diameter is equal to *D*, the fiber is said to be single mode. Please find a color version of this figure on the color plates.

er wavelength. The single mode fiber is to the fiber optics what the fundamental ideal Gaussian beam, least diffracting, is to free propagation.

The high quality of single mode fiber optics does not come cheap or easy. A fundamental problem is that the glass homogeneity and accuracy with which the index of refraction can be controlled implies a small core size – of the order of 10 μm. Such a small core size is incompatible with high optical power, since the large intensity (power/core area) will result at best in nonlinear effects (intensity dependent index of refraction, generation of unwanted wavelengths), at worst in the destruction of the fiber. Other related problems are:

- Rapid saturation of a fiber laser amplifier.
- Difficulty to effectively couple the fiber to the outside world. An extreme positioning accuracy is required to effectively couple light from a Gaussian beam into a fiber and vice versa.

- Difficulty in coupling fibers to fiber.
- Difficulty in controlling the polarization along a fiber.

The latter point is due to the fact that any motion, bending, temperature change, and acoustic disturbance of a single mode fiber affects the polarization of the beam that is propagated through the fiber. The development of fiber lasers and fiber laser amplifiers is intimately linked to progress in single mode fiber optics. The polarization instability and uncontrollability has been solved through the development of polarization preserving fibers, with a slightly different index of refraction along two orthogonal axes. Light linearly polarized along one of these two axes will conserve its polarization. Remarkably sophisticated instruments have been developed to accurately splice two fibers together (single mode or polarization preserving) with minimum loss.

A significant breakthrough came when researchers at the University of Bath created a new family of single mode fibers, by using as a preform[8] an array of capillary and rods [7]. This new fiber was fabricated by putting together glass tubes of hexagonal cross-section, forming a regular pattern, with a full rod in the center. By pulling and stretching this structure, the dimensions of the cross-section were reduced by a factor of 10 000, until the central rod was reduced to a diameter of the order of 1 μm, the pitch (spacing between holes) reduced to 2 μm, and the holes had a diameter of between 0.2 and 1.2 μm. A considerable number of variations have been made on these structure, leading to an equally large number of exotic effects. Because of the better guidance of the light by the pattern of holes surrounding the core, the »single mode« guidance is observed over a wavelength range covering the visible to the near infrared [7]. The fiber can be engineered to have the light pulse traveling at the same velocity over a broad range of wavelengths [8], which is an important property for the transmission of ultrashort signals (cf. Section 1.7.3). Because of the high intensity at the core rod, a rainbow of new wavelengths can be generated [8]. Other exotic effects are being investigated by inserting vapors or gases in the capillaries surrounding the core [9, 10].

8) The fiber are typically drawn from a preform consisting in a cylinder of glass. In this particular case, the solid cylinder is replaced by a bundle of tubes, of which the inner diameter is progressively reduced in successive stretching steps.

1.4.4.3 Fiber Amplifiers

The fiber laser amplifier is the simplest device of all. The core of the fiber is generally doped with some rare earth (erbium for 1.55 μm lasers, neodymium and/or ytterbium for 1.06 μm fibers, to cite only a few). In very early designs the fiber was wrapped around a flashtube. This practice was totally abandoned with the availability of efficient semiconductor lasers. The pump light from a semiconductor laser is coupled to a fiber which is coupled directly into the doped fiber with a wavelength division multiplexer (WDM), the fiber equivalent of the railroad switch, or beam splitter mirror. The limit to the amplified power is set by the cross-section of the core: the laser beam cannot be amplified beyond a certain »saturation intensity« (power divided by cross-section), which is discussed in Section 1.5.2. The minuscule cross-section of the fiber core sets an upper limit to the power that can be amplified. There has been considerable progress recently in the manufacture of large core fibers, with special cladding guiding the pump light, such that the amplified power has approached the kW level. It is anticipated that a very high power device can be realized by adding the *field* (i.e., adding the laser beams as waves in phase) of several of these devices.

The semiconductor laser pump pulse loses its energy as it propagates down the doped fiber to create a population inversion. For a given pump laser, how can one determine the useful (optimal) length of fiber to be used, given that the IR beams (pump and laser) are in-

Figure 1.13 Erbium doped fiber glowing in the dark, upon excitation by the pump radiation at 980 nm. Please find a color version of this figure on the color plates.

visible and hidden inside the core of the fiber? Figure 1.13 offers an answer. It shows and erbium doped fiber pumped by a 980 nm semiconductor laser. The pump photon excites the erbium to the upper state of the laser transition, as it should to create a population inversion for 1.55 μm. However, other pump photons excite the erbium from that level to a higher energy one, from which green fluorescence is emitted. Hence the green glow can be observed in the dark, emanating from an erbium doped fiber laser or amplifier.

Since there is no limit to the length of a laser amplifier (provided one can continuously add pumped sections), one might wonder how a laser pulse will evolve after a considerable distance. Will it evolve towards a steady state entity, like a light bullet speeding through the core, and without any shape distortion? We will see that this can indeed be the case, in the study of short pulse propagation in Section 1.7.

1.4.4.4 Fiber Lasers

As we have seen in Section 1.3, the laser is simply an optical amplifier sandwiched between two mirrors. The same high reflectivity, low losses, and high power mirrors that have been designed for other lasers do not apply to the fiber: the cross-section is too small to make precise multiple layer deposition on the fiber end. A simple technique employed in the past was to dip the fiber end in mercury, but the use of mercury has lost its popularity. Another technique still in use is metallic coating on the fiber end, but the intensity at the fiber core may be sufficient to vaporize the thin film. The fiber equivalent of the dielectric mirror is the fiber Bragg grating. A dielectric mirror consists of a stack of transparent materials of different indices of refraction. The material and layer thickness are chosen in such a way that the reflections produced at each interface add in phase, resulting in a near prefect mirror if a sufficient number of layers is used. The fiber Bragg grating consists of periodic changes of the index of refraction over a considerably longer distance than the thickness of a dielectric mirror. The basic principle, however, is similar: the changes of index are engineered in such a way that the backscattered radiation adds in phase. A solution that circumvents the need for mirrors is to have the laser literally as a dog biting its tail: splice the input end to the output end to form a ring. A short pulse that is let to evolve in this amplifier in a ring configuration, looks in vain for the end; the ring is in this case equivalent to the infinitely long amplifier of the previous section. In certain conditions discussed in Section 1.7, the short pulse will evolve as a light bullet circulating endlessly in the ring. Here again the equivalent of railroad switch, or WDM, will come handy in extracting the pulse at every round trip.

One of the most successful commercial fiber lasers is the femtosecond source of IMRA America, which produces a train of pulses of the order of 100 fs in duration at a repetition rate of 50 MHz. This can be seen as a train of light bullets of only 30 μm in length ($c \times 100$ fs) spaced by 6 m.

1.5 Pulsed Lasers

1.5.1 The Laser as Energy Storage

A low gain laser requires a very high quality cavity, with no more losses than the gain. The laser oscillation starts when the gain per path exceeds the loss. As the light rattles back and forth between the two mirrors of the laser cavity, the optical power increases, just as the level of water, and the pressure increases when a river is dammed (Figure 1.14). The power input to the laser eventually comes in equilibrium with the power released through the end mirror, just as the river flow into the lake eventually balances the release at the bottom of

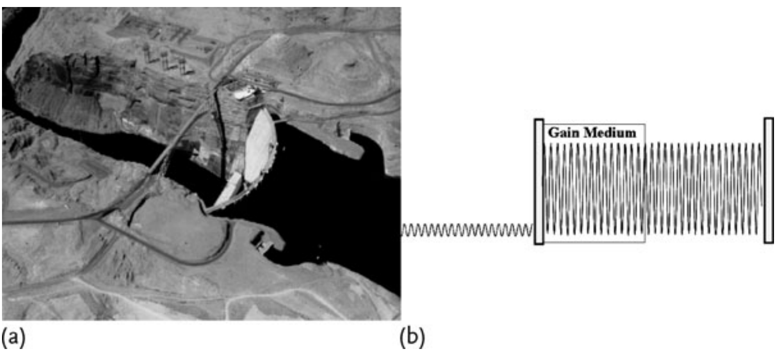


Figure 1.14 (a) A dam: most of the energy is stored in the lake in front of the dam. Only a small fraction of the stored water flows through the release of the dam. (b) Optical power is stored between the two mirrors of a laser cavity. The laser beam issued from this device is actually the trickle transmitted by the output mirror.

the dam, which increases with the increase in pressure or energy contained by the dam. In the case of the laser, the gain per pass – which initially exceeded the loss – decreases as the power inside the cavity increases, until it exactly balances the losses at the output mirror. The decrease in gain with power is called gain saturation.

1.5.2 Saturation

Saturation is a nearly universal phenomenon. Unlike the banker, for whom there is no limit to the number of coins that he can absorb, matter has a limited greed. There is only so much light that our eye can take. Beyond a given intensity, we do not see any difference in brightness, whether the power is multiplied by 2 or 10. The same applies to the temperature of a radiator, which results from a balance between the power applied to it and the cooling by radiation and conduction to the surroundings. Doubling the power applied to it will not double the temperature, because the cooling rate to the surroundings will increase.

The process described in the Section 1.3.2 assumes that the number of photons added is small compared to the total population in the upper state. Only a few of the lazy girls on top of the slides (Figure 1.4) are »stimulated« to go down. However, the total gain, which corresponds to the release of energy in emitted photons, is proportional to the number of excited atoms, which is going to decrease as a result of the transitions down. The girl that has gone down the slide cannot stimulate another transition before she has climbed the ladder again.

In the case of a constant rate of excitation into the upper state, the stimulated transitions will compete with the pump rate that creates atoms in the upper state and reduce the upper state population, and hence the gain. The *saturation rate* is the number of photons per second that results in a decrease of population difference by a factor of 2. Why population difference? This might not be an easy concept to grasp. The girls down on the ground have a potential to be up the ladder and those who are up will be pulled down. A good inversion made by a pump laser brings as many electrons as possible to the upper state. If we start with 100 girls up the ladder and none on the ground, the population difference is 100. Now only if 25 of these girls go down on the slide is the population difference reduced to 50, which is half of initial difference. In this example 25% of girls going down corresponds to the saturation rate of the transition. At the same time a gain (maybe a trampoline in our example) pumps the electrons to the upper state.

The same applies to an absorber, where the atoms are initially in the lower state. There is only so much light that an absorber can take. Once an atom has been excited by a photon, it cannot absorb another photon before it has relaxed back to its initial absorbing state. The more power in a laser beam, that is, the more photons/second are sent to an absorbing medium, the lesser the number of atoms/molecules that are available to absorb a photon, and the medium becomes transparent to the light. It can also be seen as a gate that gives way under the pressure of a crowd (in this case of photons). This property is used quite often in laser technology as a fast gate that gives way to an excess of optical energy.

1.5.3 Releasing Stored Energy

1.5.3.1 Q-Switching

How do you release the maximum energy that can be stored behind a dam in the shortest amount of time? If the release van of the dam is totally open, the water level may never rise. In the laser, if the output coupling mirror has a too large transmission, the pumping radiation may never get the population inversion to the »threshold level« that makes the laser oscillate. In other words, there is no dam anymore, just a leveled river.

To obtain a maximum flow in a short time, the release valve should be closed, to let the water level rise to the maximum, then suddenly opened to let the reservoir empty in a giant surge of water. In the Q-switching mechanism the van is open but the dam is not eliminated. In the laser, the gain is first accumulated to the maximum value that the pump source (a flashlight in the case of a ruby laser, a discharge current in the case of a gas laser) can provide. In the radiation picture of sliding girls, they are all up the ladder to create the maximum population inversion but they cannot go down. Then the resonator is suddenly formed, allowing the laser oscillation to start at a very fast pace, because the gain has reached a high value.

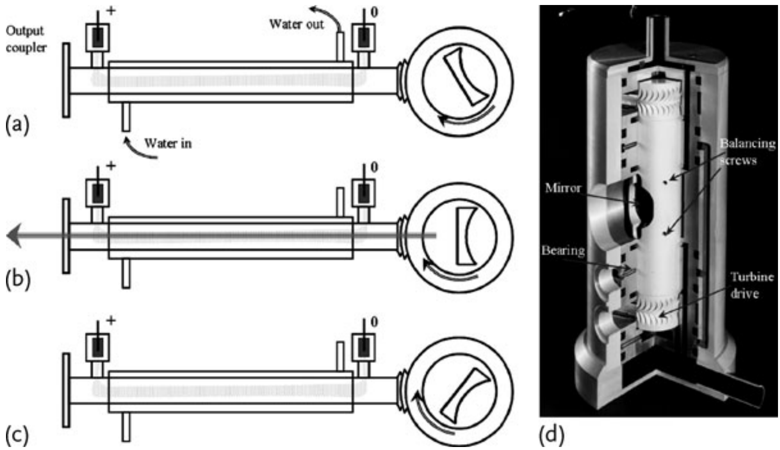


Figure 1.15 (a) A CO_2 laser tube is closed at one end by a partially reflecting mirror, an uncoated germanium plate, or a coated ZnSe plate. The other end is sealed with an enclosure containing the rotating mirror. In position (a), with the rotating mirror at a nonzero incidence with respect to the tube axis, the gain develops inside the discharge tube. As the rotating mirror arrives in position (b), the output mirror and the rotating mirror are parallel, forming a resonator in which a laser pulse forms, and depletes the gain. As the mirror pursues its rotation (c), there is no longer a resonator, and the gain can recover until the next position (b). (d) Exploded view of an air turbine used for Q-switching. The rotation speed could reach 60 000 revolutions/min, limited by the centrifugal expansion of the shaft (courtesy of Koninklijke Philips Electronics N.V., Eindhoven, 1970). Please find a color version of this figure on the color plates.

1.5.3.2 Mechanical Q-Switching

In the early years of the laser, the mirror was put physically in and out of place by placing it in the shaft of a rotating turbine. An example of such a turbine [11], that was used for Q-switching a CO_2 laser at Philips Research Laboratories in Eindhoven, the Netherlands, is shown in Figure 1.15. The alignment of the rotating mirror is rather easy: there is only one degree of freedom (around an horizontal axis), since the mirror scans all angles about the vertical axis. Such spinning mirrors are particularly convenient for Q-switching lasers with continuous gain, such as the continuous discharge CO_2 laser described in Section 1.4.2. During most of the revolution of the shaft, the laser cavity is not aligned, and the gain accumulates. For a few seconds of arc during the revolution, the two cavity mirrors come into parallelism, and the laser wave builds up from noise, extracting all the energy that was stored in the gain medium, in a pulse that lasts between 10 and

100 ns. As the mirror continues its spin into the next cycle, the gain medium recovers, in preparation for the next pulse after another revolution. The disadvantages of the rotating mirror are (i) the stringent requirement of near perfect shaft balancing, and (ii) the deafening noise (which, in the case of the CO_2 laser, was eliminated by operating in vacuum). Therefore, while this method of creating »giant pulses« had some popularity in the late 1960s, it was abandoned in favor of either electronic Q-switching or passive Q-switching.

1.5.3.3 Electronic Q-Switching

Instead of moving the mirror successively out- (to prevent laser emission, in order for the gain to evolve to its maximum value) and in-position (to suddenly dump all the stored energy in a giant laser pulse), it is easier to place an ultrafast obturator in front of the mirror, which opens at the time that the gain has reached its peak value. This technique was conceived and demonstrated in the early days of the ruby laser [12]. The principle involves the manipulation of the laser polarization discussed in Section 1.2.2.

A linear polarization can be rotated, or changed to elliptical or circular, by propagating the light in a medium which has a different propagation velocity along two directions at $\pm 45°$ from the polarization direction (»birefringent medium«, or »waveplate«). After some propagation distance, the components of the electric field oscillation along these two directions will no longer be in phase, resulting in elliptical polarization. Or they may have opposite phase, resulting in linear polarization again, but rotated by 90°. There also exist components that selectively deflect a particular polarization direction (polarizing beam splitters) or transmit only one direction of polarization (polarizers).

The birefringence property can be created by application of an electric field, since the material structure and electronic response could vary from one direction to the other. The key to optical switching is the *Kerr effect,* which is a change of the wave velocity (or index of refraction[9]) of a material under application of an electric field. The original implementation involved a liquid. Today's Q-switch elements are nonlinear crystals called *Pockels cells*. These elements are based on the

9) The index of refraction is the fraction of the speed of light in vacuum that a light wave can take inside the medium.

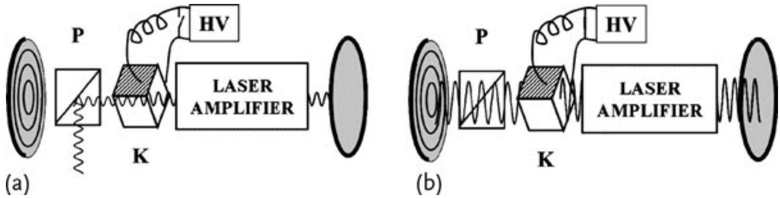


Figure 1.16 (a) The gain of the laser is activated (a flashlamp is fired, in the case of the ruby or Nd:YAG laser). A high voltage (HV) is applied to the Kerr cell *K*, such that the polarization of the beam issued from the amplifier is rotated 90° and rejected by the polarizing beam splitter *P*. The combination of Kerr cell and polarizer essentially eliminates the end mirror from the cavity. (b) After a time such that the gain has reached its maximum value, the voltage on the Kerr cell is shorted; the end mirror is part of the cavity and the laser oscillation can develop with full gain.

electro-optic, by which the index of refraction of a beam is changed upon application of an electric field. This change is different along different axes of the crystal. It results in a linear polarization being distorted in elliptical or circular polarization. Under application of a sufficient electric field, the polarization of the beam can be rotated by 90°. A »switch« consisting of a Kerr cell (or a Pockels cell) combined with a polarizing beam splitter is inserted in the cavity, as in Figure 1.16. A voltage is applied to the Pockels cell, rotating the polarization by 90°, such as to eject any light that would be generated in the cavity as the laser medium (amplifier) is being activated (Figure 1.16b). After a time such that the maximum population inversion – that is, the maximum gain of the laser element – has been reached, the high voltage (HV) on the Kerr cell is shorted suddenly, the laser cavity is closed, and a »giant pulse« develops (Figure 1.16b).

1.5.3.4 Passive Q-Switching

The advantage of electronic Q-switching is that the timing of the laser emission is well controlled, which is important when several laser systems have to be synchronized. The disadvantage is that the pulse to pulse reproducibility is not ideal. A preferred technique when synchronization is not an issue is to let the laser itself decide the opportune moment to open its cavity. This is done by replacing the electronic switch of Figure 1.16 by a »saturable absorber«. Saturation is a ubiquitous phenomenon. There is only so much light that an absorber can take. Once an atom has been excited by a photon, it cannot absorb another photon before it has relaxed back to its initial absorbing state.

As shown in Section 1.5.2, the more power in a laser beam, that is, the more photons/second are sent to an absorbing medium, the smaller the number of atoms/molecules that are available to absorb a photon, and the medium becomes transparent to the light.

One can think of a saturable absorber as a closed gate of a football stadium. After the game the crowd presses on to exit. The pressure builds up at the gate, as more and more people squeeze against it, as the light level increases inside a cavity trying to make the absorber transparent. Finally, the gate gives way, the saturable absorber opens, and scores of people are ejected through the opening.

The saturable absorber can be a dye, a crystal, a color glass (RG-8 filters of Schott glass for example in the case of ruby lasers) which is totally opaque to the laser light. Inserted in the cavity, it prevents lasing, since the amplifier does not »see« the end mirror. When the amplifier is fired, there is so much radiation from the spontaneous emission that, after a certain dose, the absorber »cannot take it anymore« and bleaches (becomes transparent). This simple technique provides the most reliable operation with the shortest pulses, but with a timing that cannot be controlled.

One can compare the »saturable absorber« and »electronic switching« to taking money from a bank account. In the saturable absorber case, the money is taken when it reaches a certain value, in the electronic method it is withdrawn at equal time intervals. As a result, one has certain values but may not be necessary timed equally and the other is timed but may not have the same value. In cavity dumping the whole bank account is emptied and then closed for the new build up.

1.5.3.5 Cavity Dumping

In our analogies of the dam, the previous Q-switch techniques amounted to close the dam, let the water level rise to the maximum, before opening the valves to maximum. Once the Kerr or Pockels cell is opened, the laser oscillation develops as fast as the »net gain« (gain minus transmission through the output mirror) allows. If the output mirror has a very high reflectivity, the optical pulse will develop fast, but the power will remain trapped in the cavity. If the output mirror has high transmission, more output will be released, but the oscillation will develop more slowly. The solution to maximize the extraction of energy from the laser and from the dam is to let the water level rise to its highest level and blow up the dam, as in Figure 1.17.

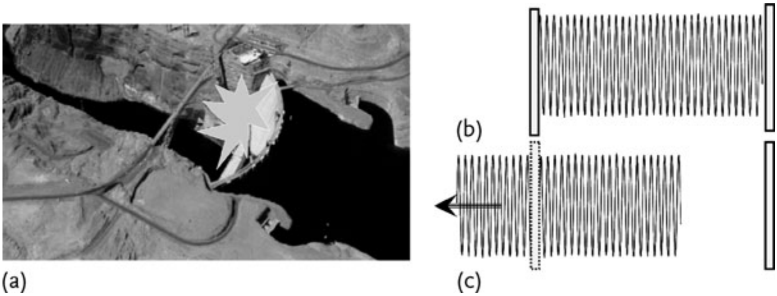


Figure 1.17 (a) A dam is filled slowly to capacity, ideally by closing all water release. The energy stored by the dam can be released in a minimum amount of time by blowing up the dam. (b) Similarly, in a laser cavity with totally reflecting mirrors, the optical power increases swiftly with time. (c) To release the energy stored in that cavity in the shortest amount of time, one of the cavity mirrors is »removed« in a time short compared with the time it takes light to make a complete round trip in the cavity. Please find a color version of this figure on the color plates.

This technique is called cavity dumping because all the energy stored between the mirrors is extracted in a pulse that will have exactly the length of the cavity. Instead of »blowing up« the output mirror, it is eliminated electronically. In Figure 1.16, the output mirror is chosen to have maximum reflectivity. As soon as the power in the cavity has reached its maximum value, a pulse is applied to the electronic switch to release all the energy via the polarizing beam splitter. The switching time has to be short compared to the cavity round trip time of light, hence it must typically have a rise time shorter than 1 ns.

1.6 Properties of a Laser Beam

1.6.1 Directionality

A simple and useful characteristic of a laser beam is its directionality: it propagates with minimal diffraction. Most light sources will expand through space, which is generally a desired feature. House light is made to illuminate a whole room without sharp exposures. As we move towards virtual words and replace material with data and images, our interest in using light as an appliance increases: we can replace a knife or a ruler with a laser beam. In Section 1.7.5.3 and in Chapter 7 we will learn about a new medium created by laser

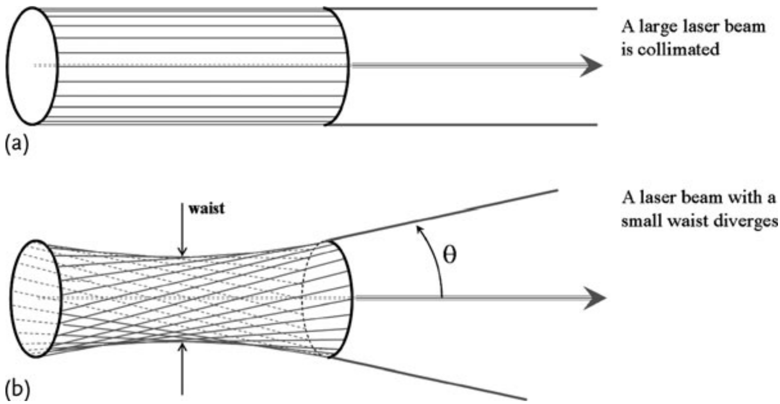


Figure 1.18 (a) A well collimated output of a laser. Rigorously speaking, such a perfect collimation can only take place for beams of infinitely large diameter. In general, the diameter of a laser beam will increase from the smallest value (the waist) as in (b). The diameter of the waist defines the angle θ of the divergence. The situation of (a) applies to a laser with flat mirrors, where the light rays are the strings spanned between the two mirrors. Curved mirrors lead to the situation of (b): the »rings« are twisted with respect to each other. The envelope of the rays (that are perpendicular to the surface of the mirror) draw an hyperboloid which can often be seen with a laser beam in a dusty environment. If the curvature of the mirrors is equal, the minimum diameter »*D*« – the waist – is at the midpoint of the cavity. Please find a color version of this figure on the color plates.

light that has a unique properties and even less divergence than laser beams.

When we compare a flash lamp with a laser pointer, we notice that the laser seems to have a well collimated output (Figure 1.18a), while the output of the flash lamp expands quickly in the space. Why can a laser beam can be collimated better than the light of a flashlamp?

The resonator is the main body of the laser (Section 1.3.3), and it defines the size of the beam. In that body, laser engineers use various components to adjust the wavelength, amplitude, or in the case of pulsed lasers, the length and shape of the pulse. One can look at the »resonator« as the cooking pot of the laser, where you can spice the beam as desired. Often the population inversion required for laser action is confined to a small volume, which imposes to design the resonator with the smallest beam size (waist) at the location of the gain medium. From the waist, the beam diverges as in Figure 1.18b, with a half angle θ:

$$\theta = 0.6\frac{\lambda}{D}\,, \tag{1.2}$$

where »λ« is the laser wavelength and »D« the minimum beam size or *beam waist*. Mirrors or lenses are generally used to recollimate the diverging beam. Another way to quantify the spreading of a laser beam with distance is the *Rayleigh length* ($\approx 2.3\,D^2/\lambda$), which is the length over which the beam diameter has increased from D to $1.4\times D$. Clearly, the smaller the wavelength, the smaller the divergence angle.

The simple Equation 1.2 tells us basically what can and cannot be achieved with a laser beam. Given the diameter D of a laser beam, it tells us how large the spot will be at a large distance. For instance, in the early years of the laser (1962), a pulsed Ruby laser was sent to the moon. The beam was expanded to fill the 48 inch diameter of the telescope at MIT Lincoln Observatory. Only a few photons were able to return back to earth, but that was sufficient to measure the time travel of the pulse and measuring the distance from the earth to the moon. With $\lambda = 694.3$ nm and $D \approx 1$ m, $\theta \approx 0.4$ µrad, which at the distance earth–moon of 300 000 km meant a 100 m radius circle. If one had replaced the ruby laser with a pulsed flash lamp, the size of the beam on moon would have been much bigger than the moon and there would be no chance for a single photon to make it to the moon.

The Equation 1.2 tells us also how small a waist can be achieved by focusing a large diameter beam. For instance, the military dream of focusing an infrared laser ($\lambda \approx 3$ µm) at 10 km distance to a spot size of only 1 cm imposes that the radius of the focusing lens or mirror be 1.8 m! The focal size is directly related to the intensity of the light that can be concentrated, as will be seen in the next section.

1.6.2 Intensity

Focusing light is akin to placing a jet nozzle on a water hose to squeeze a large flow into an intense jet. We all know how to start a brush fire with the lens of reading glasses (at least those of us who live in country where the sun shines). Large glasses may not be the fashion, but they are sure more efficient in starting a fire. The power of the sun radiation that is captured over 1 m^2 area is an *intensity* corresponding to 1 kW/m^2 or 0.1 W/cm^2. If we can make an image of the sun of 1 mm diameter with a lens, we reach and intensity of 100 kW/cm^2, which is above the threshold to start a fire.

In fine applications like dealing with nanostructures and surgery (Chapter 3 and Section 4.4), it is not only the limited resource of energy that makes us use focusing elements, but also the fine control over the material. *How finely can we focus a light? Is there any special property specific to the lasers in that matter*?

The major advantage of laser light over other electronic and thermal light sources is its *coherence*. This is partly due to the difference in the nature of radiation as discussed in Section 1.2. In stimulated radiation all excited electrons follow the stimulated photon, the radiation happens at the same time and the same direction. *Temporal coherence* or coherence in time refers to radiation that is in phase in time. This is not enough to have a coherent source, just like it is not enough if chorus members all sing at the same time, each one at their own home. Somehow we need to have all these voices together to have coherent music. This is where size of the source plays its role. For a large source, even if all the points of the source emit photons at the same time, there will be a delay between the photons due to the extension of the source. Knowing that waves change sign completely in just half a wavelength distance, we prefer to have sources as small as possible, referred to as the *point source*. Having the same phase across the source size is coherence in space or *spatial coherence*.

A laser can produce a collimated beam that is coherent over its cross-section and that will focus on a minimum size spot (Figure 1.19a). The reverse is an ideal point source (Figure 1.19b), where all the emitted photons across the source are in phase. With a proper lens one can make a collimated beam. A different situation emerges with a filament from an incandescent lamp, as shown in Figure 1.19c. Every point of the filament emits photons of different phases. The rays issued from the filament are like spears put in a trash can, all pointing in different directions.

Given a collimated laser beam as in Figure 1.19a, Eq. (1.2) tells us the minimum spot size that we can achieve with a lens. If, for instance, we use a lens of diameter $D = 1\,\text{cm}$ and focal distance $f = 10\,\text{cm}$ to focus a laser beam, $\theta = R/f = 0.1$, and the spot diameter is $D = 0.6\lambda\theta \approx 6\,\mu\text{m}$ for 1 μm wavelength radiation.

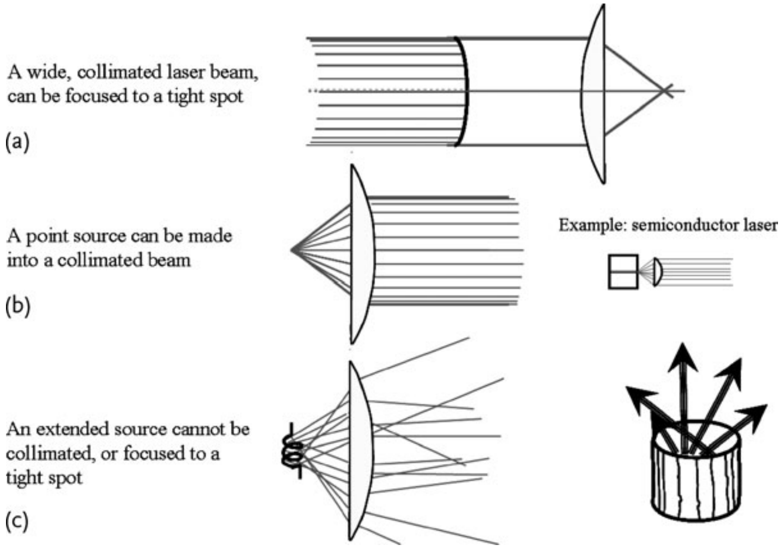


Figure 1.19 (a) The illustration of coherence at source is given by comparing a point source with an extended one like a flash lamp filament. If all rays come from a tiny (compared to the light wavelength) source, they all generate waves (photons) with the same oscillation phase. With ideal lenses and mirrors one can generate a parallel beam to infinity. (b) The same applies in reverse, if a beam is parallel it can be focused to one spot. (c) Since we do not live in an ideal word all these terms are relative, such that as the source get more extended the collimation is less. If the source emission is not spatially coherent, the radiation is like having spears out of a trash can that are all in different directions. An extended filament, even if emits light at the same time, will not generate a well collimated beam and will not be able to merge to a focal point. The smallest beam at the focus corresponds to imaging the filament. Please find a color version of this figure on the color plates.

1.7 How to Make the Shortest Laser Pulse

The methods of »Q-switching« and »cavity dumping« produce energetic laser pulses, but not the shortest possible. The shortest pulse that can be generated by the methods outlined in the previous sections correspond to the time travel in the length of the laser. Since this packet of energy propagates at the speed of light of $c = 299\,792\,458$ m/s or approximately 3×10^8 m/s, the pulse dumped from a 1 m long cavity will pass through an object in a time of $1/(3 \times 10^8) = 3 \times 10^{-9}$ s $=$ 3 ns. This is not a short time by the standard of »ultrashort pulses«, achieved two to three decades after the invention of the laser.

In Q switching and cavity dumping, the cavity is like a bucket or a dam that is filled with water and then drained partially or fully in a short time. An ultrashort pulse, in comparison, is like a high wave, compressing all the water of a dam, like a light bullet, rather than a filling material. In the language of athletics Q-switching and cavity dumping are analogous to walking through the laser cavity and a short pulse is like a »javelin long jump« that covers the whole length in a sudden high jump.

It may come as a surprise that the conformation of the laser producing extremely short pulses is as simple as the elementary device sketched in Figure 1.7b. Yet, each element of the cavity has to have its property accurately selected in order to develop the shortest pulse possible. Before going into the mechanism of pulse generation itself, let us first get into the dissection of a short pulse of light: how continuous waves can add up to create a short pulse.

1.7.1 The Nature of a Pulse

How do we construct a pulse in a mathematical language? We have seen that the nature of laser light is an electric field oscillating at a frequency characteristic of the color of the beam. A pulse is made of a combination of waves of different frequencies that add constructively at one point and destructively at other points. We will call $t = 0$ the instant at which the waves that constitute the pulse add at their crest. An example is illustrated in Figure 1.20, were five waves of increasing frequency are added on top of each other. The sum of these waves is shown with a thick red line. At the common crest ($t = 0$), the sum of the electric field of all these waves adds up to 5× the field of a single wave, which implies that the intensity is 25× that of a single wave. There is no violation of energy conservation, because after a few optical cycles, the fields add up to nearly zero.

Using our picture of radiation (Section 1.2) of girls on the slides, having many modes is like having different sets of slides that vary in height. The radiation (sliding) can be in phase if all the girls start at the same time, but eventually, since the slides are different, the landing time overlap is zero.

1.7.2 The Mode-Locked Laser and the Train of Pulses

In order to get shorter pulses, one has to manipulate the waves inside the laser resonator itself. Let us return to the analogy of the duckling paddling in a rectangular box of Figure 1.7c. It produces a series of waves that have different wavelengths, with the condition that all these wavelengths are a submultiple of the box length. All these wavelengths that fit into the duckling's pond are called modes of the pond (or laser cavity). If the duck were a real genius, he could perhaps paddle in such a way that all the waves were generated »in phase« as in Figure 1.20, creating a giant crest that would probably swallow him up. This is, however, the secret of ultrashort pulse generation in a laser: creating as many frequencies as possible, equally spaced, and adding them *in phase*.

This process of putting the modes in phase is called »mode-locking«. In the music world, this is as if many harmonics (10 000 to 1 000 000) of a note would be resonating together. The resulting pulse will propagate back and forth in the resonator, with a »splash« at the cavity end (the output mirror), creating a train of pulses at a regular interval, which is the cavity round trip time $t_{RT} = 2nL/c$, where L is the cavity length and c/n the speed of light in the medium of index of refraction n that constitutes the laser.

We have seen in Section 1.1.3.1 that there is a frequency of oscillation of the light field ν associated with a wavelength λ: $\nu = c/(n\lambda)$. The wavelengths $\lambda_1 = 2L/N, \lambda_2 = 2L/(N+1), \lambda_3 = 2L/(N+2), \ldots$ are spaced in frequency by $\Delta\nu = c/(2Ln)$. The longer the laser cavity L, the smaller the spacing between these wavelengths or »modes«

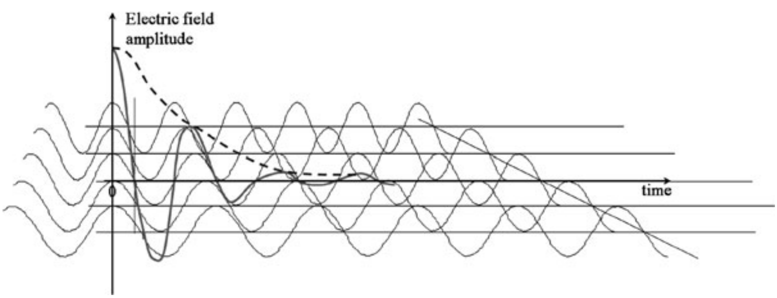


Figure 1.20 Five waves are added on top of each other such that at a given time all the crests coincide. Please find a color version of this figure on the color plates.

of the cavity, and generally the easier it will be to create short pulses. This remains true to the limit of an infinitely long cavity, as is the case when a short pulse is generated directly by propagation through an amplifying optical fiber. It also flows from the discussion of the preceding section that the shortest pulses require the broadest span in frequencies or the largest number of modes. For example, in a Ti:sapphire laser, the spacing between modes is typically 100 MHz, and the number of modes that constitute the pulse can be as high as one million.

These million modes cover a frequency range of a hundred million MHz, or a wavelength range of more than 100 nm over which not only the gain, but the speed of light varies. Indeed, while the speed of light in vacuum c is a universal constant, the index of refraction n is a property of the matter and varies across the spectrum. This property of the medium is called *dispersion* and plays an essential role in the creation (and destruction) of ultrashort laser pulses.

If each wave that constitutes a pulse propagates at a different velocity $c/n(\lambda)$, what will be the speed of the wave packet or pulse (we will assume that there is still a pulse – we will show in the next section how it will be modified)? A pulse is the sum of groups of waves; the speed of the group of wavelengths (*group velocity*) differs from the speed at a particular wavelength. This can be visualized as a group of people walking on a street; there is a collective speed for the group. It can be shown that the pulse travels at a velocity v_g (the subscript »g« for »group«) that is generally slower than the velocity of the wave at the average wavelength.

Thus we see that a short pulse rattling back and forth in a *mode-locked* laser hits the end mirror at regular time intervals $t = 2L/v_g$, even though the wave velocity is not a constant across the range of the wavelength that is contained in the pulse. The output of the laser will consist in a train of pulses, equally spaced, like a pendulum ticking at a rate of $1/t_{RT}$. This is more than an analogy, as we will see that the mode-locked laser is used as an accurate time/frequency standard.

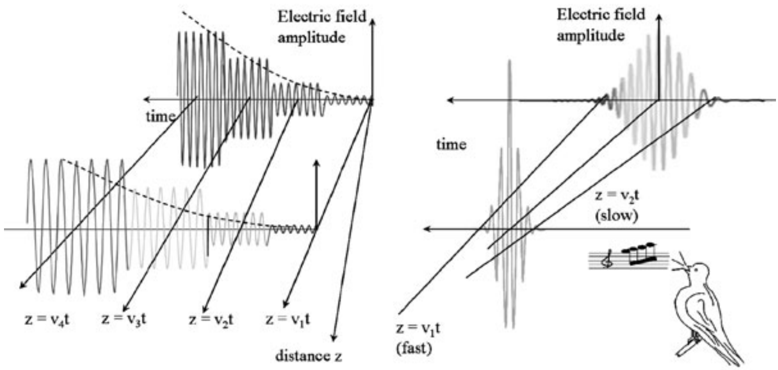
It remains now to be seen how the mode-locked laser can continuously produce a string of ultrashort *identical* pulses, despite the fact that the waves all have different velocities. This is the topic of the next section.

1.7.3 The Mechanism of Pulse Compression by Propagation

To understand how short pulses can be generated, we refer to Section 1.7.1 where it was shown that a pulse of light consists of a superposition of propagating waves that have a common crest propagating at a velocity called »group velocity«. The broader the range of frequencies involved, the shorter the pulse. There are two mechanisms in the production of ultrashort pulses in a laser: a mechanism – dubbed »nonlinear« because the speed of light depends on the pulse intensity, by which the range of frequencies is extended, and another one called »dispersion«, by which all the waves are synchronized to crest at the same point.

In the case of a laser, the waves that »fit in the box«, are equally spaced in frequency (that frequency spacing is the inverse of the round trip time of the laser cavity). In general, when such a pulse propagates back and forth between two mirrors, it will broaden in time. The reason is that there is a slight difference in velocity between the high frequency waves (short wavelength) and low frequency waves (long wavelength) that constitute the »wave packet«. This wavelength dependence of the velocity is called dispersion, and applies to water waves as well. How then can ultrashort pulses be generated, in presence of this ever present dispersion? The answer is in a nonlinear phenomenon, by which the wave velocity is linked to the intensity of the wave (Kerr effect). The speed of light is highest in vacuum: $c = 299\,792\,458\,\mathrm{m/s}$. As it propagates through matter, it is slowed down by the interaction with atoms and molecules, resulting in a velocity $v = c/n$ where n is the index of refraction. The electric field of the laser light (we will assume here that light is linearly polarized, with its electric field oscillating in a direction perpendicular to the direction of propagation) tends to orient the molecules, resulting in a higher interaction with the light field, and therefore a larger n and a slower wave velocity.

Thus, as the pulse intensity is ramped up, the wave decelerates, which implies that the optical cycles will stretch in time, or, in other words, the frequency decreases with time. The reverse occurs at the pulse tail. Near the peak of the pulse, the frequency sweeps from low to high: this is called »upchirp« (Figure 1.21a). This is the important first step in pulse compression: the sweep in frequency, such that the



(a) (b)

Figure 1.21 (a) Generation of new optical frequencies by propagation of a pulse in a medium where the wave velocity increases with intensity. The optical signal of increasing intensity is shown as having a stepwise increase on its leading edge (the time axis points to the left, for a better visualization of a pulse propagating to the right). The different intensities propagate at velocities v_1, v_2, v_3, and v_4 with $v_4 < v_3 < v_2 < v_1$. As a result, the pulse optical frequencies decrease with time along the pulse (or the wavelengths increase along the pulse) after some propagation distance. (b) Through the process shown in (a), one has generated an »upchirped« pulse, that is, a pulse of which the optical frequency increases with time. This is exactly what the little bird at the bottom of the picture is singing. This pulse is now sent through a medium with negative dispersion (i.e., a medium in which the higher frequencies (blue) propagate faster than the lower frequencies (red)). As a result, the tail of the pulse catches up with the pulse leading edge, resulting in pulse compression. Please find a color version of this figure on the color plates.

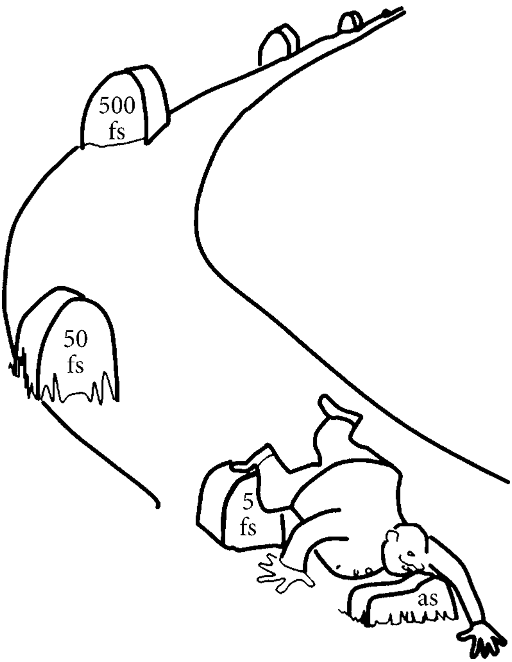
lower frequencies are pushed ahead of the pulse and the higher frequencies are pushed towards the trailing edge.

As we saw in Section 1.7.1, many frequencies are needed to make a pulse. Now the next question is how to stack those frequencies in phase to make a short pulse. The trick to continuously compress the pulse is to select a laser cavity configuration such that the lower frequencies propagate more slowly than the higher frequencies,[10] which implies that the leading edge moves towards the peak, and the trailing edge also recedes towards the peak. Hence, the pulse is compressed, as sketched in Figure 1.21b. It is the task of laser engineers to use optical components such as mirrors and prisms to modify the speed of light as a desired function of frequency.

10) This is called a cavity with negative dispersion.

1.7.4 The Real Thing: From Splashing Dyes to Crystal Lasers to Semiconductor Lasers

1.7.4.1 Milestones and Stumbling Blocks in Femtosecond Laser Development



From the nanosecond Q-switched and cavity dumped pulse, the path to ultrashort pulse generation has not been straight but full of stumbling blocks, the last one being the attosecond barrier. Historically, the field of ultrashort pulses has grown with dye lasers. It has been a remarkable circular evolution, as successive mechanisms were discovered, which led to new designs apparently repeating a much older one. The dye laser was chosen because of its high gain (up to a factor of 2 gain with continuous pumping, and a factor 3 with pulsed pumping, could be achieved through the 100 μm thick dye jet). Another advantage is that it is a visible laser, which, in addition to the beautiful palette of colors that it provides (Figure 1.22), implies rel-

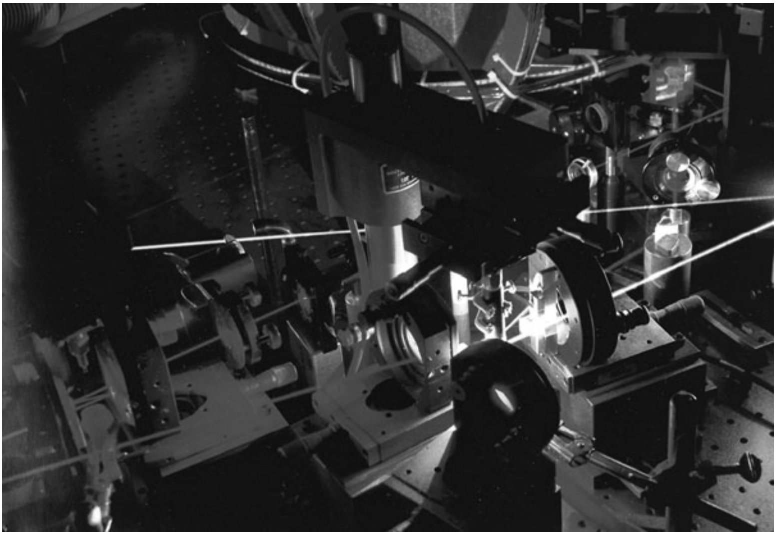


Figure 1.22 A ring dye laser. The dye jet is seen in the middle of the picture, pumped by the bright blue beam of an argon ion laser. The mirror in the foreground focuses the argon leaser beam at a tiny spot in the dye jet. This gain spot is at the focus of two curved mirrors, which direct a collimated beam in the other part of the cavity. The red intracavity beam of the dye laser can be seen on the picture. Please find a color version of this figure on the color plates.

ative ease of alignment because of the visible fluorescence[11] of the gain medium. The high gain made it possible to implement successive lossy mechanisms of pulse formation and compression inside the laser cavity. The first one that came to mind was saturable absorption, with an organic dye as saturable absorber, contained in a thin liquid jet similar to the jet contained the solution of the gain medium. The organic dye – Rhodamine 6G being the most popular gain medium – was dissolved in ethylene glycol and forced at high pressure through a thin (100 μm typically) stainless steel nozzle. The pump laser beam (argon ion laser of up to 20 W power) was focused into and nearly totally absorbed by that flowing sheet of liquid. It is because the focal volume was replenished at very high speed that such high power density could be injected into that gain medium. It should be noted that, in this configuration, the dye laser could handle higher power density than any other medium. Such properties explain why the dye

11) Radiation that is due to pumping with a different wavelength, usually a shorter pump wavelength.

laser has been one of the most popular sources for spectroscopy and short pulse generation for at least two decades. One can wonder why it seems to have vanished in the twenty-first century. Several factors contributed to its demise. First was the inconvenience of having to handle a noisy pump system and high pressure liquids. Not only did the laser produce a colorful display of colors, but most often the operator was covered from head to toe with red, orange, green colors, thanks to the occasional bursting of a high pressure hose. Second was the chemical hazard. While Rhodamine 6G was used as food coloring in the early 1960s, it was soon discovered to be carcinogenic, as most other organic dyes. A little known fact is that the viscous solvent, ethylene glycol, which is commonly used in car radiators, is listed as a hazardous liquid: when heated, its vapor can cause permanent brain damage.

As mentioned above, the first continuously mode-locked laser had a saturable jet and a gain jet in the same cavity, as sketched in Figure 1.23a [13]. The pulse duration was 0.6 ps. Then a frantic competition started, with subsequent publications citing a pulse reduction by a small percentage, due to a new physical approach of configuration. Improved saturation absorption was achieved by what was later dubbed »colliding pulse mode-locking«; the implementation is sketched in Figure 1.23b [14]. The principle is that when two traveling waves »collide« head on, they create a standing wave where the crest and trough of each wave add up at one position. Water waves will double in amplitude. Light waves will double in electric field amplitude at the crests, but quadruple in intensity, which implies increased saturation. Two traveling colliding waves can be created by reflecting a wave against a wall – in the case of optics by reflecting a pulse on a mirror. The first »colliding pulse mode-locking« used a saturable absorber flowing against an end-cavity mirror [14] and resulted in the generation of 0.3 ps pulses. A prism in these first configurations was used as in a spectrometer to select the wavelength at which the saturable absorber can operate. As we have seen, the shorter the pulse, the larger the range of wavelengths that constitute the pulse, and therefore wavelength selection by a prism is contradictory to making a short pulse. The next increment in a shorter pulse was obtained by eliminating the bandwidth limitation of the prism and using a cavity mirror that uniformly reflects only the wavelengths over which the saturable absorber functions. This simplest cavity shown in Fig-

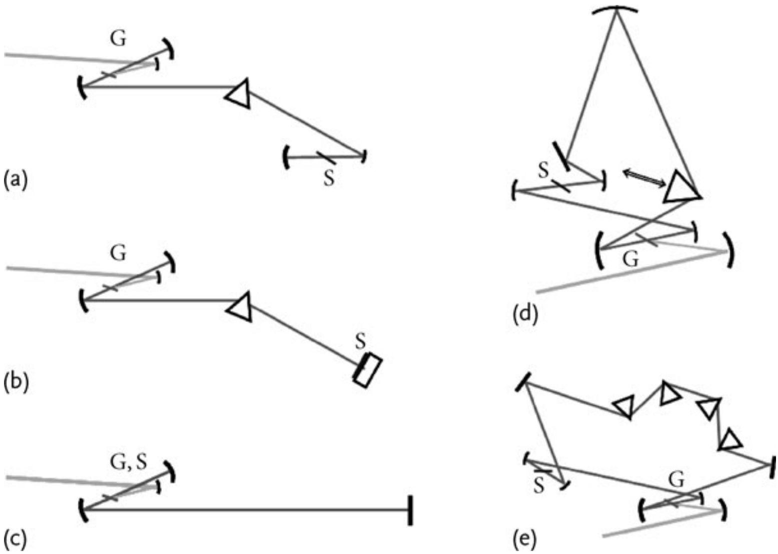


Figure 1.23 Successive configurations of mode-locked dye lasers. G is the gain jet – most commonly Rhodamine 6G – and S is the saturable absorber – most commonly diethyloxadicarbocyanine iodide. The configuration (a) of the early 1970s [13] gave way to (b) a »colliding pulse mode locked cavity« [14]. A simpler cavity in (c) used all dyes mixed in one jet, and mirrors with square spectral bandwidth [15, 16]. In (d), with the »colliding pulse« mode-locking implemented in a ring cavity, the prism is reinstated but at the center of curvature of a mirror [17]. In (e), a four prism sequence is introduced in the ring to produce negative dispersion [18]. Please find a color version of this figure on the color plates.

ure 1.23c [15, 19] produced pulses of 120 fs duration. It was realized that the thickness of the saturable absorber dye jet was setting a limitation on the length of the optical pulse. The next improvement that brought down the pulse width to 90 fs was a thinner saturable absorber dye jet, and the same colliding pulse mechanism as in Figure 1.23b but implemented by a cavity with a ring geometry [20]. The 90 fs shortened to 65 fs [21] after a group at Rochester reported 70 fs out of the configuration of Figure 1.23c pumped synchronously by a mode-locked argon laser [16]. As time seems to proceed backwards, the edge mirror was eliminated, the prism was reintroduced, but located at the center of curvature of a mirror, so that the wavelength selection it introduced was greatly reduced (Figure 1.23d). That configuration, which is identical to that of Figure 1.23a except for the ring geometry of Figure 1.23d, generated pulses of 55 fs duration [17].

The innovation was to compress the pulses inside the laser cavity by adjusting the amount of glass (translating the prism).

The mechanism is exactly that of »soliton compression«, mentioned earlier in Section 1.7.3. In this particular case, the dispersion of the prism is positive, compensating a downchirp caused by saturation of the dye (as the absorber dye saturates, its index of refraction decreases, which causes a downchirp). The soliton approach took a different twist, with the introduction of a four prism sequence to create negative dispersion (Figure 1.23d), and a positive *self-phase modulation*[12) in the solvent of a jet that, in this case, was no longer acrobatically thin. The balance of the Kerr effect and prism dispersion led to a pulse duration of 27 fs [18], which was the basis of the design of the solid state lasers that followed, such as the Ti:sapphire laser.

As the 1970s and 1980s were the decades of the dye laser, the 1990s saw the start of two decades of the ultrafast Ti:sapphire laser. Pulse durations of less than 12 fs in the early 1990s [22, 23] evolved to pulses of less than 5 fs (only two optical cycles) in 2001 [24]. This is the limit of what can be achieved directly out of a laser. The next era is in the attosecond range.

What made the Ti:sapphire laser more successful than the dye laser? The gain is lower, and the beam is barely visible. The output power of a laser is not determined by the gain but by the saturation intensity. A high gain implies a low saturation intensity, which explains that the mode-locked dye lasers had only an output power typically in the mW range. The Ti:sapphire laser has a thousand times lower fluorescence, much smaller gain, but a thousand times larger saturation intensity. Output powers of the order of 1 W can be routinely obtained from the Ti:sapphire laser. The wavelength in the near infrared is barely visible. The configuration is similar to that of the dye laser, as shown in Figure 1.24. The control of dispersion of this laser is made with a prism sequence, the first one of which is seen on the left of the picture. In subsequent lasers, the function of negative dispersion is achieved with special coatings of mirrors. The

12) Self-phase modulation is a change of phase or speed of light across the pulse due to the Kerr effect. This is a self-induced phenomena, because the medium response varies with the intensity of the pulse. A positive self-phase modulation results in a frequency sweep across the pulse, having lower frequencies at the front and higher frequencies at the tail of the pulse.

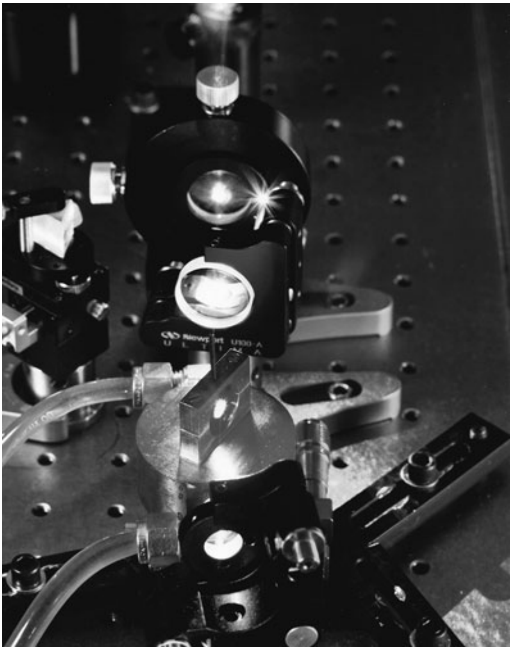


Figure 1.24 A Ti:sapphire laser. The Ti:sapphire crystal is pumped through one of the two curved mirrors projecting the gain spot into the cavity by a frequency doubled vanadate mirror. Please find a color version of this figure on the color plates.

mode-locked Ti:sapphire lasers used for ultrashort pulse generation have a pulse duration that can be as short as 8 fs. Since the speed of light is approximately 0.3 μm/fs, this represents a light bullet of only 2.4 μm, of three optical cycles at the wavelength of 0.8 μm.

It is not certain, however, that the Ti:sapphire laser has a bright future. Its biggest shortcoming is the cost of acquisition and operation. It requires a semiconductor pumped vanadate laser operating at 1064 nm, which is frequency doubled (see Section 1.11) to 532 nm, to pump the Ti:sapphire. This chain of lasers is not only expensive in acquisition, but also inefficient. The future most likely belongs to semiconductor lasers, with high wall-plug efficiency, which are slowly approaching pulse durations comparable to those of the Ti:sapphire laser.

1.7.5 Water Waves and Laser Pulses

1.7.5.1 From Water to Lasers: The Soliton

The equation that describes the compression mechanism of the previous section is famous in physics and in mathematics: it is the »nonlinear Schrödinger equation«. It has been used to describe the evolution of a pulse in a cavity, leading to a steady state solution which is a stable pulse of well defined shape, energy, and duration, propagating back and forth in that laser cavity. The nonlinear Schrödinger equation in space is also used to describe the spatial profile of a beam that collapses and creates its own waveguide in a nonlinear medium (which can be any medium, including air, as will be seen in a subsequent chapter). The soliton is one steady state solution of the nonlinear Schrödinger equation. The phenomenon was discovered long before the mathematical equation even existed, by the engineer and shipbuilder John Scott Russell (1808–1882) [25] who named it »the wave of translation«. In 1834 he was riding by the Grand Union Canal at Hermiston, Glasgow and observed that when a canal boat stopped, its bow wave continued onward as a well defined elevation of the water at constant speed. It was only in the 1960s that the name »soliton« was coined when the phenomenon was rediscovered by the American physicist Martin Kruskal. Details of the early history of the soliton can be found in a book by Robin K. Bullough [26]. The soliton took up so much importance in all areas of physics and laser optics that a recreation of the observation of John Russell was organized for the 150th anniversary of his observation. Figure 1.25 shows a picture of a re-creation of that event.

1.7.5.2 From Laser to Water: The »Freak Wave«

It is a water problem (the goal of John Russell was to design the best dimensioned canal for navigation) that led to the discovery of solitons, which brought a revolution in the field of lasers and fiber communications. Most recently, the same »nonlinear Schrödinger equation« that became an essential tool to understand the propagation of ultrashort optical pulses came under renewed interest to solve a puzzling problem for oceanographers. It was the biggest mystery of the seas. Large ships disappeared over centuries, without leaving any tracks. This led to the creation of myths of sea monsters and then that of »gi-

Figure 1.25 Recreation of the soliton in 1984 – soliton home page, Heriot Watt University (Reprinted by permission from Macmillan Publisher Ltd: *Nature*, **376** (1995), 373).

ant waves«. These stories were dismissed as seamen's tales, until two well documented events in 1995.

The first was an automated recording at the Norwegian Oil platform Draupner-E, which indicated in the New Year night a single wave of 26 m height. The second was on 11 September of the same year, when the luxury liner Queen Elizabeth 2 on its way to New York was hit by a giant wave (report of Ronald Warwick, Captain of the Queen Elizabeth 2, interviewed on the BBC Radio 2 on 14 November, 2002). All oceanographic models so far predicted a statistical distribution of waves not exceeding 7 m, while the freak waves recorded reached more than 30 m.

The wave equations used were similar to the linear wave propagation in optics, including a frequency dependent wave velocity. The breakthrough came when the same nonlinear term as in optics was introduced: an intensity (in this case height) dependent wave velocity. One can justify this behavior by arguing that the higher the wave, the less its velocity would be affected by friction with the deeper water. Unlike the case of lasers where there is a deterministic, controlled distribution of waves, the random distribution of water waves in a storm

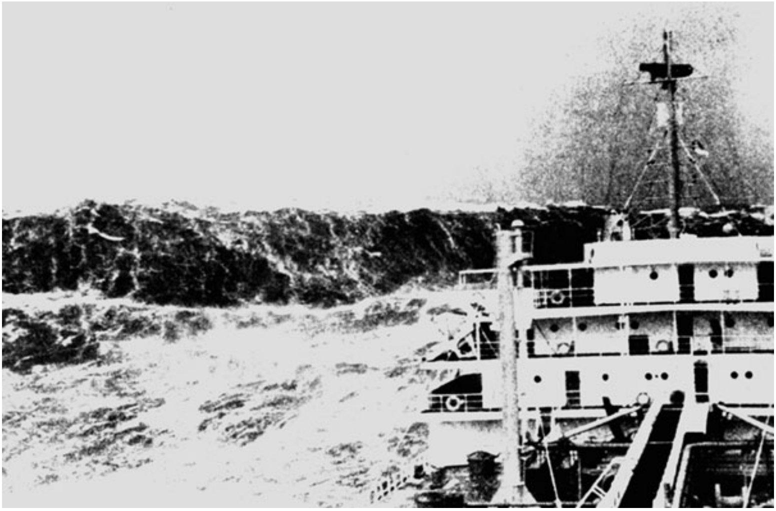


Figure 1.26 Huge waves are common near the 100-fathom curve on the Bay of Biscay. Published in the 1993 Fall issue of Mariner's Weather Log.

have only a very small, but still existing probability to be in the condition of »pulse compression« defined in Section 1.7.3, hence the freak occurrence of the »giant wave«.

There is a more scientific name than just »rogue« or »freak« for large events that have a nonzero probability of occurring. The *probability distribution* – that is, the probability that a wave of size h occurs, has a characteristic heavy tailed »L-shape«. In stark contrast to *Gaussian probability*, where the probability of being in the mean (middle) value is the most likely, events much larger than the mean occur with significant probability.

1.7.5.3 Back from Water to Lasers: Freak Colors

The »rare but significant« statistic [27] had stirred some excitement among mathematicians and physicists, who started to search for similar statistical events in other areas [28]. Once again, theoretical findings of water waves found their analogy in laser physics. This time, it is not »freak waves«, but »freak colors« as shown in Figure 1.27.

One of the key characteristics of laser light is the ability to form a nearly perfectly, uniform collimated beam (see Section 1.6.1). Driving your car at night with the best large laser headlight, you would be able to uniformly illuminate a wide road at 1000 km distance! This would

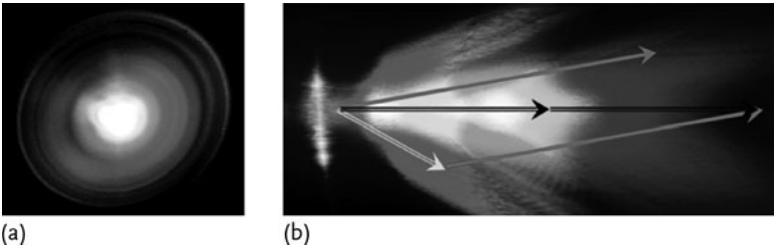


Figure 1.27 (a) The annular display seen on a door, 25 m away from the intense short pulse laser source. The beam has collapsed into a single filament, which has produced these concentric colorful cones. (b) A filament produced in glass. The color spectrum is displayed horizontally (from long wavelength to the left, to short wavelengths to the right), and the angle the individual rays make with the horizontal is the vertical axis. The intense beam propagates along an horizontal axis (shown in black). The directions of the rays is indicated for different colors. Please find a color version of this figure on the color plates.

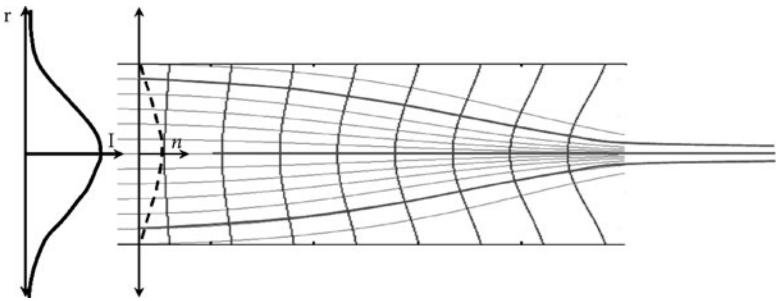


Figure 1.28 Formation of a »filament« or a self-guided intense beam in air. A laser beam is propagating from left to right, with an intensity versus radius sketched at the extreme left. Given a sufficiently high intensity, the index of refraction will increase proportionally to the intensity, as indicated by the dashed curve. This spatial dependence of the index of refraction results in a lensing effect. The wavefronts will curve, and the rays, perpendicular to the wavefronts, will bend towards the axis. A waveguide is formed by the beam itself, similar to the fiber sketched in Figure 1.12. Please find a color version of this figure on the color plates.

work only if our earth were flat, and if there were no distortion due to atmospheric turbulence. However, that ideal headlight would no longer give you good uniform illumination if you were to try to increase the optical power beyond reasonable limits. At powers exceeding 10 GW (10 GW or 10 000 MW), the hitherto uniform beam will collapse into tiny light needles or »filaments« (Chapter 7, Section 7.1). Of course this can only be observed for very short times: generating such high power, your car battery would run empty in less than a μs.

The physical origin of such collapse is the same intensity dependent wave velocity that was exploited in Section 1.7.3 to generate ultrashort pulses. However here, at these intensities, it is the index of refraction (Kerr effect) of air that becomes intensity dependent, creating a lensing effect where the intensity is the highest, as sketched in Figure 1.28. The beam is focused by that self-induced lens, until it reaches a very small diameter; it creates its own waveguide, guiding light in a similar manner as a fiber (Figure 1.12). The spatial shape (intensity versus radius) of these filaments is also governed by the »nonlinear Schrödinger equation«, another contribution from water science to the laser optics field. These filaments are »solitons in space«, as opposed to the »solitons in time« presented in the previous section. However, a dashing display of colors is associated with these filaments, as shown in Figure 1.27. Beauty, however, does not come with Gaussian statistics. It was recently suggested that the widest display of colors is related to the freak wave statistics. For instance, the appearance of the violet–blue in Figure 1.27 is characterized by the same »L-shaped« statistics as the freak oceanic waves [29].

1.8 Ultrashort Ultraintense Laser Pulses

When dealing with pulses one must consider the extension of pulse in time. One joule per second output of a continuous laser with spot size of 1 cm^2, gives the intensity of 1 W/cm^2. For a pulsed laser output of 1 J and 10 fs long and the same size, the intensity is 10^{14} or 100 million million Watt per square centimeter. Short pulses are used whenever extreme high intensity is needed, at the expense of the exposure time.

1.8.1 Definition of »Intense«

The perception of what is an »intense« laser pulse varies over an immense range. For the medical user, a beam that burns the skin can be qualified as intense, and this requires no more than 10 or 100 W/cm^2. A chemist will consider high the intensity that will break a chemical bond, which can be in the range of MW/cm^2 to GW/cm^2. The most power hungry are the physicists. At the lower end of the scale, the atom physicist will only get excited if the field of the laser[13] reaches a sufficient value in one oscillation to extract an orbiting electron from the atom (Figure 1.29a), and pull it back at the next half cycle of the field (Figure 1.29b). The disturbed electron comes back to the atom with a vengeance, producing a burst of x-rays of incredible short duration, in the attosecond range (Figure 1.29c). One attosecond, 1000 times shorter than the femtosecond, is in the same ratio to the second as the age of the universe is to the second (10^{18}). The intensities to reach electron extraction – return to the atom – are now in the terawatt (10^{12}) to petawatt (10^{15} W/cm^2) range. To move away from the abstraction of these numbers, let us try to get a feeling for what these intensities mean by considering the pressure of light. The photon has no mass, but it acts like a solid particle, having a momentum $h\nu/c$. When bouncing off a surface such as a mirror, it induces a recoil momentum $Mv = 2h\nu/c$, where v is the velocity given the mirror of mass M. A beam with a flux of N photons/(cm^2 s) has an intensity I (in Watts/cm^2) and exerts a pressure of $N2h\nu/c = 2I/c$ on the mirror. Sunlight has an intensity of 0.1W/cm^2. The pressure that sunlight exerts on the 1 cm^2 area of the reflecting »light mill« shown in Figure 1.29d is equivalent to one millionth of a 1 mg flea distributed over a cm^2 area! Definitely not sufficient to make a light mill spin.[14] At the intensity level of 10^{16} W/cm^2 used in attosecond pulse generation, the radiation pressure is 1000× higher than the pressure at the deepest point of the ocean (Figure 1.29e).

As impressive as these intensities may seem, there is another breed of physicists that looks upon them with disdain. At sufficiently high intensities, electrons can be accelerated during a half optical cycle to relativistic velocities, that is, velocities close to the speed of light. As one tries to accelerate an electron more by increasing the light field, the mass of the electron increases (to reach infinity at the speed of light). For the relativist plasma physicist, high intensity means above 10^{18} W/cm^2, for 1 µm radiation. That intensity corresponds to an op-

13) Remembering that laser light is an electric field that oscillates in time.

14) One may wonder what makes a light mill spin? Each of the four planes of the light mill has a black face and a mirror face. The radiation pressure acts on the reflecting surface. One may notice that the irradiated mill turns as if the light was pushing the *black* surface. This is because the black surface absorbs the photon and heats the surface, which partially vaporizes. It is the recoil from the molecules escaping the black surface that makes the light mill spin.

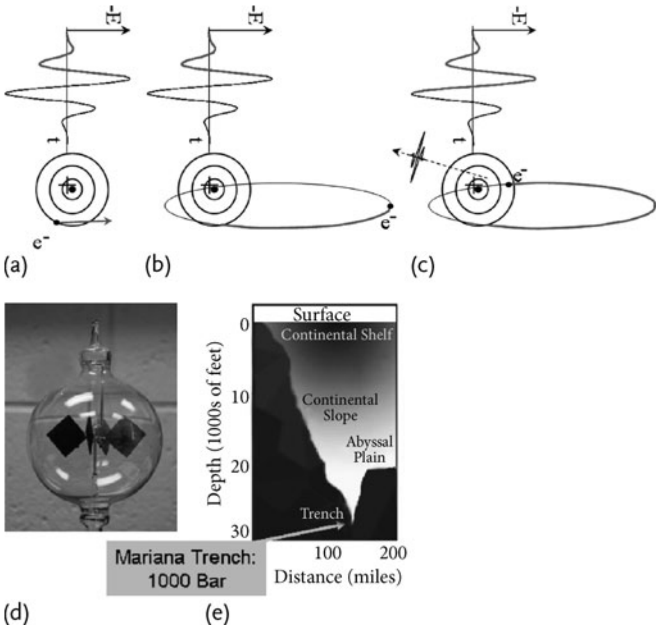


Figure 1.29 The electric field of a pulse, near the peak of a cycle, is sufficiently high to eject an electron from its orbit (a). The electron is accelerated away from the atom, then decelerated to a halt the next half cycle, as the light electric field reverses sign (b). During the next quarter cycle of the light pulse, the electron is accelerated back towards the atom. Numerous complex physical phenomena can occur during that recollision, one of them being the emission of an extremely short (typically 100 as) burst of x-ray radiation. (d) The pressure of sunlight or a He-Ne laser is not sufficient to make the »light mill« (or »Crookes radiometer«) spin. However, the radiation pressure at intensities used to create attosecond pulses is 10 000 times larger than that at the bottom of the ocean (e). Please find a color version of this figure on the color plates.

tical field strength that accelerates the electron to a speed at which the electron mass has increased by 50%.

There is a group of physicists even greedier for power: the particle physicist. For him, an intense laser field E is such that, for instance, an electron would be accelerated over a wavelength λ_c to an energy $eE\lambda_c \geq 2mc^2$ where m is the mass of the electron (or another particle). mc^2 is, according to Einstein, the energy equivalent to a particle of mass m at rest. As will be seen in Section 6.2, λ_c is the wavelength associated with the accelerated electron, or the »Compton wavelength«.

A back of the envelope calculation shows that the corresponding laser intensity is above 10^{23} W/cm^2. The concentration of energy is such that the creation of matter – a pair of electron–positrons – will emerge from vacuum. A plethora of other effects are expected at such intensity levels, which are totally beyond the scope of this overview.

One question to answer, however, is whether such intensities belong to science fiction or real research. Numerous countries have national facilities in the PW (10^{15} W) range. The peak power of the next generation laser that is contemplated is above the »exawatt« (or 10^{18} W) range. Such a laser is no longer at the scale of a national laboratory, but requires resources at the scale of a continent. The European Community has started such a project: the »Extreme Light Infrastructure« or ELI. Extreme is even an understatement when trying to describe the highest intensities contemplated in this project. To get another appreciation of the meaning of high intensity, let us embark on a thought exercise of what is required to keep a beam collimated, despite the diffraction effect mentioned in Section 1.6.1. In air, at atmospheric pressure, it has been established that a power of at least 3 GW peak power is required to create a self-induced of waveguide, as described in the previous section. The power required is inversely proportional to the density of air, since the intensity dependent increase of index or refraction is proportional to the number air molecules that create the nonlinear index. Could a filament be produced in the mesosphere (approximately 100 km altitude), for instance, to guide a reentry vehicle? The density of air there is 10^{16} molecules/cm^3, or 10 000 less than the 10^{20} molecules/cm^3 at sea level. The power required to create a light filament is then of the order of 10 000 GW or 10 TW. In deep space, the density of molecules drops down to $N = 10^5/\text{cm}^3$, and the power required to create a filament is then 10^{23} W. At this level of intensity, we are out of classical physics. Quantum field theory tells us of the existence of self-focusing »by vacuum polarization« and »birefringence of vacuum«; in short vacuum itself will cause the beam to self-focus at a power level of $\approx 10^{23}$–10^{24} W. For these powers, vacuum itself is a nonlinear medium, since it will absorb the light energy through creation of matter. There will also be nonlinear phase changes; all effects that are accessible in the range of power and intensities are contemplated by the ELI project.

1.8.2 How Ultraintense Pulses are Generated

We have described a laser source as an optical amplifier sandwiched between two mirrors. The shortest pulses are produced in a laser where a short pulse rattles back and forth in a laser cavity, hitting the end mirror at regular time intervals (Section 1.7). These mode-locked lasers are the source of the shortest optical pulses that can be generated (a couple of optical cycles), but the energy/pulse is generally small, at most a few nanojoules. Amplifiers are required to boost the energy of one or a few pulses from the train of pulses emitted by the laser. As in the case of the laser, the amplification process is limited by saturation of the gain medium. The pulse to be amplified has to be sent through several amplifier stages of increasing diameter, so that the intensity of the amplified pulse remains below the saturation intensity of the gain medium. The energy required to keep the media amplifying (maintain a population inversion) increases with the diameter of the gain medium (Figure 1.30). It is like threading a growing elephant through tubes, of which the diameter and strength have to increase with the growing elephant size. The problem can be solved by stretching the ultrashort pulse, so that its intensity is reduced by the stretching ratio and it can be amplified to considerably higher energies before its intensity reaches saturation or damage levels.

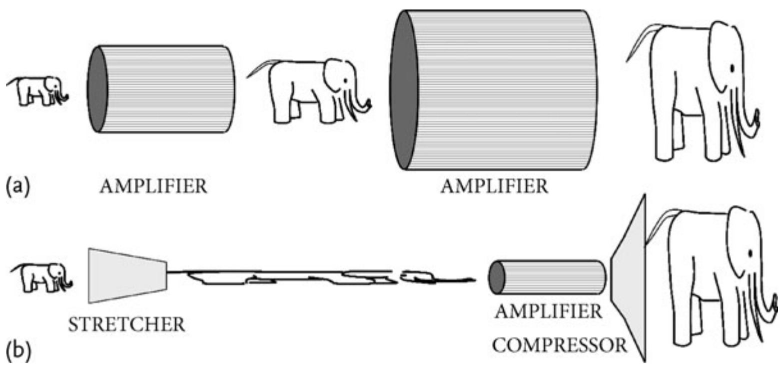


Figure 1.30 (a) Any amplifier stage has to be matched to the size of the amplified pulse. For a given amplifier diameter, the saturation limits the maximum pulse energy that can be extracted, as the diameter of the tube limits the size of the elephant that can pass through it. (b) Instead of increasing the diameter of the tube, why not stretch the elephant to make him pass through a narrower tube and give him the original proportion after amplification? Please find a color version of this figure on the color plates.

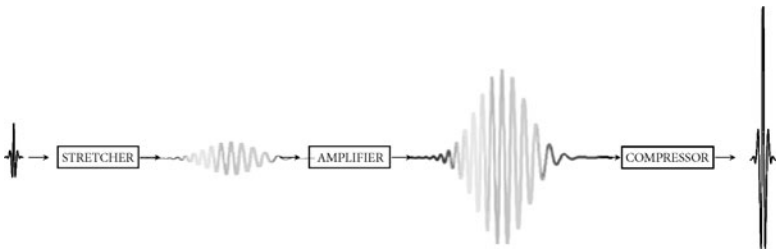


Figure 1.31 Chirped pulse amplification. An ultrashort pulse is sent through a stretcher, which can be constructed with discrete elements (gratings, prism) or be a piece of glass or a fiber. The different frequency components of the pulse are delayed with respect to each other, resulting in chirp and pulse stretching. The 10 000 to 100 000 times pulse stretching ratio allows considerable amplification before the damage limit to the components of the amplifier is reached. The action of the stretcher is reversed in the amplifier, resulting in the creation of an extremely intense ultrashort pulse. Please find a color version of this figure on the color plates.

The mechanism of stretching is dispersion, a mechanism that was discussed in Section 1.7.3, Figure 1.21. In a medium with dispersion (gratings, prisms, glass), different frequency components of the pulse spectrum propagate at different velocities, resulting in pulse stretching. This mechanism is linear and reversible as the sign of the dispersion is changed. »Chirped pulse amplification« (CPA) [30] refers to an amplifier system where an ultrashort pulse is stretched by four to five orders of magnitude, sent through several stages of amplification, before being compressed back to the original pulse width. The successive components, as sketched in Figure 1.31, are stretcher, (linear) amplifier, and compressor. In femtosecond high energy systems, the peak intensity reached are so high that the compressor has to be put in a vacuum chamber. Indeed, as will be seen in more detail in Section 7.1, the air itself is a nonlinear medium at these extremely high intensities.

1.9 Ultrashort Ultraprecise Laser Pulses

In the previous sections we introduced ultrafast events, which at first sight would have little relevance with the time scales associated with our daily life. By a bizarre twist of nature, it is the fastest event that ends up providing the most accurate time measurements for long duration events. Let us take, for instance, the rotation of the earth about its axis. Because of the huge mass involved, one would expect the length of the day to be a perfect clock for long term events, years, centuries, and millennia. The rotation of the earth is not constant: the tides cause a small friction that slows down the earth rotation. Paradoxically, motions of electrons in an atom, which are on the femtosecond scale, provide a more accurate clock than astronomical events. A quartz clock ticking at kHz has a considerably longer range accuracy than grandma's pendulum clock ticking at a second rate. Atomic clocks, however, ticking at petahertz (10^{15}), considerably outperform the quartz clock in long term accuracy. Atomic clocks are not only used as a time standard, but also as a distance standard. Here also, accuracy and stability are provided by microscopic standards rather than by large objects. The meter was initially defined at the time of the French revolution as being 1/100 of the decimal degree on the equator (or 140 000 of the circumference of the earth). This definition has been replaced by a smaller object: a block of quartz a meter long stored at constant pressure and temperature in Paris. However, even that object does not have the long range stability of the wavelength of the cesium clock. Presently, the length standard is defined through the time standard (the period of oscillation of the Cs clock, in the fs range) multiplied by the speed of light in vacuum (defined as a fixed number $c = 299\,792\,458\,\mathrm{m/s}$).

While accuracy may come as a surprise, it should be obvious that the shortest clock period will provide the most sensitivity or resolution in time measurement, since the measurement is performed with finer tick marks. A seemingly impossible challenge is to count time, when the time interval between clock ticks is only a couple of fs, a million times faster than standard electronics can resolve. This is where the laser made a remarkable revolution, which was recognized by the Nobel Prize in Physics in 2005. It refers to a property of the mode-locked laser that has puzzled researchers for some time [31]. The sketch of Figure 1.32 will help explain the dilemma. We have seen that lasers used for generating ultrashort pulses by mode-locking have gain over a very broad range of wavelengths. Therefore, if they are not mode-locked (see Section 1.7.2), they can be operated over a broad range of wavelengths. As we tune that wavelength, we can record the round trip rate of that cavity on a frequency counter. Since the speed of light in the components of the cavity is a function of the wavelength, we

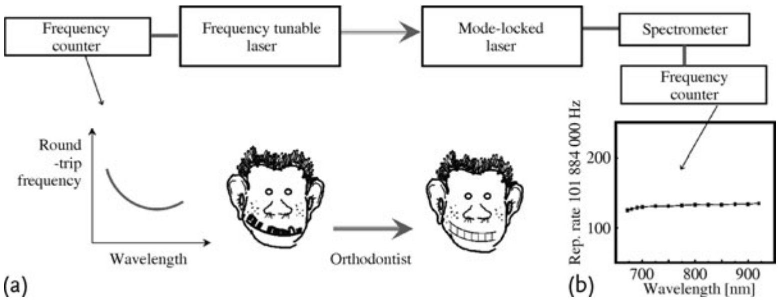


Figure 1.32 On the left: the output of a tunable laser (such as a dye laser or a Ti:sapphire laser) is sent to a detector, connected to a frequency counter. The latter records the repetition rate (round trip rate) of the laser as a function of wavelength. The repetition rate varies across the spectrum. The transformation of the laser from a continuously tunable into a mode-locked laser is equivalent to sending the laser to an orthodontist. As the output of the laser is sent to a spectrometer and thereafter to the frequency counter, the same number (repetition rate of 101 884 130 Hz) is observed across the spectrum.

will record a curve as shown in Figure 1.32a. What is measured is the separation between the optical frequencies, or *modes*, that can be produced by this laser. These optical frequencies form a *frequency comb*, of which the spacing between teeth is not constant. If, by a strike of magic, we make the same laser produce ultrashort pulses, we can perform a similar experiment, consisting in measuring the pulse rate after selecting a particular wavelength region. We find that the repetition rate is constant over the spectrum. The *frequency comb* produced by the laser in mode-locked operation has a constant spacing between teeth [32]. Mode-locking the laser is like sending the laser to the orthodontist, it corrects the tooth spacing. The mechanism by which the teeth spacing is »corrected« is rather complex [31] and is related to the soliton operation discussed in Section 1.7.3. Having a perfect comb in frequency has important consequences in metrology. It means first that this comb can be used to measure frequency differences, just as a metric ruler is used to measure distances. It also implies that, in the time domain, the pulse train that is issued from the mode-locked laser can be represented by a single frequency wave (labeled the »*carrier*«) that is sampled at regular intervals (which correspond to the round trip time of the laser cavity), as shown in the top part of Figure 1.33. In frequency, the mode-locked laser can be represented by a comb of equally spaced teeth, as shown in the bottom part of Figure 1.33.

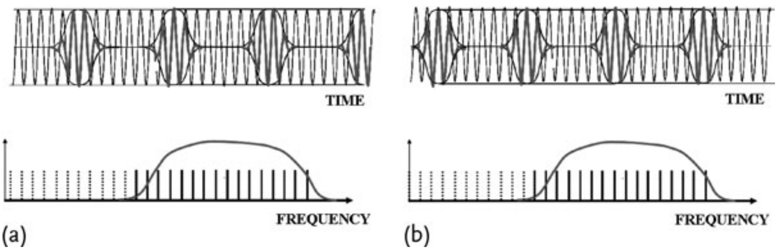


Figure 1.33 The mode-locked pulse train, in the time domain (top) is shown as a wave at a single carrier frequency, modulated by and envelope. The corresponding comb of optical frequencies is represented on the bottom. (a) A general case where the envelope spacing is not an integer number of optical cycles. (b) The envelope spacing is an integer number of light periods, and, in addition, the carrier to envelope phase is zero. Please find a color version of this figure on the color plates.

For each pulse, the phase of the carrier at the peak of the envelope is called the carrier to envelope phase (CEP). In Figure 1.33a, the spacing between *envelopes* is not an integer number of optical cycles of the carrier and, therefore, varies from pulse to pulse. The frequency at which this CEP varies (the ratio of CEP for two successive pulses to the pulse spacing) is called the carrier to frequency offset (CEO). The situation represented in Figure 1.33b is that where the envelope spacing is an integer number of light periods. Thus the time between the pulses is defined with the precision and accuracy of the light period (typically 2.5 fs) and is of the order of a nanosecond, and thus can be electronically counted. If the carrier frequency is linked to that of an atomic clock, one has created a time standard of femtosecond precision. In the frequency domain, one tooth of the comb has been defined with absolute accuracy. The spacing between teeth is also defined with the same accuracy since it is being forced to be an integer number of light periods (forcing the CEO to be zero). The frequency comb is then a frequency ruler of utmost accuracy and precision, which is particulary useful in astronomy.

1.10 Ultrashort Ultrasensitive Laser Pulses

The near perfection of the laser output itself makes it very sensitive to any perturbation. As an example, if we consider only the propagation of the frequency comb of zero CEO shown in Figure 1.33b, the velocity of the pulse envelope will generally be different from that of the carrier. As a result, the CEP will change; a change that can be exploited to monitor the properties of the medium traversed. Highest sensitivity can be achieved if this change in CEP is exploited inside the laser itself, as will be analyzed in more detail in Chapter 8. Other properties of ultrashort laser pulse that can be exploited to sense properties of the traversed media are the possibilities of high power pulses to project high intensities at distance through filaments (as discussed above in Section 8) and create other wavelengths through the nonlinear process to be described in Section 1.11 that follows. Methods to exploit filaments for remote sensing will be the topic of Chapter 7.

1.11 The Nonlinear Wizard: Juggling with Frequencies

1.11.1 Stacking up Photons

The nonlinear wizard is not a scary cross-sighted scientist, but instead a jewel: a small crystal. The generation of harmonics is common with electronic amplifiers. If a pure note is given by the amplifier, and we turn up the volume, the sound will be distorted. When a wave is no longer a pure sinusoidal wave, that means it contains higher frequencies – the harmonics. The first of these harmonics is the »second harmonic«, that is, an electromagnetic oscillation as twice the frequency of the light or half the wavelength.

For instance, the invisible, IR Nd:YAG laser or the vanadate laser at 1064 nm can be made to generate in a crystal a second harmonic at the green wavelength of 532 nm. This has become the most common source of green light used in green laser pointers, in powerful (up to 20 W) continuous lasers to pump Ti:sapphire lasers, or for rock concerts.

There are some stringent conditions to be met by the crystal to generate efficiently the second harmonic. The first condition is a lack of symmetry: the crystal structure should not have a center of symmetry. The second condition is called »phase matching«. The generating wave (called the »fundamental wave«) will create its second harmonic at any point of the crystal. The fundamental propagates at the velocity of the wave $v_{w1} = c/n_1$ where n_1 is the index of refraction of the crystal for the fundamental wavelength along the direction of propagation and polarization of the fundamental. Figure 1.34 illustrates three cases of second harmonic generation in a crystal with a »snapshot« of the waves passing through the crystal at a certain instant. The wave F is the fundamental wave, the same in all three cases. In all three cases, a second harmonic is generated at the entrance plane A, and propagates through the crystal at a velocity $v_{w2} = c/n_2$, where n_2 is the index of refraction of the crystal for the shorter second harmonic wavelength, along the direction of propagation and polarization of the second harmonic. Case (a) corresponds to the case where the crystal is phase matched, that is, $n_2 = n_1$, and the second harmonic and the fundamental propagate at the same velocity in the crystal. Consequently, the second harmonic generated in the plane B, SH_B is in phase with the second harmonic generated in A that has propagated to B. The two signals add in phase to create a larger second harmonic field SH. Case (b) shows the more general case when the crystal is not phase matched, $n_2 \neq n_1$ and the second harmonic SH_A generated at the entrance plane A of the crystal, having propagated to a plane B, may destructively interfere with the second harmonic SH_B created at the plane B. The resulting second harmonic field SH is zero. In the case of phase matching (a), the second harmonic generation can then be very efficient: up to 80% of the fundamental light can be converted into the second harmonic. However, one cannot always find in a crystal an orientation for which $n_2 = n_1$. In that case, there is another possibility to generate a second harmonic efficiently by using the property that the crystal has no center of symmetry. In (c), the second harmonic generated at the entrance plane A and propagated to plane B is SH_A as in case (b). However, by reversing the crystal orientation

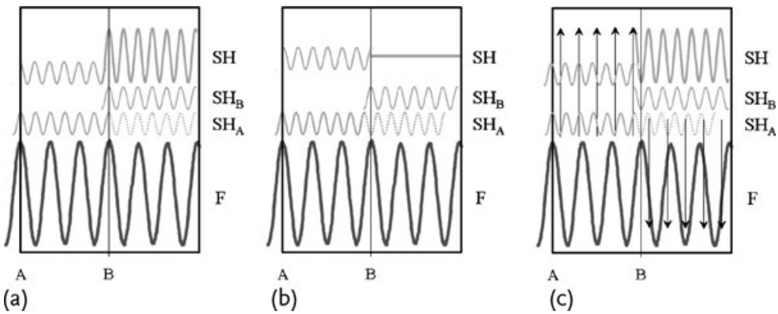


Figure 1.34 Simplified sketch to illustrate the second harmonic generation in a nonlinear crystal. F is the fundamental wave sent through the crystal. In (a) the crystal is phase matched: the second harmonic generated at the entrance plane *A* propagates to the plane *B* (SH_A), and adds constructively with the second harmonic produced by the fundamental at plane *B* (SH_B, to form a large second harmonic field SH). In (b), case of a nonphase matched crystal, the second harmonic SH_A is out of phase with the second harmonic produced by the fundamental at plane *B* (SH_B: the two fields cancel out to form a zero second harmonic SH). (c) is the case of a periodically poled crystal. With the optic axis oriented as shown by the arrows, the propagation and second harmonic generation from plane *A* to *B* are the same as in case (b). In case (c), the optic axis is reversed after plane *B*, and the second harmonic generated in *B* is reversed as compared to cases (a) and (b). Consequently, the two fields SH_A and SH_B add in phase to create a large second harmonic SH. Please find a color version of this figure on the color plates.

at plane *B*, the phase of the second harmonic generated at that plane, SH_B, is also reversed, and therefore adds in phase with SH_A. The crystal where the optical axis is flipped periodically is called a periodically poled crystal. This technique is called quasi-phase matching and is used most often with lithium niobate crystals, which have a very high nonlinearity and good transparency. The acronym PPLN is quite often used to designate these crystals. The nonlinearity is the highest along an optic axis of the crystal, the z-axis. Poling is achieved by applying thin electrodes (10–40 μm wide, depending on the length of the individual domain desired) on the faces perpendicular to that axis. The »poling« or orientation of the axis is made by applying a very high electric field at high temperature on these electrodes.

Nonlinear optics can easily be described through the photon picture. Two photons of the fundamental radiation are converted into one photon of the second harmonic of twice the photon energy, under the influence of the crystal. The two generating photons do not need to be of the same frequency: if one photon has the energy $h\nu_1$ and the other the energy $h\nu_2$, they can combine in the crystal to form the *sum frequency* photon of energy $h\nu_3 = h\nu_1 + h\nu_2$. As almost everything is reversible with laser light, there is also a process of *difference frequency generation* where two light beams at optical frequencies ν_3 and ν_2 are sent into a crystal to generate a wave at frequency $\nu_1 = \nu_3 - \nu_2$. As in the case of the second harmonic generation, the process has to be phase matched to be efficient: all three waves have to propagate at the same velocity.

Two photons of equal frequency or wavelength can add up in second harmonic generation or »frequency doubling«, or they can subtract from each other resulting in zero frequency generation, or optical rectification. In that case, a field of zero frequency, which is a continuous field, is applied to the crystal. The reverse of that operation is the electro-optic effect, which was introduced in Section 1.5.3.3, by which the sum of a zero-frequency photon (continuous electric field) and an optical photon at frequency ν_1 is made, to result in an optical photon still at frequency ν_1 with slightly different phase and/or polarization.

1.11.2 Parametric Generation and Amplification

In the previous section a higher frequency photon was created by adding two lower energy ones. Two photons are lost from the fundamental beam, in order to create a single photon of higher energy. In the reverse process, if starting with a higher energy photon of energy $h\nu_3$, there is *gain* for radiation at the frequency $\nu_s < \nu_3$. This is called *parametric gain* and is fundamentally different from stimulated emission gain. In the presence of a beam of frequency ν_s, the »pump« photon of energy $h\nu_p$ gives birth to two photons, respectively, of energy $h\nu_s$ (the »signal photon«) and $h\nu_i$ (the »idler photon«), such that $h\nu_3 = h\nu_s + h\nu_i$ (Figure 1.35). As in the case of gain with population inversion, the photon $h\nu_s$ is undistinguishable from the other photons of the beam at frequency ν_s. Despite the similarity, parametric gain is fundamentally different from gain produced by a population inversion, as sketched in Figure 1.35. In this case, we consider a square pulse pump (in time), that is, the pump beam is turned on for a very short time, then turned off. The propagation of a weak pulse in a medium with population inversion is similar to a skier going downhill (Figure 1.35a). The signal pulse extracts more and more energy from

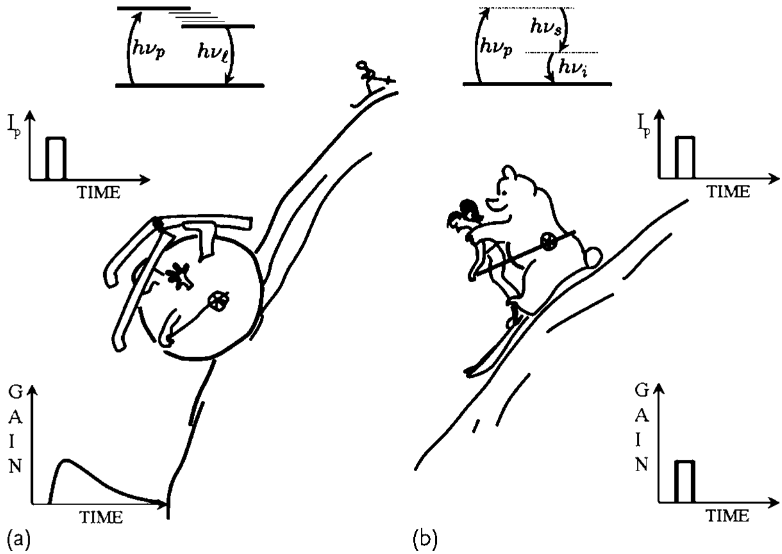


Figure 1.35 Comparison of gain through population inversion and parametric gain. (a) In the case of gain through population inversion, the signal pulse extracts more and more energy from the medium as it grows. (b) In the case of parametric gain, the signal pulse only gains energy as long as the pump is present.

the medium as it grows, because the gain has a lifetime of the order of microseconds in the case of crystal host lasers such as Ti:sapphire, Nd:YAG, Yb:YAG, etc., which is a very long time in the laser world. For a parametric gain however (Figure 1.35b), the signal pulse at ν_s only gains energy as long as the pump (the bear at ν_p) is present. With parametric gain, there is no background noise from fluorescence, as there is with a population inversion gain medium.

1.11.2.1 Optical Parametric Oscillators and Optical Parametric Generators

As we have seen in Section 1.3.3, a laser is an amplifier with the feedback of some mirrors, which can be arranged in a linear configuration or a ring cavity. An optical parametric oscillator is very similar to a laser with gain. The main difference is that the gain medium is a crystal, and that the pump radiation has to be provided by a laser. The main use of the optical parametric oscillator is to be a source of laser radiation in the infrared, since it provides photons of lower energy than the pump photons. At each round trip through the cavity of the beam at frequency ν_s, pump photons of energy $h\nu_p$ are replaced

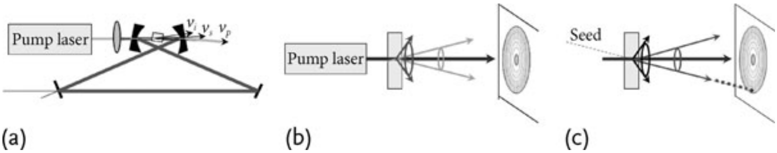


Figure 1.36 (a) An optical parametric oscillator in a ring cavity. (b) An optical parametric generator. (c) A seeded optical parametric generator. Please find a color version of this figure on the color plates.

by two photons of energy $h\nu_s$ and $h\nu_i$. The photon of energy $h\nu_s$ is called the signal photon and adds up coherently (that is, in phase) to the beam of wavelength $\lambda_s = c/\nu_s$. In general, the cavity will only be resonant for the signal wavelength, as sketched in Figure 1.36a. There would be too many constraints if both the idler and signal were resonant with the cavity. Indeed, the idler frequency would be simultaneously fixed by two conditions that, in general, may conflict: to be the difference of the pump and signal frequencies and at the same time a mode of the cavity.

We have seen in the case of a nitrogen laser (see Section 1.4.2.2) that a mirrorless laser can operate if the gain is sufficiently high: the fluorescence is amplified along the longest dimension of the gain volume. In the case of the pumped nonlinear crystal, there is no fluorescence to be amplified. Yet, with sufficient excitation, a crystal used for optical parametric oscillation may produce a rainbow of colors, as illustrated in Figure 1.36b. Complementary colors for which the sum of the optical frequencies equal that of the pump are generated at angles such that all three waves remain in phase throughout the crystal. This is called an optical parametric generator (OPG). Since there is no fluorescence to be amplified, what is the radiation that is being amplified? We have seen that vacuum itself is filled by a sea of photons (cf. Section 1.1.1). It is this vacuum photon or zero-point energy that seeds the optical parametric generator. In the typical arrangement of Figure 1.36, the pump radiation will be green laser light near 500 nm. The signal will be in a range of 700–1100 nm and the idler at the complementary wavelength, so that the sum of photon energies (idler and signal) equals the pump energy.

There is a remarkable application to the OPG: that of being a source of light that has its own intensity calibration. The intensity of the vacuum radiation is known from theory. The gain along a path of amplified radiation can be measured by sending seed radiation along that same path and measuring the ratio of amplified to initial intensity (Figure 1.36c). The amplified seed radiation is seen as a bright spot within the ring of optical generation of the same color in Figure 1.36c. Absolute calibration of a light source by such an arrangement has been demonstrated with high power pump lasers [33]. If miniaturized and implemented with efficient, compact lasers, it can become a valuable tool for spacecrafts and satellites in need of detector and source calibration that is not dependent on lamp standards that are susceptible to aging.

1.11.3 Too Many Photons to Swallow: Multiphoton Absorption

The phenomena described in the previous sections have a remarkable property: no energy is lost from the light waves. The material acts as a catalyst; exchange two or more photons for a higher energy photon. In harmonic generation, the crystal is a generous social worker, definitely not a capitalist: he does not keep any energy for himself. The sum of the product of the photon energies by their number is conserved in harmonic generation. We have seen in Sections 1.3.2 and 1.5.2 that an atom/molecule with energy levels separated by the photon energy will absorb the photon. The total energy of the radiation-matter system is conserved, but energy has been transferred from the beam to the matter. In another situation, a medium that is transparent to low intensity radiation may become absorbing for high intensity light, if there are some energy levels at twice the photon energy. The mechanism of multiphoton absorption is important for depositing energy inside a transparent medium. Indeed, when focusing an intense pulse inside a material, the intensity increases along the beam to reach a maximum at the focus. Likewise, the absorption will increase to a maximum at the focus. In the case of a two-photon absorber, the beam absorption, or the number of pairs of photons absorbed, is proportional to the *square* of the intensity of the laser radiation. For n-photon absorption, the attenuation is proportional to the nth power of the exciting beam intensity. Radiation may be emitted by fluorescence following multiphoton absorption. This radiation is quite different from the harmonic generation discussed in Section 1.11.1. Harmonic generation of intense radiation at the wavelength λ_0 is instantaneous and at a wavelength that is an exact submultiple of the fundamental $\lambda_n = \lambda_0/n$. Fluorescence following multiphoton absorption is not instantaneous [34], and the radiation that follows the excitation, at a wavelength $\lambda_F < \lambda_0/n$, lasts for a »fluorescence lifetime« in the range of ns to ms. Applications of multiphoton absorption are discussed in Chapter 5.

Ultrashort pulses can typically eject an electron from an atom, in a processus called multiphoton ionization. This phenomenon has an impact on filamentation (negative lensing due to the electron plasma – see Section 1.7.5.3), attosecond pulse generation (see Chapter 6), and plasma shutter.

1.11.3.1 Plasma Shutter – How It Leads to a Better Understanding of Absorption

The plasma shutter deserves a few lines of introduction, as one of the oldest and simplest applications of multiphoton ionization. It is generally used in combination with a TEA laser (see Section 1.4.2.1). The MW peak power of that CO_2 laser is focused in air (or any other gas), creating a plasma of electrons by multiphoton ionization. These electrons are accelerated by the field of the laser, to an energy sufficient to ionize all the other surrounding molecules, a process called cascade ionization. The latter cascade ionization results in a total ionization of the focal volume, or creation of a »plasma« of electrons and ions as dense as the atmosphere. Within this volume, the air has become a perfect conductor and has all the properties of a metal, including the reflectivity of a metallic surface. The air that was initially transparent to the CO_2 laser pulse has suddenly become totally opaque and reflecting, and therefore the pulse emerging from the focal spot has its tail abruptly cut. By creating pulses with an abrupt (picosecond) cut off, the plasma shutter has been an early tool for subnanosecond pulse shaping [35]. The experiment performed with such a plasma shutter, sketched in Figure 1.37, leads to an understanding of absorption as an interference. In Figure 1.37a, a powerful beam of a CO_2 laser is sent through an absorbing cell of sufficient length, so that the complete nanosecond pulse is absorbed and the detector placed at the end of the tube does not observe any signal.

The phenomenon of absorption can be understood in the following way. The photons that are absorbed excite molecular dipoles, at the frequency of the light. We have seen that an oscillating dipole is a source of radiation (see Figure 1.1 at the beginning of this chapter), which

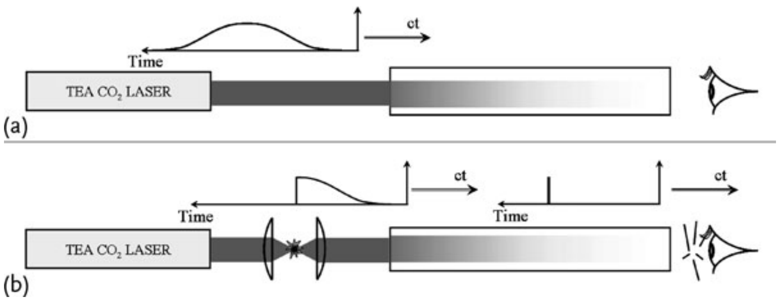


Figure 1.37 Absorption can be interpreted as being due to the incoming light exciting dipoles that radiate with opposite phase. In (a) A CO_2 laser pulse[15] is sent through a resonant absorber (typically heated CO_2). The excited molecules emit a wave that destructively interferes with the incoming wave, resulting in a null signal on the detector. In (b), a plasma is created in air, which abruptly cuts the tail of the ns pulse. There is no more incoming wave to destructively interfere with the radiation from the excited molecules. An intense pulse is observed on the detector, which has a duration determined by the time that the excited molecules remain in phase. That time is related to the collision time between an excited molecule and any other atom or molecule in the cell. Please find a color version of this figure on the color plates.

is emitted at the same frequency as the exciting radiation, but exactly 180° out of phase. Waves that are out of phase tend to cancel each other. If a number of dipoles equal to the number of photons in the incoming pulse are reradiated out of phase, the incoming pulse is completely destructively interfered. The plasma shutter can provide a dramatic demonstration of this effect. In Figure 1.37b, the plasma abruptly cuts the tail of the strong CO_2 laser pulse, near the peak of its intensity. All the dipoles that were excited by the slowly rising pulse continue to reradiate, but, since there is no more incoming wave to cancel, the detector will be blinded by an intense pulse. This pulse will last as long as these dipoles have not lost their relative phase by collision. The time it takes for dipoles to dephase by collision is inversely proportional to the pressure and of the order of ns torr (depending on the particular molecules involved). For instance, at 20 torr pressure, the pulse created in this manner would have a duration of the order of 50 psr.

15) In the figure, the source is labeled as a TEA laser. In general the bandwidth of this laser is too large compared to that of the absorber, which is a low pressure heated CO_2 cell. Some »tricks« are needed in the actual experiment to make the source a narrow line, such as injecting it with another laser, or inserting a low pressure CO_2 laser in the same resonator.

References

1 Haisma, J. and Spierings, G.A.C.M. (2002) Contact bonding, historical review in a broader scope and comparative outlook. *Mater. Sci. Eng. Rep.*, **37**, 1–60.

2 Haisma, J. (1962) *Construction and properties of short stable gas laser*. PhD Thesis, Rijksuniversiteit te Utrecht, Utrecht, the Netherlands.

3 Strong, C.L. (1974) The amateur scientist. *Sci. Am.*, **230**, 122–127.

4 Snitzer, E. and Osterberg, H. (1961) Observed dielectric waveguide modes in the visible spectrum. *J. Opt. Soc. Am.*, **51**, 499–505.

5 Snitzer, E. (1961) Optical Maser action of Nd^{3+} in barium crown glass. *Phys. Rev. Lett.*, **7**, 444–448.

6 Heard, H.G. (1968) *Laser Parameter Measurements Handbook*, John Wiley & Sons, Inc., New York.

7 Knight, J.C., Birks, T.A., Russell, P.S.J., and Atkin, D.M. (1996) All-silica single-mode optical fiber with photonic crystal cladding. *Opt. Lett.*, **21**, 1547–1549.

8 Kumar, V.V.R.K., George, A.K., Reeves, W.H., Knight, J.C., Russell, P.S.J., Omenetto, F., and Taylor, A.J. (2002) Extruded soft glass photonic crystal fiber for ultrabroad supercontinuum generation. *Opt. Express*, **10**, 1520–1525.

9 Bhagwat, A.R. and Gaeta, A.L. (2008) Nonlinear optics in hollow-core photonic bandgap fibers. *Opt. Express*, **16**, 5036–5047.

10 Slepkov, A.D., Bhagwat, A.R., Venkataraman, V., Londero, P., and Gaeta, A.L. (2008) Generation of large alkali vapor densities inside bare hollow-core photonic bandgap fibers. *Opt. Express*, **16**, 18976–18983.

11 Trum, H.M.G.J. and Diels, J.C. (1970) Quiet turbine for high speed optical applications. *J. Phys. E: Sci. Instrum.*, **3**, 564.

12 McClung, F.J. and Hellwarth, R.W. (1962) Giant optical pulsations from ruby. *J. Appl. Phys.*, **33**, 828–829.

13 Ippen, E.P., Shank, C.V., and Dienes, A. (1972) Passive mode-locking of the CW dye laser. *Appl. Phys. Lett.*, **21**, 348–350.

14 Ruddock, I.S. and Bradley, D.J. (1976) Bandwidth-limited subpicosecond pulse generation in mode-locked CW dye lasers. *Appl. Phys. Lett.*, **29**, 296.

15 Diels, J.C. and Sallaba, H. (1980) Black magic with red dyes. *J. Opt. Soc. Am.*, **70**, 629.

16 Mourou, G.A. and II, T.S. (1982) Generation of pulses shorter than 70 fs with a synchronously pumped CW dye laser. *Opt. Comm.*, **41**, 47–49.

17 Dietel, W., Fontaine, J.J., and Diels, J.C. (1983) Intracavity pulse compression with glass: a new method of generating pulses shorter than 60 femtoseconds. *Opt. Lett.*, **8**, 4–6.

18 Valdmanis, J.A., Fork, R.L., and Gordon, J.P. (1985) Generation of optical pulses as short as 27 fs directly from a laser balancing self-phase modulation, group velocity dispersion, saturable absorption, and saturable gain. *Opt. Lett.*, **10**, 131–133.

19 Diels, J.C., Stryland, E.W.V., and Benedict, G. (1978) Generation and measurements of pulses of 0.2 psec duration. *Opt. Comm.*, **25**, 93.

20 Fork, R.L. and Shank, C.V. (1981) Generation of optical pulses shorter than 0.1 ps by colliding pulse mode-locking. *Appl. Phys. Lett.*, **38**, 671.

21 Shank, C.V. (1982), Progress in ultrashort optical pulse generation,

Paper WE3, presented at the XIIth Int. Quantum Electron. Conf.
22 Asaki, M.T., Huang, C.P., Garvey, D., Zhou, J., Kapteyn, H., and Murnane, M.M. (1993) Generation of 11 fs pulses from a self-mode-locked Ti:sapphire laser. *Opt. Lett.*, **18**, 977–979.
23 Stingl, A., Spielmann, C., Krausz, F., and Szipöcs, R. (1994) Generation of 11 fs pulses from a Ti:sapphire laser without the use of prisms. *Opt. Lett.*, **19**, 204–406.
24 Ell, R., Morgner, U., Kärtner, F.X., Fujimoto, J.G., Ippen, E.P., Scheuer, V., Angelow, G., Tschudi, T., Lederer, M.J., Boiko, A., and Luther-Davis, B. (2001) Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser. *Opt. Lett.*, **26**, 373–375.
25 Russell, J.S. (1844) Report on waves, in *Report of the fourteenth meeting of the British Association for the Advancement of Science*, York, pp. 311–390; plates XLVII–LVII.
26 Bullough, R.K. (1988) The wave, »par excellence«, the solitary, progressive great wave of equilibrium of the fluid – an early history of the solitary wave, in *Solitons* (ed. M. Lakshmanan), Springer Series in Nonlinear Dynamics, pp. 150–281.
27 Coles, S. (2001) *An Introduction to Statistical Modeling of Extreme Values*, Springer-Verlag, London.
28 Solli, D.R., Ropers, C., Koonath, P., and Jalali, B. (2007) Optical rogue waves. *Nature*, **450**, 1054.
29 Kasparian, J., Béjot, P., Wolf, J.P., and Dudley, J.M. (2008) Optical rogue wave statistics in laser filamentation. *Opt. Express*, **17**, 12070–12075.
30 Maine, P., Strickland, D., Bado, P., Pessot, M., and Mourou, G. (1988) Generation of ultrahigh peak power pulses by chirped pulse amplification. *IEEE J. Quantum Electron.*, **QE-24**, 398–403.
31 Arissian, L. and Diels, J.C. (2009) Investigation of carrier to envelope phase and repetition rate – fingerprints of mode-locked laser cavities. *J. Phys. B: At. Mol. Opt. Phys.*, **42**, 183001.
32 Jones, R.J. and Diels, J.C. (2001) Stabilization of femtosecond lasers for optical frequency metrology and direct optical to radio frequency synthesis. *Phys. Rev. Lett.*, **86**, 3288–3291.
33 Migdall, A., Datla, R., Sergienko, A., Orszak, J.S., and Shih, Y.H. (1998) Measuring absolute infrared spectral radiance with correlated visible photons: technique verification and measurement uncertainty. *Appl. Opt.*, **37**, 3455–3463.
34 Rudolph, W. and Diels, J.C. (1986) Femtosecond time resolved fluorescence. *Picosecond Phenomena V* (ed. A.E. Siegman), Springer-Verlag, Berlin, pp. 71–74.
35 Yablonovitch, E. (1974) Self-phase modulation and short pulse generation from laser-breakdown plasmas. *Phys. Rev. A*, **10**, 1888–1895.

2
Laser Coherence at Home

What is in the laser that makes it play a part in the »laser printer and scanner«, »laser pointer«, and »DVD burners«?[16] Knowing the properties of lasers as discussed in the previous chapter, we can apply them anywhere that suits our purpose, just like a cook who knows where to put a particular spice. It can be compared to the properties of a spinning wheel to transfer motion at low energy cost, exploited in toys and cars, printers, and so on. One of the main properties of a laser used in the technologies mentioned above is its »divergence« (Section 1.2.3). The laser light, unlike other sources, can be well directed in a small spot. Moreover, its energy can be tuned and used to change material, as in DVD burners.

2.1 The Laser Printer

Printing has come a long way from carving on a stone to the mass publication of today. The goal is to print data as fast as possible, with the highest fidelity, at the lowest cost, for the enjoyment of the few of us that still favor reading from paper rather than staring at a screen.

Today's printer technology stands on the shoulders of advances in mechanics, chemistry, electronics, and optics. In early photography printing the main role was given to the optical lenses that projected the image of the negative on a paper sensitive to light, from there the proper chemical reaction and development of photography defined the quality of the image. Laser printers, on the other hand, are based on xerography (or electrophotography), which is a dry photocopying technique. The process consists of three steps as outlined below: (1) charge initialization, (2) exposure, and (3) development.

16) DVD is one of these acronyms for which the meaning has been forgotten by most. It stands for digital video disc.

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

In the first step (charge initialization) a cylindrical roll called the *drum* is uniformly charged. In some designs the cylindrical drum is replaced by oval or triangular belts. The initialization platform consists of two materials, one conductor and the other photosensitive. Initially, amorphous selenium was used as a photosensitive material, but this is now being replaced in favor of organic materials. In a typical laser printer, drums are made of a doped silicon diode sandwich structure with a hydrogen doped silicon light chargeable layer, a charge leakage layer (boron nitride), and a surface layer of doped silicon.

In the exposure step, the data is recorded on the drum by neutralizing or changing the sign of charges. This is done by turning the laser on and off (which is being scanned across the drum in laser printers) or a light emitting diode (LED) array projected onto the drum. In the case of lasers and LEDs the image recorded on the drum is a positive image, which means that the charges on the drum are neutralized or change sign with the illumination that carries the data. For copy machines based on the exposure from the original paper, the image on the drum is a negative one. The drum is not exposed where there are letters.

In the last step (development), with the proper bias for positive and negative imaging of the previous step, charged toners will find their proper place on the drum and sit on the digital »ones«. The recording is based on electrostatic attraction of opposite charges. This image is then transferred onto a piece of paper and run over a heated drum where the toner is melted onto the paper. This process is repeated for other toner colors in the case of a color printer.

The mechanism of the laser printer is shown in Figure 2.1. In this figure, the drum is uniformly negatively charged before the exposure. The laser has its role in the second part, to transfer the information on the drum. Here is where we remind ourselves of properties of the laser that justify its use: it has a small spot size that can propagate with less diffraction so as to maintain its size. With a proper lens and steering mirror the laser spot size on the corner of the drum is the same as that in the middle. Here, mechanical stability and reproducibility are essential, especially when various toner colors are used. We want to make sure that the laser hits the same spot for the various toners added. This is where we know that we would not have a laser printer if our technology in machinery were limited to carriage designs.

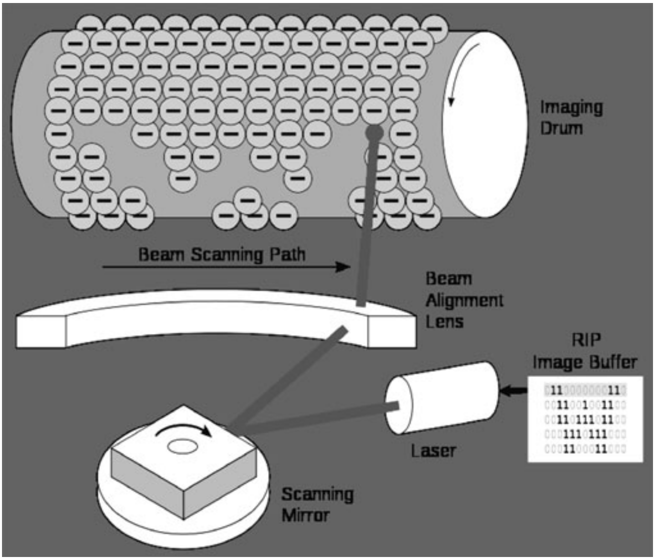


Figure 2.1 Schematic of a laser printer. The computer digital data of the image is transferred to brightness and darkness of the laser. Then the laser is steered with a mirror and a lens to discharge the negative charge of the drum where there is brightness (ones). Based on the electrostatic charge attraction, negative toners will ride on the discharged points of the drum. The toner is picked up by paper and the image is transferred for a particular toner color (picture from Wikipedia). Please find a color version of this figure on the color plates.

Another common type of printer is the *inkjet printer*, which does not involve optical imaging or electrostatic attraction: the liquid droplets are pressed on the paper to print the image.

From the palette of laser properties, such as ultrashort pulse, multicolor, wavelength selectivity, we can see that laser printers ignore most of the many potentials of the laser, focusing on just one property: the directionality.

2.2 The Laser Scanner

A scanner works like a camera. An object is illuminated and the reflected beam is recorded by a photosensitive material. Whenever there is illumination one can use laser light. The technology of charged-coupled devices (CCD) converts optical signals to electronic signals that can be digitized and saved in a data file, or used directly as analog

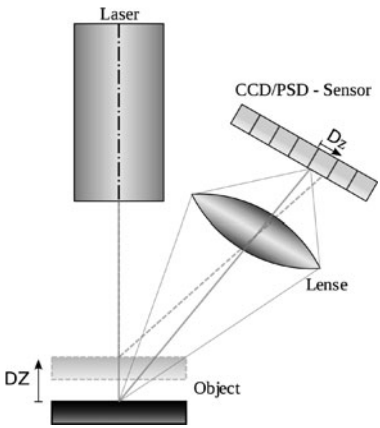


Figure 2.2 Principle of laser scanning based on triangulation. The object and image are fixed in space and only the laser light is steered across the sample. Reflection from front and back faces and corners of the object end up on different spots on a CCD. Please find a color version of this figure on the color plates.

signals to drive the printing mechanism. Using a laser in the scanning process enables 3D scanning.

There are two main classes of 3D scanners: one based on »triangulation« and the other on »time of flight measurement«. In *triangulation*, the point of observation is illuminated with a laser beam (collimation is again the important property of the laser that is exploited). The reflected beams from various surfaces are imaged with a lens on a CCD. Reflection from different depths are transferred to different positions on a CCD, as shown in Figure 2.2. The technique is called triangulation because the laser source, object, and the image make a triangle, in which one point in the triangle (the object) is unknown. The beam is scanned across the object to collect the full image. The quality of this imaging technique depends on the laser beam size, lens quality, CCD pixel size, stability in laser scan across the object, and the stability of the object itself. This technique takes advantage of our knowledge of geometrical optics and ability to follow the rays from various layers and corners to the imaging screen.

In *time of flight measurement*, a light pulse is sent to an object and the total travel time is measured. Light travels with a known speed that depends on the medium it propagates in. This application of the laser is similar to a radar. Light detection and ranging (LIDAR) is a technique based on time of flight measurement of laser pulses; in a military context it is often referred to as laser detection and ranging or LADAR. Here we can use our knowledge of pulses and make the first legitimate comparison between a laser scanner and a radar, based on the pulse length. The laser pulse can be engineered in much shorter lengths so as to have a better resolution. Laser scanners are used at various wavelengths, from environment scan with green pulses, the underwater scan of coral reef in the wavelength range of 430–460 nm, to minefield scans of a half inch resolution. In museums and at historical sites one can see the noninvasive application of 3D laser scanners to discover artwork hidden under mold. Here, the time taken for a laser pulse to make a trip to the sample and back to the origin, which is travel of twice the distance, gives the distance as $t \times v/2$, where »v« is the speed of light in the medium and »t« is the travel time. So the accuracy of a time of flight 3D laser scanner depends on how precisely we can measure the time; 3.3 ps resolution in time measurement corresponds to 1 mm.

Scientists used time of flight measurement of 10 Hz laser pulses at 1064 nm to record the variation of snow depth on the surface of Mars in a Martian year. The Mars Orbiter Laser Altimeter, or MOLA, was an instrument launched on a spacecraft in 1996. From 400 km altitude above the surface of Mars, the difference between the center of mass and the surface was measured over a Martian year. The same idea of time of flight measurement is applied on a totally different scale to image the eye. For the latter application, purely optical techniques have to be used, since the »time of flight« has to be measured with considerably better temporal resolution than electronics means can afford. These techniques will be presented in Section 3.9.

One can combine the short pulse capability of the laser with the wavelength resolution in an interferometer to achieve subwavelength resolutions. This is a more subtle application of the laser and will be discussed in Chapter 8. Unlike the above-mentioned techniques that shoot laser pulses like a bullet, in this method, the inner structure, which is the wavelength of the laser, is used. A crude estimation of the distance is made by overlapping (timing) of a sample and a reference pulse. A finer inner structure overlap is done with adding the two pulses in phase and out of phase (half a wavelength apart).

2.2.1 The Laser Barcode Reader

The barcode is an optical representation of data. Originally developed to label railroad cars with blue and yellow stripes, today's barcodes are mostly noticed for their use in labeling supermarket products. Most barcodes consist of black and white stripes of different thicknesses that correspond to numbers. Barcodes were also realized in 2D, but in most cases coloring is not a parameter in the pattern that has to be recognized.

Various ways of imaging barcodes converge towards the single goal: *imaging* the reflected light from the barcode.

- *Pen type readers* In this method the barcode is illuminated with a narrow light source in the tip of a pen. The reflected light from the pen is recorded with a photodiode. To record the entire barcode, the light source is scanned with a steady strike over the barcode.
- *Laser barcode scanner* This is the same as the pen type reader, only the light source is replaced by a laser source. Because of the directionality (Section 1.6.1) of laser light, the barcode no longer needs to be in close proximity to the barcode.
- *CCD barcode scanner* The reflected light from the barcode, which in this case is more scattered, is recorded with an array of tiny light sensors in the head of the barcode reader.
- *Camera barcode reader* The camera based barcode reader takes the image of a bar code. The snapshot is then analyzed using sophisticated image processing techniques.

The application of lasers in barcode reading does not use any special property of this form of light. The only benefit of using lasers is better illumination and detection of the reflected light, due to the laser directionality. The main credit for this technology goes to signal detection and computer programming. After the scan, the optical modulation of the reflected light is transferred (electronically) to numbers that identify the product. The data is assigned to a particular product by a computer program using the data base. The price of the product is pulled out of the data base and the inventory is updated as the product is purchased.

2.3 The Laser in Data Storage

The demand for recording visual and vocal data has existed since the early days of television. The oldest patents of *optical* storage goes back to John Logie Baird, the inventor of modern TV. He presented a system in which the storage consisted of a transparent film of modulated darkness. The information retrieval involved the focused radiation of a lamp illuminating the black and white storage medium, and the modulated transmitted light being recorded by a detector. The first optical storage had a very small bandwidth of 20 kHz and was only able to record 15 min of a TV program, with a quality that was not even sufficient at the time. Until 1983 the main device for storing data was through magnetic storage devices.

The invention of semiconductor lasers, made cheap by mass production, digital coding, and error correction, contributed to making the first compact discs (CD) available for audio data in 1982. The race in making higher capacity optical data storage has since been unabated. The CD uses gallium aluminum arsenide (GaAlAs) semiconductor lasers at 780 nm for storing and recovering data. The next improvement in data density came with the digital video disc (DVD) in 1995; which used basically the same principle, but shorter wavelength lasers for reducing the size of the »bit«. The latter lasers are aluminum gallium indium phosphide ($Al_yGa_xIn_{1-x-y}P$) diodes (wavelength 650 nm). The storage capacity of the DVD is not sufficient to satisfy the demands of high definition digital television. The violet laser came to the rescue. The gallium indium nitride (GaInN) lasers came to light in 1990 and are a key element in the high-density optical data storage in »Blu-ray« disks and HDVDs (high definition digital video disc).

Lasers play an important role in optical data storage, as more and more characteristics of the laser light are included in adding dimensions to the data storage. Lasers are used both for reading and writing (burning) on the optical storage medium. The laser intensity for reading is around 5 mW and for writing on the storage medium the intensity can go up to 400 mW. In writing, a laser light is focused on the surface and a permanent mark as a bit of information »1« or »0« is recorded. Depending on the material used for the storage, the in-

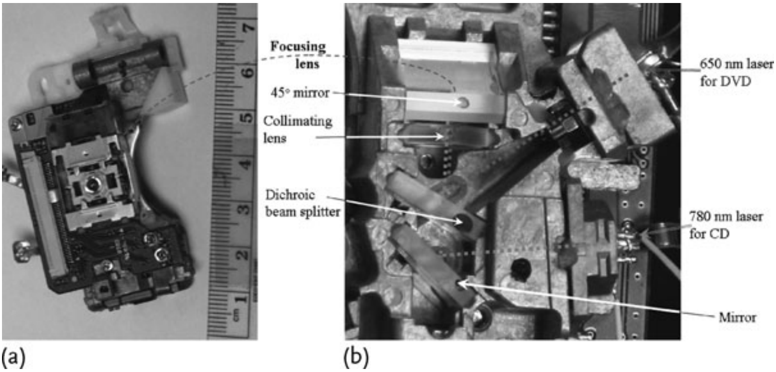


Figure 2.3 (a) Laser portion of a CD/DVD reader/writer. The lens focusing the beams onto the disk is in the center of (a). On the left of the lens is the drive screw for translating the focal point along the radius of the disc. (b) The »bottom part« is shown magnified. The 780 nm laser is for CD read/write, and the 650 nm laser for DVD read/write. The two beams are combined via a beam splitter that transmits the 780 nm beam and reflects 650 nm. Next, one can distinguish the collimating lens, followed by a 45° mirror sending the beam towards the focusing lens seen in (a). The remarkable compact device includes temperature control electronics.

formation can be reversible and rewritten. The first thing to consider is the size of the spot allocated to a bit of data, or the size of the focused laser beam. The physical size of the bit is of the order of the laser wavelength, with a depth ranging from one-quarter to one-sixth of the wavelength.

The marking on the storage associated with the data recorded is called a *pit*. It is important to maintain the laser spot over the spiral path (*groove*) while recording and reading the data. Two electrical servo loops control the motion of the laser across the groove and maintain its distance to the layer. In some cases, the laser head needs to be maintained as close as 30 nm to the storage screen. Note that the focus can be at different depths of the storage media. In the case of audio CDs, the data is recorded at the bottom of the disc through a transparent media. A DVD is written in the middle of the disc through a transparent media and Blu-ray discs have data recorded very close to the top layer.

The density of data storage is defined by the Rayleigh criterion (Section 1.2.3) that specifies the limit of how close two resolvable spots can be. The spot size itself is a function of the imaging lens and the light wavelength. There is a limit on how tight light can be focused with a lens. In air the highest *numerical aperture*[17] »N_A« is 1. In a material with index of refraction »n«, the numerical aperture is N_A/n, which makes tighter focus feasible. The closest two data points can get is $0.6\lambda/N_A$.

One can estimate the density of data storage on a single layer by dividing the useful area by the size taken by a spot:

$$\text{density} = \frac{1}{8}\frac{\text{area}}{\left(0.6\frac{\lambda}{N_A}\right)^2} . \tag{2.1}$$

Considering a DVD system, operating with 650 nm light and the DVD having a useful area of 92.7 cm^2 (inner and outer recording radii of 23 and 59 mm), the Rayleigh criterion prediction leads to 2 GB capacity. Due to improvement in digital signal theory and practice, the realized capacity is 4.7 GB, which is more than a factor of 2 higher than predicted. The Blu-ray DVD employs a higher numerical aperture and a shorter wavelength to achieve an even higher capacity (2.1). When data is only recorded on a single surface of the storage, the volume used for recording is 1% of the total volume of the disc.

A dramatic increase in data storage capacity did not occur through changes in wavelength or numerical aperture, but by multilayer writing and information multiplexing. For a three-dimensional recording one can use recording and reading of data at various distances from the surface, hence one can access layers at different depths inside the storage volume. In order to have more precision on layer access and smaller spot size, nonlinear effects (Section 1.11) are used. In 2008 researchers recorded 200 layers of data using two photon absorption with 5 GB capacity in each. Two photon absorption is a nonlinear effect, very sensitive to light intensity, so that material transformation takes place only at the tight focal spot, rather than along the path to the focus. Note that the typical thickness of a DVD substrate is 1.2 mm.

There is more to laser light than just its intensity and spatial confinement in the focus. A fourth dimension in data recording is light polarization (Section 1.2.2). When the pattern generated by various types of polarization can be sorted out in the reflected beam, one can record more than a bit at one spatial location. More dimensions to the data storage arise from adding frequencies and the spatial phase of

17) *NA* is the sine of the half angle by which the spot sees the lens, times the index of refraction. For imaging with a lens in air, the numerical aperture is approximately $D/2f$, where »f« is the focal length and »D« is the diameter of the lens.

the laser light that creates the pattern, and detect those qualities in the return beam. We can thus make a more delicate usage of the laser, as if we could see and detect an x-ray and a blood test of a person according to its appearance and be able to follow the pattern associated with these inner structures and metabolism. This is called multiplexing, where various parameters of the light are detected in the fingerprints left as the data.

2.4 Miscellaneous Applications

2.4.1 Laser Level

The laser appears as a virtual ruler to draw a straight line over a large distance. Mass production of semiconductor lasers have reduced their price to the point that one can find various affordable laser sources widely used in construction and home applications. Laser illumination can be in two and three dimension with various colors. The idea behind using the laser is very simple: light travels along a straight line, and the bundle of rays that make up a laser beam stays confined, that is, laser light travels with least divergence. A line can be well defined within the size of the laser beam, so that everyone can hang frames at home in a straight line without the need for strings and rulers.

2.4.2 Laser Pointers

Laser pointers are used as a tool for communication in speeches and presentations. The laser light is shined on a screen and reflected light from the surface is observed by the audience. We usually do not see the beam path on the way to its target, unless there is a scattering material on the way. The colors used for this pointer can vary from originally red (633 nm from helium-neon), deep red (650–670 nm from the diode laser), the green laser (532 nm), the yellow orange laser (593.5), up to the blue, violet laser at 405 nm.

The main reason for using laser sources as pointers is the small beam size over long distance or directionality (Section 1.6.1). The brightness of the spot seen by the audience is a function of the laser output power, scattering of the surface, and the chromatic response of the human eye.

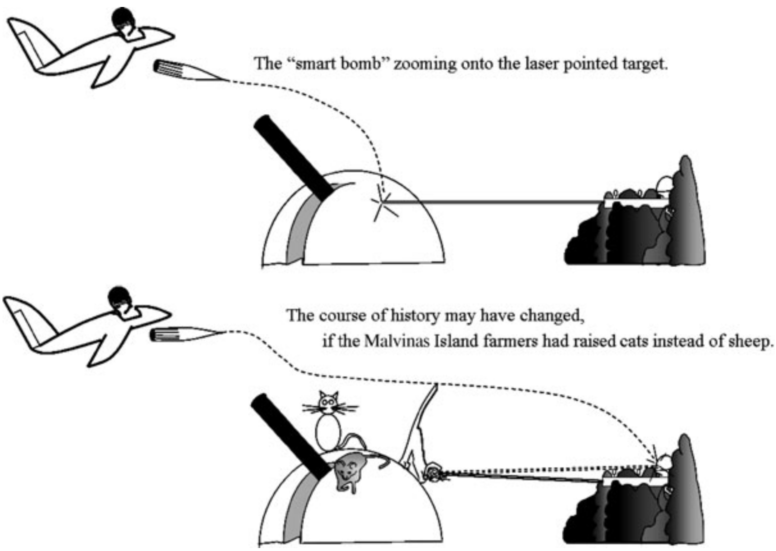
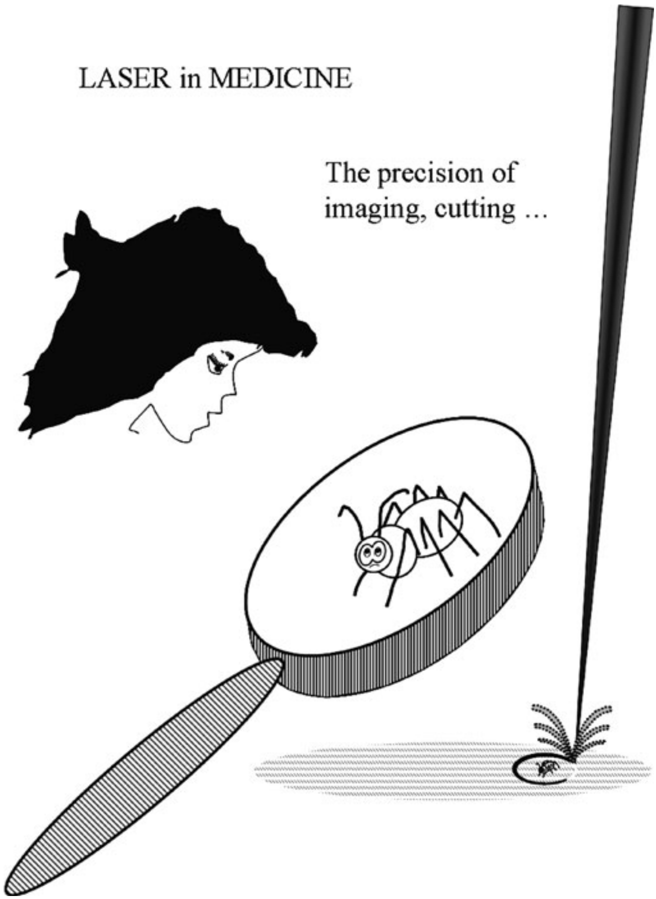


Figure 2.4 The laser pointer makes »war history«. A soldier points on a target with a laser pointer. In a scenario if the defender has a cat with »cat's eye« or any mirror to deflect the laser, the bomber would be mislead and aim at his own comrade.

2.4.2.1 The Laser Pointer as the Ultimate Weapon

The brightness of a laser is not only used to emphasize a part of a technical presentation, but has also been used to emphasize a target for a smart bomb. A propaganda video of the British illustrated the role of a laser in marking an Argentine antiaircraft gun during the Malvinas island (some call it Falkland islands) war. The video was a bit shaky: bullets were heard whistling near the ears of the cameraman and the infantry soldier holding a Nd:YAG laser and trying to keep it pointed as steadily as possible on a not-so-distant antiaircraft battery. Thanks to the brightness of the laser spot, a pilot could release his »smart bomb« from a safe distance. The smart bomb could guide itself onto the marked target. After all, the infantry man is dispensable, but not the pilot. Maybe the course of history may have been changed if the farmers that populated the bare Malvinas islands had raised cats instead of sheep. The cat's eye is a good retro-reflector and would have guided the not-so-smart bomb to the laser instead of the antiaircraft gun.

LASER in MEDICINE



3
The Laser in Medicine

3.1 Introduction

»Magic« is portrayed in most cartoons with a magician brandishing a stick, uttering some mumbo jumbo resulting in a flash of *light*. The flash of light coming out of Harry Potter's wand results in healing or death. We do have some preconception that there is healing power in light. Does it originate from biblical and other religious stories? Or it is triggered by observation of the majestic power of light in lightning, fire, and even the sun?

One can trace back the use of light for healing to 1500 BC, when the Greeks suggested that exposure to light was essential for the restoration of health. Indian medical literature dating to 1500 BC describes a treatment combining herbs with natural sunlight to treat nonpigmented skin areas. Buddhist literature from about 200 AD and tenth century Chinese documents make similar references.

A well documented application of light to healing, which was rewarded with a Nobel prize, is red light therapy applied to the treatment of smallpox and tuberculosis. Niels Ryberg Finsen suffered from an illness now called Pick's disease, which is characterized by progressive thickening of the connective tissue of certain membranes in the liver, the heart, and the spleen. Having a great interest in the healing power of the sun, he conducted studies both in the laboratory and thorough clinical experiments, adopting a procedure very similar to the one used today to find applications of lasers in medicine. The fact that he did not know the details of the light–tissue interaction in the laboratory did not prevent him from using light in clinical applications. He devised the treatment of smallpox in red light (1893) and the treatment of lupus (1895) and was recognized with the Nobel prize in 1903. In beautiful but simple experiments Finsen demonstrated that rays from the sun or from an electric arc may have a stimulating effect

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

on tissues. If the irradiation is too strong, however, it may give rise to tissue damage. It is the same fine line that medical applications of lasers need to walk on.

Light therapy or phototherapy (classically referred to as heliotherapy) is the application of light for various therapies such as skin, sleep disorder and some psychiatric disorders. Other holistic applications of light therapy are more involved in metaphysics and are beyond the scope of this book.

Lasers not only provide various coherent color sources, but also with their unique capability of focusing and high peak pulsed operation, will materialize the use of light as a sharp cutting knife that can be switched on and off with femtosecond speed. In its high power application it can act like a virtual knife (with submicron blade) that does not need sterilization. Beyond simply cutting, some laser radiation can induce *coagulation*, which is a complicated process of forming blood clots, hence reducing bleeding. Laser ablation can be used to remove materials from skin or teeth, or cutting in depth by moving the focal point. Selective absorption is used to blast a kidney stone or for hair removal. Low laser light level dosages are used for wound healing and »cold laser therapy«.

Technological advances in various branches of laser optics have stimulated growth in the medical field. This is the case for imaging and light transfer. New understanding of light, and progress in measuring its phase and frequency, leads to high resolution tomography (optical coherent tomography) applied to biological tissues, fluorescence labeling and cell manipulation (optical tweezers). Surgical laser endoscopy is made possible through light transfer in optical fibers.

3.2 The Laser in Dentistry

Few of us may remember the mechanical dentist's drill, a grinding bit making a chilling noise as it churns it way slowly through the tooth, rotating at a speed of only 3000 rpm. These monstrous drill bits were slowly replaced in the late 1960s and early 1970s, by air turbine driven miniature bits, spinning at rotation speeds of the order of 400 000 rpm. Not everybody, however, enjoys the shrill, high pitch sound of the spinning tungsten carbide bit speeding through the tooth. So why not use an intense continuous or pulsed laser beam to blast away decaying tooth material and make a clean hole, in preparation for the filling material? The prospect of having teeth sculpted in total silence and painlessly is quite appealing.

»Dental lasers« – the type of lasers used in dentistry – can be applied as low level lasers (Section 3.7) for oral surgery (Section 3.6) as well as for periodontal treatment. The laser beam is attractive in dentistry because of its cleanliness: bacteria cannot ride on the laser beam as they can on hand scalers. Compared to ultrasonic devices, the laser beam produces less stress on the patient since it does not induce vibration or high pitch sound. It may reduce bleeding (coagulation effect) and remove the need for local analgesia.

Lasers can be manufactured in various wavelengths, time durations, and energies. There are a large number of »knobs« or parameters that can be used as control of laser–tissue interaction. The opportunities are multiple, provided that the details of the interaction can be better understood. The complexity of the study of the dynamics of a single molecule interacting with a laser will be alluded to in Chapter 6. The road is long for a fundamental scientist to gain a complete, thorough understanding of the phenomena. We have to be thankful to engineers, medical doctors, and dentists for taking a more practical route, exploiting a technology right after its scientific birth.

Some of the lasers that are used in dentistry are: neodymium-doped:yittrium–aluminum–garnet (Nd:YAG) at 1.064 μm and carbon dioxide (CO_2) at 10.6 μm for soft tissue and erbium-doped:yittrium–aluminum–garnet (Er:YAG) at 2.94 μm for hard tissue. The CO_2 laser radiation is highly absorbed at the surface. Diode lasers at shorter wavelengths of 655, 810, and 980 nm are also used for calculus detection and bacterial decontamination. Nd:YAG lasers are used in periodontics for their excellent soft tissue ablation. Applying to the root surface or to the alveolus[18] results in carbonization and thermal damage.

White teeth means good reflective properties for visible light, and very poor penetration and heating. For this reason, a red laser such

18) The part of the jaw from which the teeth arise.

as the Alexandrite (750 nm) is reflected by the tooth, but absorbed by the calculus, which can thus be selectively removed. Dental enamel and dentin are comprised of hydroxylapatite, also called hydroxyapatite (HA),[19] which is strongly absorbed by the 2.94 μm wavelength of the Erbium:YAG (Er:YAG) laser. This wavelength is also strongly absorbed by water, which means that the Erbium:YAG laser is often applied to biological tissues. The Er:YAG laser is a crystal laser, pumped either by flashlamps as was the early ruby laser, or by semiconductor lasers. The possible operations are either »free running« (the simplest – no intracavity element and an emission consisting of random streams of pulses following flashlamp excitation) or Q-switched. The free-running operation generates long (hundreds of microseconds) pulses, the Q-switched operation short (tens of nanoseconds) pulses. Recent research showed better results when Q-switched Er:YAG pulse radiation is used, with a substantial increase in bond strength after filling the cavity. The shorter, more intense pulses can create a smoother smaller cavity, for very precise microsurgery [1].

Lasers can also be used for implant maintenance, for its bacterial decontamination effect that will reduce the peri-implant inflammation of the surrounding soft tissue responsible for the breakdown of the implant. Lasers are used for plaque removal as well. Instead of scraping the tooth surface with metal pieces, low level laser light is used to remove plaque. One may surmise that the heat generated by the laser will slow down the bacteria growth as well.

The purpose of this short overview is not to judge and compare techniques, but to pinpoint the properties of *laser light matter interaction* that are exploited. The take home message for comparing dental lasers with ultrasonic and manual scales is that the energy can be deposited in a very short time, the local heat generated can be high and concentrated, and light matter interaction can select various tissue bonding and materials.

3.3 The Laser and Vision

It is not a surprise that when dealing with laser safety, the first thing that comes to mind is the *eye*. The eye is a very sensitive organ, which

19) A form of calcium apatite with the formula $Ca_5(PO_4)_3(OH)$.

also has a lens that can focus the beam and increase its intensity on a retina by orders of magnitude. Horror stories abound about unfortunate encounters between laser beams and eyes. On the other hand, from the midinfrared to the deep ultraviolet, dozens of lasers have been used in ophthalmology for diagnosis and treatments of the eye. The most popular applications are excimer lasers for *refractive surgery*, femtosecond laser for making corneal flap in refractive surgery, green and yellow lasers for *retinal photo-coagulation* for diabetic treatment, and IR laser iridotomy for *glaucoma treatment*. How can the worst enemy of the eye be its savior at the same time? Let us first review the hazards posed by laser beams, before focusing on their benefits in ophthalmology.

3.3.1 Lasers and Sight Loss

Most laser related accidents have occurred in research laboratories, which is not too surprising, since the construction of a laser involves exposed high voltage lines, unprotected beams, and unknown output power levels. How could the first He-Ne laser be aligned, if there was no alignment He-Ne laser available? It is a sort of chicken and egg story: what appeared first, the chicken or the egg? Autocollimators existed in the early 1960s, which could be used to position a mirror perpendicular to an optical-axis with sufficient accuracy. However, such instruments required an aperture of several centimeters – it was not possible, for instance, to align the large autocollimator beam through the narrow tube (mm diameter) of the He-Ne laser. In the 1960s, a senior researcher had an original solution by using his own eye as autocollimator. He first adjusted the end mirror beyond the laser tube to center the reflection of his pupil. He then put the second mirror in place, looked through the-axis of the tube for an increase in fluorescence as the second mirror came close to parallelism, and jumped skillfully away as the laser beam was produced. He still maintained a 20/20 vision over the several decades that followed: while disturbing, a brief exposure to a He-Ne laser beam of 1 mW is not harmful. This is, of course, not a recommended procedure, alignment lasers and detectors as well as light viewers at various wavelengths are on hand for a laser engineer.

The eye is a sensitive detector of visible radiation (a very sensitive one at night). It saturates easily: it is impossible to estimate the diameter of a visible laser beam impinging on a piece of white paper, even if the laser power is only 1 mW. The reason is that the eye (like any other detector), cannot distinguish any level of intensity beyond a certain value, corresponding to the saturation intensity of the eye at that particular wavelength. Since the intensity distribution of most lasers is bell shaped, the eye will generally see a uniform illumination at its saturation intensity, over a diameter much larger than the real one (defined as the full width at half the peak intensity). The indirect illumination of the impact of a visible laser on paper or on a wall is still of a considerably smaller intensity than if the beam were directed straight into the eye. It is not surprising, therefore, that temporary blinding results from having a direct hit from a laser pointer at night, when the pupil is dilated at its widest opening. It is a very unpleasant experience for pilots in the landing phase, who have been the object of bad jokes from idle kids. There have been various reports of laser pointer misuse around the world, many of them resulting in a big fine and jail sentence for the blameworthy. It was mostly targeted on a pilot eye, police officer, or even in the football stadium by a wild football fan. To handle this problem some governments imposed restrictions on laser pointer import. In only 6 years there were 2800 incidents of laser light directed to aircrafts within the United States. FDA regulation is that pointers are limited to 5 mW output power in the visible wavelength range from 400–710 nm. There are also limits for any invisible wavelengths and for short pulses.

If the laser pointer and He-Ne laser beam of only a few mW power can be a nuisance, the 20 W Argon ion lasers used in open air concerts can be a serious hazard. The »coolest« acoustic effects are to have a rock concert in a deep valley, and for an unforgettable light show scan the surrounding flanks of the valley with green and blue beams of the argon laser. This application of lasers, referred to as *audience scanning* or *crowd scanning* is based on a hope that no one in the audience will be exposed for a long time at a wrong spot, as the special effect is created. The unfortunate resident of the surrounding houses who opens his window to express his displeasure at the noise may lose his sight from the passage of the laser beam. The laser hazard would increase with usage of short pulse lasers, since higher peak power is encapsulated in a pulse.

The high power visible lasers at least come with a warning: their brightness. This is no longer the case for infrared lasers. The wavelength of the titanium sapphire laser, 800 nm, is at the limit of the eye sensitivity. Therefore, the beam appears as a harmless pale red spot on ones shirt, which turns to bright red when the tissue is set ablaze! This type of hazard increases with the wavelength. A number of researchers building the first CO_2 laser as described in Figure 1.9 were taken by surprise by the ease of alignment of the end mirror of this high power/high gain laser, resulting in a burned shirt and belly button, and a bruised ego.

Perhaps the most harmful lasers emit around the wavelength of 1 μm, for which the eye cornea lens and liquid are totally transparent. Strict adherence to safety rules without being cautious has sometimes not been sufficient to prevent serious injury. For example, a researcher of a US national laboratory was wearing prescribed goggles to protect from the radiation of a Nd:YAG laser at 1.06 μm. A stray reflection of the 100 W laser melted the plastic goggle material and burned his retina. An infrared exposure of the eye, although it might be painless and un-noticed, may result in a 100 °C temperature increase and boiling of the retina resulting in a permanent blind spot, while the same exposure with visible light would lead to 10° heating and damage to photoreceptor cells in the retina.

There are various criteria for classifying a laser: output power, wavelength, and peak intensity. It is trivial to relate the risk associated to a laser with its power, just like the way the danger to the electrical power is categorized. Holding the wires coming out of a home battery is safe but holding the wires coming out of an electrical wall plug is not. It might not be so trivial to consider the wavelength and the pulse length. As we saw in Chapter 1, the energy stored in the cavity can leak out continuously or in pulses (sometimes very short pulses). We need to know the material (here tissue) response to the laser light to understand the damage mechanism. There are two types of damage mechanism: *thermal damage* and *photochemical damage*.

Laser radiation can deposit a lot of heat on the material, a deposition of energy that depends on the laser pulse length. The abrupt heat that is impinged at the focus will transfer through the material. Using lasers, material scientists and mechanical engineers are faced with orders of magnitude of time scale of material response that lead to completely different structure (Chapter 4). Short pulses induce fast heating of a tissue, which can be a good thing because it reduces the exposure time. At the same time, one should consider the shock wave created by rapid and local temperature increase.

Another concern is the light wavelength and resonance effects. Any material is made of molecules and structures that have different responses to the wavelengths. For example, microwave wavelength excites the vibration resonance in water molecules and has a different effect on plastic and glass containers. Visible light is absorbed by melanin pigments behind the photoreceptors. Also, the eye is equipped with a »blink reflex« for visible light. At shorter wavelengths of less than 400 nm (violet) into the ultraviolet, the light is absorbed in the lens and cornea, and it takes less power to create a photochemical damage. The hazards associated with short wavelength irradiation of the eye are discussed in Section 3.3.2.1 that follows. Near infrared lasers induce thermal damage on the retina. The frontal part of the eye will absorb longer wavelengths: mid infrared to long infrared (the CO_2 laser for instance).

3.3.2 Lasers to the Rescue of the Eye

The human eye is different from other organs in light scattering. For the vision window of 400–760 nm it is an almost transparent medium without significant scattering. The ocular media display clarity beyond the visual range up to 1400 nm. The response of the cornea and lens are different and depend on the size and consistency of the cells and the spacing between molecules. One advantage of the eye over other organs is its small scattering coefficient. Despite the hazards posed by laser light, one has attempted to find applications of laser light in ophthalmology, just as antipoison can be made out of a poison.

3.3.2.1 Choice of Wavelength

A big concern is, of course, the risk laser radiation poses to the eye. It seems that arbitrary boundaries have been set for the wavelength allowed in ophthalmology. For instance, the FDA has banned the use of lasers at wavelengths between 230 and 350 nm. This wavelength range is considered carcinogenic. Why would such a wavelength range be more harmful than shorter or longer wavelengths? The argument is that at wavelengths shorter than 230 nm, the penetration depth of the light is even small compared with the size of a cell. Before it reaches its nucleus, the cell has been destroyed by the radiation. At 230 nm, the penetration depth being of the order of the cell size, the radiation might perturb the nucleus of the cells and modify their reproductive properties before destroying them. This argument is used in the range of 230–350 nm. At wavelengths longer than 350 nm, the photon energy is considered to be too weak to affect the cell properties.

Lasers with emission wavelengths that are absorbed in the eyes's cornea and lens are generally labeled »eye-safe«. The reason is that because of the absorption no significant radiation can reach the retina. This criterium applies to wavelengths below 350 nm and above 1400 nm. It should not be taken as literally as one company did, which in a Science report (2003) advertised a laser producing »eye-safe pulses of 1 J, 100 fs at 250 nm«. Such a pulse would blast its way through most of the eye structure, and probably what is behind too!

3.3.2.2 Shaping the Cornea

At the two extremes of the spectrum, shorter than 230 nm or longer than 3 μm, laser radiation penetrates less than 1 μm at these wavelengths.[20] The whole radiation energy is absorbed in the corneal tissue. Therefore, a pulse of the proper energy will blast away (»ablate«) a minuscule thickness of the cornea. Since the latter accounts for a big portion of the focusing property of the eye, shaping the cornea can correct astigmatism or imperfection of the imaging properties of the eye. While various lasers are being researched for this type of ablation, including the Er:YAG laser at 2.94 μm [3], the ultraviolet excimer krypton fluoride laser has been mostly used. The procedure is called laser assisted *in situ* keratomileusis. The surgeon uses a mechanical oscillating blade called a microkeratome to cut a flap 100–200 μm thick in the cornea. Thereafter, the inside of the cornea is reshaped with the ablating laser. After the procedure, the cornea with its restored flap heals. In the healing process, stresses may modify the shape of the cornea, resulting in new aberrations.

Always in search of the latest most sophisticated laser application, ophthalmologists are now replacing the cutting blade by tightly focused ultrashort pulses. As will be seen in Section 4.4, interaction with matter of these ultrashort pulses is different to the standard heating, vaporizing, and burning effect seen with longer pulses. It is the high

20) The absorption coefficient of water is 10 000 cm^{-1} at a wavelength of 3 μm [2].

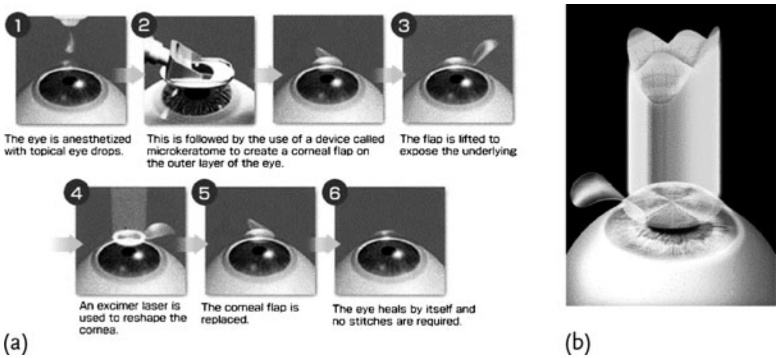


Figure 3.1 (a) The LASIK operation procedure. (b) Wavefront LASIK which not only looks at correcting the focal point on the retina but also follows the whole wavefront of the eye as seen and collected on the retina. Please find a color version of this figure on the color plates.

field of the femtosecond laser pulse that ionizes the molecules, subsequently dissociating, in some cases creating some »bubbles« making it easier to separate the flap cut by the laser.

In a standard LASIK procedure (Figure 3.1), the eye's ability to focus light rays is measured, and a 3D map is created by wavefront technology to map the irregularities in the way that eye processes images (see Section 3.9.3). Information contained in the map guides the laser in customizing the treatment to reshape the eye's corneal surface so that these irregularities can be corrected. Wavefront technology is groundbreaking because it has the potential to improve not only how much one can see, in terms of visual acuity measured by the standard 20/20 eye chart, but also how well one can see, in terms of contrast sensitivity and fine detail.

3.4 Lasers and the Neural Network

Nerve cells form a complex network in the human body. To understand the correlation between electrical function and morphology and to monitor spike activity from ordered networks in culture, there is a need for network simplification through surgical intervention. Microsurgical intervention at the cellular level is a remarkable demonstration of the precision of laser beams [4]. Burn patterns that are much smaller than the focal spot can be created with nitrogen lasers

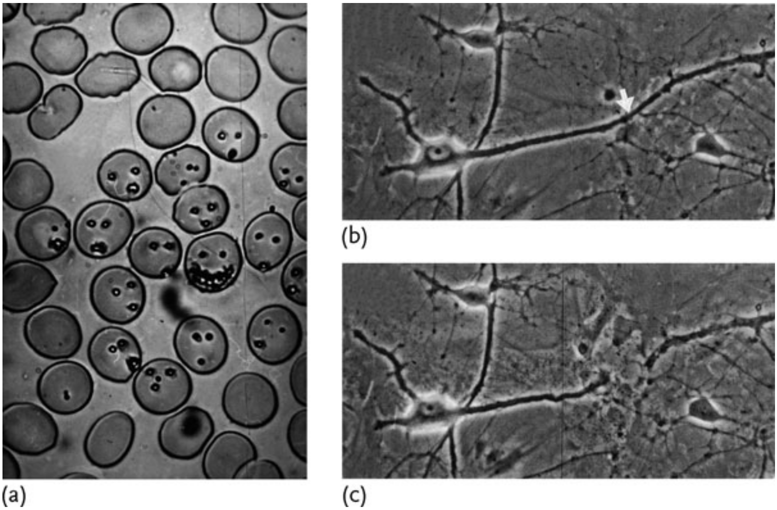


Figure 3.2 (a) Patterns created in white blood cells by focusing under microscope the nanosecond pulses from a nitrogen laser at 357 nm. (b) Irradiation by 120 ns shots of the nitrogen laser at the location of the arrow. (c) 30 s after irradiation transection is observed (courtesy of Guenther Gross, University of North Texas).

at 337 nm. For example, Figure 3.2a shows happy and not-so-happy faces engraved by a low power nitrogen laser on blood white cells. The reason that such small size features can be drawn is that the intensity threshold above which damage occurs is very sharply defined. Therefore, if the pulse energy is accurately controlled, only the top of the intensity distribution of the beam is sufficient to create a mark. Of course, the goal of laser microsurgery is not to force microorganisms to smile at you. The capability of the nitrogen laser to perform precise microsurgical manipulations on neuronal and/or glial cells, and thereby modify/simplify complex networks, is illustrated in Figure 3.2b, c. In Figure 3.2b, the arrow indicates the location where the cell is irradiated with 120 shots of the nitrogen laser, with an energy of approximately 1.5 $\mu J/\mu m^2$, which is far below the threshold for nonlinear processes. Shortly after irradiation, pinching of the cell is observed at that site. Figure 3.2c shows that complete transection has been achieved 30 s after irradiation.

3.5 Lasers for the Skin and Cosmetics

The skin is the largest organ in the human body, measuring 2 m^2 and weighing 5 kg. It is made of two distinct layers, the outer epidermis and inner dermis. Below the dermis lies a subcutaneous layer, composed of proteins and adipose tissue (fat), not part of the skin itself. Figure 3.3 schematically shows the layered structure of the skin. The epidermis is made of four to five layers, together measuring about 100 μm. They are made of *keratinocytes*, cells which produce fibrous protein keratin, and compose 90% of the epidermis. Deeper layers are made of younger cells, which gradually travel outwards, transforming into a hard protective layer along the way. Scattered between the keratinocytes are melanocytes, which are the cells producing the pigment melanin responsible for the skin color, which is important from the point of view of the laser. Groupings of these cells are called melanosomes, whose main function is the protection of keratinocytes from UV light (protection originally intended against sunlight). All people have a roughly equal number of melanocytes, but they produce different amounts of melanin. Its distribution can also vary (e.g., forming freckles, patches, and age spots), hence different skin colors. A much thicker dermis (1 mm), unlike the epidermis, is richly supplied with blood and nerves. Most of the dermis, about 75%, is made of two proteins: collagen and elastin, which provide skin strength and elasticity. There are many structures in the dermis: tiny loops of blood vessels with an important role in regulation of body temperature, glands, receptors for various stimuli, and hair follicles. Hairs protruding from hair follicles are made of keratin, while melanin gives them color. The heavy presence of blood provides yet another important pigment, hemoglobin, which is by contrast extremely scarce in the epidermis.

How will each one of these components react to photon energies of various wavelengths, to pulsed or continuous light? One can separate each structure and study its interaction in an experimental setup; a biological research program in itself (the study of laser–tissue interaction with multiphoton microscopy, Section 1.11). It is, however, difficult in the real world to separate other effects, such as scattering in the tissues and thermal effects. Here again the laser with its multicolor and various energy and pulse characteristics opens challenges and opportunities for light–tissue interaction.

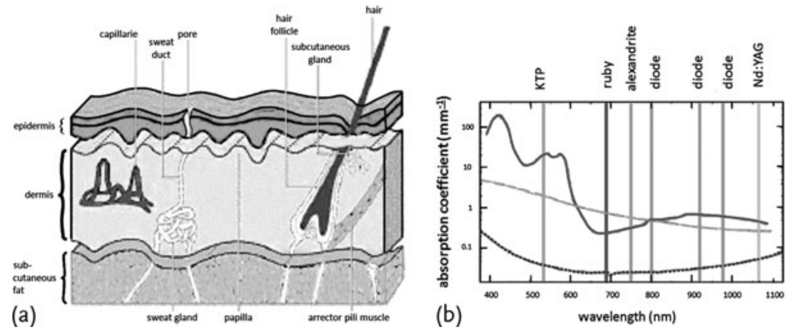


Figure 3.3 (a) The skin has a layered structure of epidermis and dermis with many small structures embedded. (b) Absorption spectra of the skin main absorbers: water (blue), melanin (brown), and hemoglobin (red). Also shown are wavelengths of some important dermatological lasers.Please find a color version of this figure on the color plates.

The absorption of light in biological tissues is mainly through water molecules (in the infrared), proteins (in the UV), and pigments (in the visible region of the spectrum). As light propagates in the medium, photons are absorbed or scattered, leaving less photons for further interaction. This can be expressed as an exponential decay with the *Beer–Lambert law*. The intensity of the light at depth »z« for the wavelength »λ« is $I(z, \lambda) = I_0 e^{-\alpha_{\text{total}}(\lambda) z}$, where α_{total} is the total attenuation coefficient of the tissue, including scattering (α_s) and absorption (α_a): $\alpha_{\text{total}} = \alpha_s + \alpha_a$. Both the scattering and absorption coefficients are wavelength dependent, with the scattering coefficient $\alpha_s \propto 1/(\lambda^4)$ for a given tissue and the absorption coefficient dependent on the particular substance. Water strongly absorbs above 2 μm with the strongest peak at 3 μm. Proteins have a peak absorption in the UV (280 nm), leaving pigments dominating in the visible and NIR (400–2000 nm) regions of the spectrum. Figure 3.3b shows the absorption coefficient for water and for the two main absorber pigments melanin and hemoglobin. Melanin varies among individuals with different skin types. For Caucasians at Nd:YAG wavelength it is approximately $\alpha_a = 0.1\,\text{cm}^{-1}$.

The absorption process could lead to various phenomena based on the energy deposited on the skin and on the pulse length. For energies in the range of 1 J/cm^2 to 100 J/cm^2, a crude classification of events is as follows.

- *Photochemical* for 1000 s pulses.
- *Thermal* for millisecond pulses.
- *Photoablation*[21] for microsecond and shorter pulses.
- *Plasma-induced ablation;*[22] .
- *Photodisruption*[23] for picosecond and femtosecond pulses.

The local temperature increase is a function of the pulse length as well. For the same energy deposited on the skin, as the pulse gets shorter, the local temperature increases. Usually the temperature difference is kept under 100° C. A thermal shock induced by the temperature gradient must also be taken into consideration.

Lasers are used for skin therapy and cosmetics because of their fine focal spot, selective interaction, and because they cause less bleeding and contamination. Excimer lasers, diode lasers, CO_2 lasers, and Nd:YAG lasers with different pulse lengths and wavelengths are used. The argon laser[24] successfully treats *telangiectasias* [5] and venous lakes [6]. Telangiectasias are small dilated blood vessels near the surface of the skin or mucous membranes, measuring between 0.5 and 1 mm in diameter. Venous lakes (Bean–Walsh) of the lips are blood-filled dome-shaped lesions; their treatment often requires surgery. Deep capillary or cavernous hemangiomas and those of the oral cavity may be best managed using the Nd:YAG laser. Tattoos can be removed by the carbon dioxide (CO_2) laser, although some scarring of the overlying skin usually occurs. A list of laser applications for the skin are:

21) When matter is exposed to focused excimer light pulses of less than 230 nm wavelength (for instance the argon fluoride laser at 193 nm), the pulse energy is absorbed in a thin layer of materials, typically less than 0.1 μm thick, due to an extremely large absorption coefficient at that wavelength. The high peak power of an excimer light pulse, when absorbed into this tiny volume, results in strong electronic bond breaking in the material. The resultant molecular fragments expand in a plasma plume that carries any thermal energy away from the work piece. As a result, there is little or no damage to the material surrounding the produced feature.

22) Where local pressure from the generated plasma results in material removal.

23) When exposed to very short and focused laser pulses the interaction region is reduced to less than 1 μm and the energy deposited in the tissue is confined to the focal region. This results in material separation or photodisruption with minimal effect on the surroundings.

24) Most applications that use an argon ion laser at 514 nm are shifting to the more efficient neodymium:vanadate laser frequency doubled to 532 nm.

- *Photodynamic therapy (PDT) using excimer lasers* Photodynamic therapy (PDT) is a treatment that uses a drug, called a photosensitizer or photosensitizing agent, and a particular type of light. When photosensitizers are exposed to a specific wavelength of light, they produce a form of oxygen that kills nearby cells. Each photosensitizer is activated by light of a specific wavelength. This wavelength determines how far the light can travel into the body. Thus, doctors use specific photosensitizers and wavelengths of light to treat different areas of the body with PDT. The major concerns are phototoxicity induced by photosensitizers and their limited penetration.
  The xenon fluoride excimer laser emits wavelengths from the ultraviolet-blue spectrum (308 nm) and selectively targets lesions. Advantages offered by the excimer lasers have been exploited to treat psoriasis, vitiligo, and several other skin diseases. Earlier, high fluences gave excellent results but with a high level of side effects. Lower fluences are now being used to avoid side effects. Numerous studies have confirmed the efficacy of and tolerance to excimer lasers.
- *Actinic keratoses (AK) treatment* Actinic keratosis refers to precancerous, scaly patches on the skin caused by chronic sun exposure. A midinfrared laser (for instance the thulium (Tm) fiber laser with a 1927 nm wavelength) is used to precisely remove the actinic keratoses and the affected skin underneath. Local anesthesia is often used to make the procedure more comfortable. Some pigment loss and scarring may result from laser therapy.
- *Basal cell carcinoma (BCC) treatment* Skin cancer is divided into two major groups: nonmelanoma and melanoma. Basal cell carcinoma is a type of nonmelanoma skin cancer and is the most common form of cancer in the United States. According to the American Cancer Society, 75% of all skin cancers are basal cell carcinomas. Basal cell carcinoma starts in the top layer of the skin called the epidermis. It grows slowly and is painless. A new skin growth that bleeds easily or does not heal well may suggest basal cell carcinoma. The majority of these cancers occur on areas of skin that are regularly exposed to sunlight or other ultraviolet radiation. When treated with an infrared laser, the skin outer layer and variable amounts of deeper skin are removed. Carbon dioxide (CO_2) at 10.6 μm or erbium YAG (1.55 μm) lasers are often used.

Lasers give the doctor good control over the depth of tissue removed and are sometimes used as a secondary therapy when other techniques are unsuccessful.

- *Squamous cell carcinoma (SCC) treatment* Squamous cell carcinoma (SCC) is a form of cancer of the carcinoma type that may occur in many different organs, including the skin, lips, mouth, esophagus, urinary bladder, prostate, lungs, vagina, and cervix. Localized squamous cell carcinoma of the skin is a curable disease. CO_2 lasers are helpful in the management of selected squamous cell carcinoma *in situ*. They are the preferred treatment when a bleeding diathesis is present, since bleeding is unusual when this laser is used.
- *Psoriasis treatment* Psoriasis is a common skin condition where the skin develops areas that become thickly covered with silvery scales. It is a common problem and millions of people in the United States have psoriasis. The course of psoriasis is quite variable, but in most sufferers it is a chronic problem that continues for years. The presence of psoriasis can cause emotional distress. Psoriasis is considered a skin disease, but really it is the result of a disordered immune system. The xenon chloride excimer laser with wavelength of 308 nm (Ultraviolet) targets the psoriasis effectively. The short pulses (nanoseconds) can be focused on areas such as the scalp, knee, and elbow, where removal of psoriasis by other means is more difficult.
- *Vitiligo treatment* Vitiligo is a skin condition where there is loss of pigment (color) from areas of skin, resulting in irregular white patches that feel like normal skin. The laser treatment involves using also a xenon chloride excimer laser, sometimes called an XTRAC system. The light is guided and focused on the area affected by vitiligo with a special fiber optic device. A series of treatments can often lead to dramatic repigmentation of the skin.
- *Acne laser treatment* Laser treatment of acne is now an established therapy. With its direct action on the sebaceous glands, it gives superior results. It has to a great extent overcome the drawbacks of traditional therapies. Many kinds of lasers giving variable results are now in use. The 1450 nm diode laser gives the best results. Optimum results are obtained when laser treatment is combined with other therapies.

- *Laser treatments for other skin lesions* Other skin lesions, such as, warts, nevi, rhinophyma, seborrheic keratoses, and ulcers are some of the vast number of skin lesions where laser treatment is a viable option. In the majority of cases, high-power short-pulsed CO_2 lasers are used. For rhinophyma, the CO_2 laser with anesthesia gives precise tissue removal. For severe rhinophyma, prior excision may be necessary before laser treatment. Epidermal nevi therapy was difficult to treat before the advent of CO_2 lasers. Surgery was difficult due to the size and configuration of the lesions and left ugly scars. The pulsed CO_2 laser gives, arguably, the best results. CO_2 lasers have been very effective in clearing thick and large seborrheic keratoses. although there is some scarring. Scarring is much less with pulsed lasers.

3.5.1 Laser Hair Removal

Hair removal is one of the most popular medical application of lasers. Laser hair removal is based on preferred absorption in the endogenous chromophore melanin, which is mainly found in the hair shaft, compared to other parts in the tissue. For light wavelengths between 700 and 1000 nm the absorption coefficient of melanin is close to two orders of magnitude higher than water and oxyhemoglobin. In this window of wavelength, when the laser is directed at the skin, light is primarily absorbed in the hair shaft melanin. Heat is generated and diffuses to the surrounding follicular epithelium.

The laser discrimination in hair removal treatment borders on racism. It is relatively easy to treat in the winter a hairy Caucasian living in Alaska, if he has black hair. Any visible laser will do: there is considerably more absorption by black hair than by white-bleached skin. The same individual will feel like being interrogated in Guantanamo, if he undergoes the same treatment after spending a summer month on the beaches of Florida: the laser will have a hard time distinguishing between hairs or the dark sun cooked skin. More problematic even is the treatment of a Norwegian blonde sun tanned on the Riviera: a visible laser will selectively burn the skin rather than the fair hair. Ruby lasers (643 nm) were used initially because they were the most »picky« in their choice of skin color. Less color sensitivity is expected at longer wavelengths, where the beam penetrates deeper in the skin. Therefore, the ruby laser has been successively replaced by the Alexandrite (750 nm), diode lasers (810 nm) and the Nd:YAG laser (1064 nm), each advertised as being more »skin color blind«.

The typical pulse width of the laser is 5–100 ms, which is longer than the thermal relaxation time of the epidermis and comparable to that of the follicle. This pulse width range can effectively damage the follicle. However, the epidermis also contains some melanin and must be protected. There is a fine line to be walked in terms of pulse duration. Longer pulse durations allow the skin to heat up more slowly and are safer for darker skin tones. Alternatively, shorter pulse durations can be more effective for treating fine and light colored hair.

The spot size of the laser beam is a few millimeters. The smaller the spot size, the less radiation sent to the skin. When applying the laser for hair removal, the beam is usually not aimed at a particular hair and the laser beam is scanned across the skin. There is an optimum spot size that reaches the threshold for damaging follicles without thermal damage to the skin. Even so, the distance from the lens to the skin is very critical: the laser should be focused on the root of the hair, beyond the surface of the skin, or a certain burn will result. Since hair is a living cell it goes through stages: *anagen* is the active growth phase, *catagen* is the regression phase, and *telogen* is a resting phase. One expects that the best time for hair removal is in the early phases, since the hair is only held in its tube and would fall soon anyway in the last phase. The response of the hair to the laser light varies in different stages. The removal is not permanent. How long the effects of the treatment will last depends on the phase in which it is applied. Complete or partial reduction of hair is a clinical application of pulsed laser beams.

3.6 Lasers in Surgery

One can give the biggest applause to the invention of fiber optics, for making it possible to transfer the light into deep tissues. Without the fiber laser all the medical applications of the laser would have been limited to the surface, although a slight improvement of penetration depth can be achieved through multiphoton interaction (1.11). For example, a fiber optic cable can be inserted through an endoscope (a thin, lighted tube used to look at tissues inside the body) into the lungs or esophagus to treat cancer in these organs.

It seems that »surgery« is getting further away from its original Latin meaning of »hand work«. Surgeons are introducing finer mechanical and optical tools to the surgery, and the laser is indeed one of them. Lasers can be used for ablation of hard material such as teeth and bones. Short pulses are preferred for these type of operations because the peak intensity that can be applied is much higher and induces less damage on surroundings (thermal damage). For example, with 150 fs pulses of 775 nm of 1 kHz repetition rate a very precise cutting of mouse bones has been observed.

Soft tissue removal can be controlled within a precise depth with lasers; this can be used for skin cancer and tumors, and for wound healing caused by surgery or cancer treatment. Lasers can be used for welding veins or in a medical term coagulation. The coagulation (clotting) of tissue uses a coagulation laser that produces light in the visible green wavelength, which is selectively absorbed by hemoglobin, the pigment in red blood cells, in order to seal off bleeding blood vessels. Studies have shown that ulcers can be successfully treated by CO_2 and Nd:YAG lasers. These treatments also improve the healing process.

3.6.1 Blasting Kidney Stones or Laser Lithotripsy

Laser application to the body parallels its application in industry (Section 4.2): it can be used for scratching the skin, welding veins, and blowing up kidney stones. The technique aimed at breaking stones is laser lithotripsy, which is a surgical procedure to remove stones from urinary tracts, such as the kidneys, the ureter, the bladder, or the urethra. A urologist inserts a scope into the urinary tract to locate the stone. A laser fiber is inserted through the working channel of the scope and laser radiation is directly beamed into the stone. The fiber diameter is of the order of few 100 μm. The stone is disintegrated and the remaining pieces are washed out of the urinary tract.

The study of the destruction of urinary calculi *in vitro* started with the early days of the ruby laser (Section 1.4.2). The 694 nm light was focused through quartz rods shaped to allow delivery of the laser energy through an endoscope. The stones vaporized into steam because of the excess heat generated in this process. Staining the stones blue and black enhanced the absorption. Different calculi had different responses: some stones, apatetic and struvite, broke easily and oxalates with more difficulty.

Later it was realized that creating shock waves with laser pulses could be even more efficient than removal of the stone through heat generation. A Q-switched ruby laser with 20 ns pulse duration can generate 20 kbar stress waves. As a result of this study both peak pressure and pulse duration were considered as factors for treating urinary calculi.

A systematic search for the best laser and proper wavelength was initiated to tackle this problem. Continuous wave (CW) carbon dioxide lasers mainly drilled holes in the stones, without inducing shock waves and breaking them. It was hard to pass CO_2 lasers in fibers and the generated heat was too high. Moreover, the aim was not to design patterns on the stones with drilling holes, but to break them. Continuous wave Nd:YAG lasers with a high energy level of (50 J s^{-1}) had only thermal action on the stones and damaged the fibers. The same Nd:YAG laser operating in the pulsed mode (1 J pulses, 15 ns long) in full power had no measurable thermal effect and resulted in fragmentation of stones for 30 min of operation. The problem at the time was the energy transfer through the fiber, which is why the study was pursued with tunable dye lasers.

Tuneable flashlamp pumped dye lasers with a variety of dyes were used to emit light at 445, 504, and 577 nm. Different fiber diameters and pulse width were used to find the optimum parameters for stone fragmentation. One should not be surprised to see the rise of fragmentation threshold with the increase of fiber diameter (less intensity) or increase of pulse duration (less intensity). The 445 nm light had the strongest impact on the stone, but the 504 nm wavelength was selected due to the differential absorption of the stone over the ureter. The 504 nm wavelength is not well absorbed by hemoglobin and, therefore tissue, but is well absorbed by yellow pigment of many calculi.

Why should a short pulse work better? There is an opportunity of plasma formation at the focal spot of the laser: the plasma expands and contracts, hence creates a shock wave. This optico-acoustic effect results in high pressures of 1000 bar. From there it is all mechanical, shock wave forces fracture on the stone through natural fault lines.

The residual fragments may be either retrieved with stone grabbing forceps or may be left to pass.

3.7 Biostimulation Lasers for Ulcer Treatment

Biostimulation lasers, also called low level laser therapy (LLLT), cold lasers, soft lasers, or laser acupuncture devices are used to stimulate healing in the tissues. The laser usually emits in a narrow band in the range of 600–1000 bar. Low density laser irradiation was introduced as a noninvasive, therapeutic modality for acceleration of wounds for the treatment of chronic ulcers due to poor microcirculation. It appears that low intensity laser enhances metabolic pathways by different mechanisms. These include activation of previously partially inactivated enzymes, mainly ATPases, induction of reactive oxygen species, stimulation of Ca^{2+} influx and mitosis rate, augmented formation of messenger RNA, and protein secretion. At the cellular level, enhancement of cell proliferation and mobility of fibroblasts[25] and keratinocytes were frequently noted after laser irradiation and play a major role in wound healing. There is evidence that low level laser application also improves the skin circulation. There are reports on low intensity light radiation for the reduction of dermal necrosis after x-radiation. Low level laser application can also treat ulcers resulting from radiotherapy.

For this low level laser application, a continuous wave 30 mW He-Ne laser was used. Unlike many other applications of lasers that required tight focus and a small spot, the beam was expanded to cover a large area. The intensity of the light was of the order of only a few mW/cm^2, for an extended period to achieve a total dosage of tens of J/cm^2.

3.8 Lasers in Diagnostics

Lasers are used in clinical diagnostics and biological studies. Looking at the shape of the wave in space or the *wavefront* as it propagates and reflects from a surface is one example of diagnostics. The very

25) A fibroblast is a type of cell that synthesizes the extracellular matrix and collagen.

intuitive picture of a wave that is generated by disturbing a quiet pond with throwing a stone is quite familiar. The generated waves start nice and circular, but, as they are diffracted and reflected from leaves and stones on the pond, their shape is deformed. Measuring the change in the wave front gives information about a reflective object with sub-wavelength accuracy. The wavefront across the beam is the spatial *fingerprint* of the light.

Nowadays thousands of dentists are getting help from a device called »Diagnodent«, which shines new light on easy-to-miss cavities. The hand-held instrument uses a red laser to penetrate the outer layer of the teeth. By measuring the way light reflects back, Diagnodent detects signs of decay, in a reassuringly gentle manner.

3.8.1 Detection of a Single Virus in a Nanostructure with Laser Light

As mentioned previously, there is another *fingerprint* aspect of the light: its frequency. A continuous laser will have a well defined single frequency, due to a stiff and high quality laser cavity resonator. A multicolor mode-locked laser (Section 1.7.1 and Chapter 5) will provide a frequency comb with sharp teeth. Light interaction with material can change this frequency, due to excitation and reemission. In most cases, at the end of the photon interaction process, a photon is ejected with less energy and the difference is consumed to induce excitation in vibration, rotation, or electronic excitation.

Raman spectroscopy is a technique that involves the measurement of a change in a single frequency light (near infrared, visible, near ultraviolet) by an amount corresponding to the rotation or vibration of a molecule. An intense laser is sent through the material to be analyzed (the wavelength of that laser does not have to match any requirement other than being able to be transmitted through the medium). A spectrometer is used to detect light reemitted at a wavelength close to the laser wavelength. What is measured is the wavelength shift of the reemitted radiation. Since each molecule has a unique level structure, one can use this change in frequency (energy) to define the unknown molecule. Although the Raman technique involves laser light, the Indian scientist Sir C.V. Raman – who received the Nobel Prize of 1930 and has his name imprinted on this phenomenon – made this observation by using as a source sunlight passing through a narrow band filter.

The process defined above is generally called »spontaneous Raman scattering« and is not a very efficient process. Only one out of a million photons will experience Raman scattering, and also there are many modes in rotation and vibration. For a typical molecule like a protein there are many atoms, and as a result a large number of connections between atoms (bonds) can be excited. The use of lasers in this application chooses to selectively excite a particular bond in a molecule. Both the selectivity and efficiency of Raman scattering are considerably enhanced in impulsive stimulated Raman scattering, made possible by the control of light signals with femtosecond precision. The basic principle is to repeatedly excite the particular bond to be analyzed at its resonance frequency. The analogy is that of a bridge which is stepped upon at exactly a natural frequency of resonance of the mechanical structure. Each step is a light impulse (which has to be much shorter in time than the vibration period of resonance of the bond). The bridge will start oscillating with a large amplitude if the time interval between steps is equal to the period of vibration of a beam of the bridge. With light, the time interval has to be in the hundred femtosecond range, since molecular bonds vibrate in the THz range. Various pulse shapers have been devised, which can, for instance, create a train of regularly spaced femtosecond pulses out of a single pulse. As in spontaneous Raman scattering, a single frequency laser is sent through the material along the same path as the pulse train, and the frequency shift (between the laser frequency and that of the vibration) is measured.

Having tunable laser sources in hand, either the shifted or the incoming beam can be set close to a particular charge transition. For example, in a biomolecule such as hemoglobin by tuning the laser to energy associated to charge-transfer of the iron, the resulting spectrum shows the shift in spectrum only due to stretching and bending of the iron group. This way there is less complexity in the spectrum, but the researcher must have a smart guess and know what he/she is looking for. The technique of selecting a particular bond through resonance is called *resonance Raman spectroscopy*.

From spontaneous to stimulated Raman scattering, one has a huge sensitivity enhancement, but this is not yet sufficient to detect a single virus. Nanotechnology comes to the rescue, to provide a further enhancement in sensitivity by 100 million. It is well known that an electric field can be enhanced at the tip of a sharp needle. This is the reason that all metallic parts of high voltage installation are shaped as much as possible as spheres. The same applies to the electric field of light. At the molecular level, nanowires can act like antennas and enhance the laser field or the detection signal. Silver nanorods with a density of 13 nrad/mm^2 with angle of $72 \pm 4°$ are arranged normal to a silver film. The thin silver film is on a glass slide and the thickness of the nanorods are 10 000 times finer than a human hair. The physics is a little more complex than the static electric field enhancement at the time of a needle, because the light field oscillates at such a high frequency. The field is said to be enhanced by surface *plasmons*, which are optical frequency oscillation of electron gas in a surface. *Surface enhanced Raman scattering* (SERS) has been around since 1974. A proper design in size and spacing and material of the nanostructures enhances the signal, so that even a single virus can be detected. A typical experiment uses a fiber-optic coupled infrared 785 nm diode laser, with power in the range of 10–15 mWm. The virus sample needed for detection is only 0.5–1.0 µl volume.

3.8.2 Optical Tweezers

Have you ever been caught in a crowd trying to scape from a tiny opening? When everyone is pushing hard towards the door and you experience all forces in different directions and cannot predict what will be the result of it all? That is what happens to a tiny particle with incident light. As we saw seen in Chapter 1 (1.1.2) each photon has an energy proportional to its frequency that scales with Planck's constant ($h\nu$). Mechanics is the most intuitive branch of physics, many of its concepts are realized in life with running, collisions, turning, and jumping. If you have the privilege to have a chance of hitting a real ball on the wall, rather than an imaginary one in a computer game, you have had the chance of having a feeling about how energy is converted to momentum. In a collision momentum is transferred based on Newton's law, the total momentum is conserved before and after the accident. In the game of pool the fast running »cue ball« has the energy of $1/2mv^2$, where »m« is the mass and »v« is the velocity of the ball. In the nine-ball game after the first hit of the cue ball, the total system of the nine ball has the same initial energy, and the nine-ball system as a whole still moves in the same direction as of the cue ball with the total energy of $1/2(9m)v'^2$. The value of v' is calculated from the conservation of linear momentum $mv = (9m)v'$, which is a mathematical statement that the momentum of the cue ball before hitting the balls at rest is the same as the momentum of cue ball plus the other eight balls after the collision.

The above example is for objects with mass, but anything that carries energy has also momentum, the photon being one object without mass but with momentum. The pressure exerted by a light beam is called »*radiation pressure*«. Due to the gravity of the earth, a grain of salt with a mass of 5.85×10^{-5} g exerts pressure on a flat surface equal to $6\,\mathrm{kg/ms^2}$ or 6 Pa, which is million times more than the pressure of sun radiation on earth. As discussed in Section 1.8, a tightly focused laser beam can reach intensities of $10^{16}\,\mathrm{W/cm^2}$, which is 1000 times more than the pressure at the deepest part of the ocean. Is this a contradiction? This huge difference is just an illustration of the huge difference in orders of magnitude of intensities that can be achieved with light, concentrating photons in time and space. The laser light can be focused tightly and on the tight focal spots the photons are organized to move parallel to each others, and all the photons can be organized to hit the surface for a very short time. As we had tamed the power of horses, we can take advantage of this force by manipulating the light profile and intensity. Although the radiation pressure was known in the nineteenth century, it only had a noticeable effect in astronomy, where no friction opposes the motion of interstellar dust and light intensities and distances are huge.

With the mass production of laser sources, it is easy to buy a simple kit to manipulate and trap individual cells and particles. The same effect of radiation can be used for optical cooling of atoms as discussed in Section 6.3. As we see in Chapter 6, in a tight laser focal spot molecules tear apart, and high energy electrons can be used for nuclear reaction. Clearly optical parameters such as wavelength, intensity, and intensity gradient have to be tailored to manipulate small particles without inducing optical damage. We can put pressure on a book and by pressing it to the wall, the forces are balanced in such a way that the book stays still on the wall and gravity is compensated. However, if we try to do the same on a ripe berry, and try to hold it on a wall by putting some pressure, the berry might get deformed and just leave a mark on the wall.

With optical trapping we can manipulate particles remotely, without any mechanical tweezers to hold or push things around, using the transverse variation of laser intensity as shown in Figure 3.4. A focused beam of 1 W exerts only a force of 10 μnN on a particle the size of a wavelength. This seems a minuscule force, but if the particle reflects all the light back on itself, for a small mass (for example 10^{-11} g) the acceleration received by the change of light momentum (acceleration) F/m is of the order of $10^5\,g$, where »g« is the acceleration of gravity on earth. This is a huge acceleration that can be tamed for watching the dynamics. One of the important studies that can be done with this controlled dynamics is watching the motion of a single motor molecule such as kinesin. Kinesin is a motor protein that (in most cases) walks towards the »plus« end of a microtubule.[26] The motion of these motors appears to have a role in cell division or *mitosis*. These motors are necessary for separation of chromosomes into the daughter cells during cell division. With optical tweezers the detailed motion of this motor protein with a stepping motion of only 10 nm per step on the submicron tube is resolved.

The control is based on the light pressure or *radiation pressure*. Here we can think of photons as balls on a pool table (although we know that light photons do not carry mass). A cue ball hits the arrangement on the table and balls move in all directions on a pool table. Looking carefully at the ensemble of balls moving in various directions, we realize that the net momentum of the ensemble motion is in the direction of the cue ball. This is the same for a particle sitting on a beam of light that has a higher index of refraction than the surroundings. Photons hit the ball in the entire region of the illumination. As a result there is a net force towards the center of the beam where the intensity is higher. This force is both in the transverse direction and in the direction of propagation. The transverse component is called the *gradient force* and the component along the propagation is the *scattering force* [7]. As shown in Figure 3.4, one can follow the path of the light beam as it goes through a sphere. The bending through the sphere is due to the change of speed of light (change of index) between the sphere and surroundings. The force on the particle is in the direction of change of the beam path.[27] In this figure only the propagation of two beams is shown. The inclusion of all rays results in a net push

26) Microtubules are polymers and one of the active matter components of cytoskeleton.

27) The force in mechanics is $F = \Delta mv$, where mv is the momentum. So that force is in the direction of the difference of the momentum.

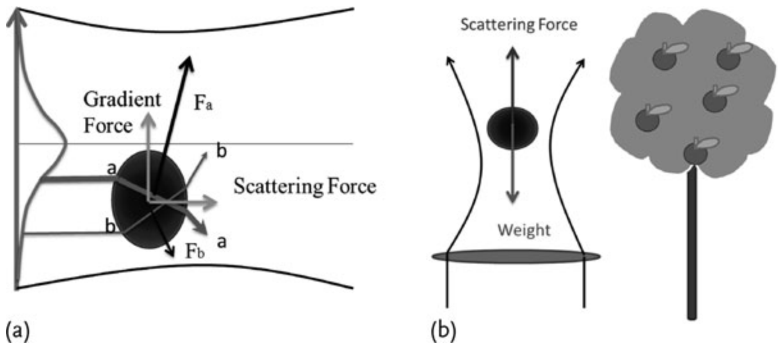


Figure 3.4 (a) The effect of the light pressure on small objects. A incident beam with a spatial intensity gradient creates a nonuniform push to a particle and steers it towards the center (high intensity) part of the beam, in the transverse direction (gradient force). In the longitudinal direction the beam pushes the particle along the propagation axis. This is a scattering force from reflected photons that bounce back from the surface. Transmitted light also transfers some momentum; for a gradient intensity profile, we can follow this force as normal to the beam ray bending in the sphere. The thickness of the line representing each ray is an indication of the intensity of that portion of light. (b) With proper adjustment of the light intensity, radiation pressure can be used to make a levitation trap. If the force due to radiation pressure cancels the weight of the particle, a stable suspension is achieved. Please find a color version of this figure on the color plates.

along the laser propagation axis and towards the center. If the index of refraction of the particle is less than the surroundings, the particle will be pushed away from the center and along the propagation axis.

Instead of a single beam illumination from the left as shown in Figure 3.4a, a second beam can be sent from the right. If the two focal spots (from left and right) are made to overlap, the neutral particle is trapped in the common focus of the two beams. The two identical beams focusing from opposite sides have equal forces that cancel each other. The net force $(F_1 - F_2)$ exerted on the particle is zero but the surface force stretches the particle by $(F_1 + F_2)/2$, and this force can be up to several hundred piconewton [8]. This technique is attractive for stretching single cells or a long molecule and is known as *optical stretching* (OS).

An *optical lattice* is formed with multiple beams to make a sorting sieve based on intensity and phase of the beams. This application of lasers is more used in basic research studies as discussed in Section 6.3.

Radiation has similar effect on smaller particles like atoms and molecules. Here we cannot use the simple picture of bending rays, since we are dealing with absorption and emission in units of photons as seen in Section 1.2. The photon incident on an atom or molecule might be on resonance with one of its intrinsic levels separation. The low intensity absorption or »linear« absorption has a probability related to the ratio of the size of the particle (atom or molecule) to that of the photon. Since the characteristic size of the photon is its wavelength, it should not come as a surprise that the absorption probability varies as the square of the wavelength, it being higher for the lower wavelengths. The collision of light and matter at this microscopic level is not instantaneous and the lifetime of the upper state must be included. The photon ball that hits the atom is going to a gooey-sticky level and will stay on that upper state for a time that is averaged to the »*spontaneous emission lifetime*«, then it is emitted. It is just like hitting the jelly ball with a photon: the momentum transfer and the resulting pressure are different in this case. For an ensemble of atoms the saturation needs to be included. Considering a simple two level structure and a single electron, the electron is either in the lower state or the upper one. In the fully saturated case, the population in the upper state is $f = 1/2$. The scattering force to the atom resonant with the light is $F_{\text{scat}} = hf/\lambda t$, where »$f$« is the population in the upper state and »t« is the spontaneous emission lifetime.

The scattering force is not negligible when dealing with atomic beams. As a result of this force, when incident on a sodium beam at room temperature, at saturation intensity, the atomic beam is diverted to a circle of radius of 40 cm. This force accelerates the atoms moving in the same direction as the light and slows down those moving in opposite direction. It can be exploited to design an *atomic beam velocity selector* or an *isotope selector* [9].

The force on atoms in the transverse direction is more complicated because it depends on the polarizability of the atom, or the strength of slushing the electrons back and forth.[28)]

28) The classical formula for the gradient force on a neutral atom is $1/2\alpha\nabla E^2$, where α is the polarizability. The polarizability changes sign at resonance, just like the gradient force reverse sign when the index of particles relative to their surrounding changes sign.

Carefully matching all these forces one can balance out the gravity and keep the particle suspended with light pressure. Many experiments and devices have been designed by exploiting the radiation pressure. A *Levitation trap* is achieved when the weight of a particle is balanced with the scattering force. Hollow glass spheres that are used as small fusion targets are levitated with laser beams. An *optical tweezers trap* may be realized with a single strongly focused laser beam. Changing the position of the lens moves the focal spot and the trapped particle accordingly. In *high quality optical microresonators* the tuning of the wavelength changes the radiation pressure forces, which in turn influence the resonance of the resonator. A minute change in force or a evolution of the force on a particle can be measured precisely by tuning laser intensity.

3.8.3 Monitoring Blood Velocities

3.8.3.1 The Doppler Effect

The Doppler effect is not unique to light, but is simply a manifestation of how a moving observer perceives a wave – any wave. To illustrate this point, we return to our ducklings paddling in a windy pool. Figure 3.5 is a space (in the direction of propagation of the wave) –time representation of the water wave. The z axis (towards the right) shows the distance (an axis normal to the wave), and the time axis indicates the position of the nonmoving duckling on the far left, at $z = 0$. The »vertical« axis is the position of the up-and-down motion of the object on the wave. The dash-dotted line $t = z/v_w$

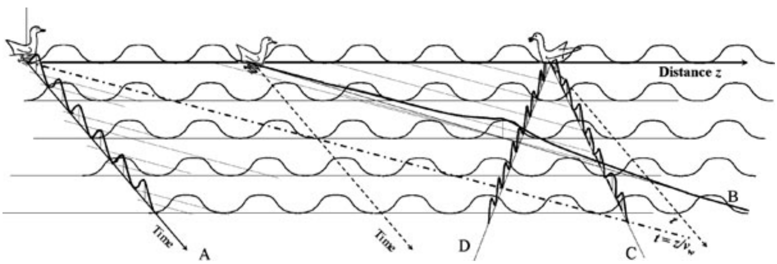


Figure 3.5 Illustration of the Doppler shift. (*A*) No Doppler shift for the duckling that is at rest and goes up and down at the frequency of the wave. (*B*) Red shift (lower frequency) for the duckling moving in the direction of the wave. (*C*) and (*D*) Blue shift (higher frequency) for the duckling moving with a velocity opposite to the wave.

indicates the propagation of the wave (the wave propagation is also indicated by the thin dotted lines parallel to the dash-dotted line). The duckling at rest goes up and down at the true frequency of the wave ν_w (*A*). The center duckling is paddling in the same direction as the wave, at a velocity v_{surfing} nearly »surfing«, and experiences the Doppler down-shifted frequency $\nu_{\text{surfing}} = \nu_w(1 - v_{\text{surfing}}/v_w)$ along the line *B* in Figure 3.5. The third duckling is quacking, flying, and paddling full steam ahead at a velocity $v_{C,D}$ against the wave (lines *C* and *D*). He is clearly bouncing up and down at a much higher frequency $\nu_{C,D} = \nu_w(1 + v_{C,D}/v_w)$.

3.8.3.2 Doppler Anemometry

These expressions for Doppler shift apply also to light. The only difference is that the speed of the wave is the speed of light c, which is considerably higher than the motion of any object in our common world. Therefore, measuring a relative change of the optical frequency of v/c, where v is the velocity of a moving car, animal, particle, gas, to be determined, is a nearly impossible task. However, the frequency of the light, $\nu \approx 10^{14}$ Hz, is also a gigantic number.[29] Therefore, the product $\nu v/c$, which is the Doppler shift, is a frequency easily accessible with standard electronics. To measure directly that frequency, we are blessed by the fact that a light detector measures an *intensity*, rather than an electric field. Therefore, if we mix into a detector the original signal with an electric field oscillating as $\cos(2\pi\nu t)$ at a frequency ν with the Doppler shifted signal $\cos[2\pi(\nu + \nu v/c)t]$ at the frequency $\nu + \nu v/c$, the intensity seen by the electronic detector is proportional to $\{\cos(2\pi\nu t) + \cos[2\pi(\nu + \nu v/c)t]\}^2$, which is a signal oscillating at the difference frequency (the Doppler frequency $\nu v/c$). The mixing is easily realized in the arrangement of Figure 3.6a. The beam from the laser is split into a reference beam and an interrogating one. The reflection of the latter by a moving object is Doppler shifted and mixed on a detector by the reflection of a fixed object. Note that the detector sees a Doppler shift of $2\nu v/c$: the moving object sees the incoming light shifted by $\nu v/c$ and »reemits« the light with another shift of $\nu v/c$. The moving object and the reference are generally not mirrors, but objects that backscatter the light in all directions, with

29) One should probably use an adjective derived from tera (10^{12}), since »gigantic« is derived from »giga« (only 10^9).

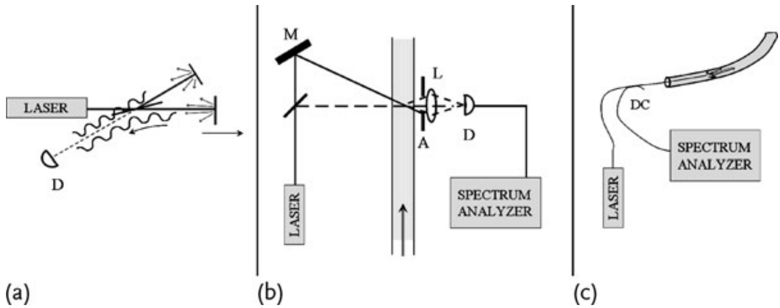


Figure 3.6 Various implementations of laser Doppler anemometry. (a) the beam from a laser is split into a reference arm, directed to a fixed (diffuse) reflector and a probe beam directed to the moving object. The backscattered reference and backscattered Doppler mix in the detector *D*, giving rise to an AC signal at the Doppler shift frequency. (b) A reference (weak) beam and a strong probe cross at an angle in a flowing liquid. The Doppler shifted scattered light mixes with the reference in the detector *D*. *A* is an aperture, *L* a lens. (c) Blood anemometry. The laser is delivered via a fiber in the artery. Part of the backscattered radiation of the moving and fixed particles is recovered by the fiber, sent via the tap DC to the detector *D*.

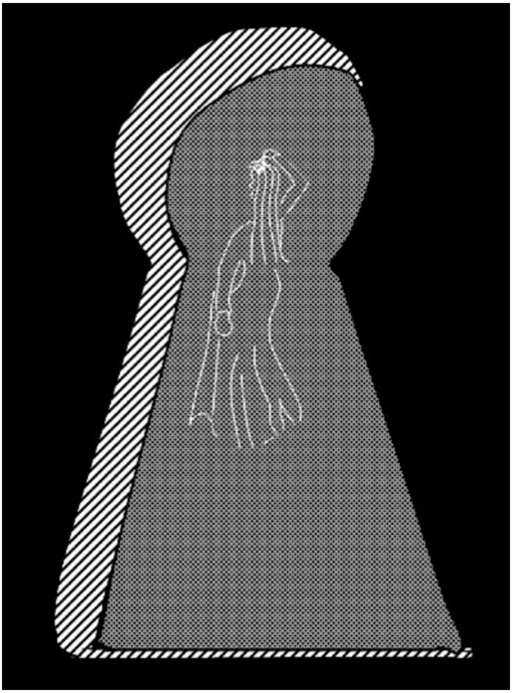
random phase. It is thus a sum of N (where N is a very large number) elementary Doppler contributions of random phase that contributes to the detected signal. We have seen in Section 1.1.3.1 that such a sum is not zero, but an electric field of $\sqrt{N}\times$ the elementary contribution (photons adding incoherently rather than coherently). An interpretation of the signal recorded by the detector – which is equivalent to the Doppler picture – in Figure 3.6a is that the signals from the reference and interrogating arms add successively in and out of phase as the object is moved.

Doppler anemometry is also used to measure flow velocities of gases and liquid. Two different configurations are shown in Figure 3.6b and c. In Figure 3.6b, a very weak reference is set to intersect at an incidence normal to the flow of a liquid, a more intense probe beam. Because the particles in the liquid have a velocity component along the probe beam, the scattered light is Doppler shifted. Components of the scattered light along the weak probe beam create a beat signal on the detector, with a frequency proportional to the flow velocity.

The configuration of Figure 3.6c has been used since the 1970s to monitor the flow of blood [10]. This arrangement is simpler than the previous ones, as there is no »reference arm«. A fiber is introduced into the artery to be tested. The backscattered radiation is collected in the same fiber and »taped« by a coupler DC into the detector. Since both moving particles and the fixed walls of the artery contribute to the backscattering, the detector sees a beat note at the difference frequencies between all particles, at rest and in motion. The interpretation of that broad spectrum is not straightforward. One chooses the highest frequency as representative of the Doppler shift corresponding to the blood velocity. In some cases, a separate fiber is used to collect the backscattered light. The difficulty of the Doppler blood anemometry is the short penetration depth of light. The wavelength range that has the best transmission for biological substances is between 1.1 and 1.25 μm.

Blood anemometry plays a crucial role in the latest method of imaging through optical scanning tomography, as will be described in Section 3.9.2 to follow.

3.9 Ultrafast Peeking



In the previous section we saw what the laser can do to the eye and for the eye. Here, we discover that the laser can be a kind of eye for us, making it possible to achieve three-dimensional pictures with unprecedented resolution. The inspiration behind this technique comes from the radar, applied to ultrashort laser pulse technology.

3.9.1 Time Domain Reflectometry

A striking example of the influence of the radar is in the imaging of the eye. The radar is an important invention of the early 1940s, since it contributed ultimately to the defeat of the German Luftwaffe. As sketched in Figure 3.7a, the principle is simple. A pulse of electromagnetic radiation at a frequency of a few GHz scans the sky. The pulse is short by GHz standards: a few optical cycles will constitute a nanosecond pulse. As it encounters a reflecting object such as an airplane, a weak reflection retraces to path of the interrogating beam.

The time it took for the pulse to propagate from the radar site to the plane and back to the radar site is measured. The resolution is typically a meter (a 3 ns pulse has a spatial extension of $3\,\text{ns} \times c = 1\,\text{m}$). The principle of the »optical radar« is the same, as sketched in Figure 3.7b, but the scale quite different. An ultrashort pulse from a mode-locked laser (see Section 1.7.2) is beamed towards the eye, where it encounters a considerable number of reflecting interfaces. As in the case of the classical radar, it is the time it takes for the light pulse to propagate to an interface and back to the laser (or to a suitable detector) that is measured in order to determine the exact location of the interface. For a pulse duration of 30 fs, the resolution is $30\,\text{fs} \times c = 10\,\mu\text{m}$. The analogy stops here: there is no electronic light detector that can resolve an event in the femtosecond scale. It was soon realized that light pulses themselves would have to be used to provide a temporal resolution of a fs [11, 12]. The laser beam is split in two: one pulse is sent to the target (the eye), the other to a reference mirror. Both reflections (from the eye and from the mirror) are sent to a »black box« that makes the product of the two beams, a product that is only nonzero if the two pulses overlap, that is, if the reference mirror is at the same distance as the interface (Figure 3.7b). The simplest »black box« used first consisted of a »nonlinear crystal«. If two laser pulses of sufficient intensity are sent simultaneously to a crystal, they will create radiation at the optical frequency equal to the sum of the frequencies of the two pulses. In the case of Figure 3.7b, the two pulses have the same optical frequency, and the light that is generated in the crystal is at twice that frequency of the half wavelength (usually UV). Thus, by scanning the position of the reference mirror M, the detector D will record UV radiation each time the position of M corresponds to an interface. There was only one flaw to this scenario: the »nonlinear detection« required light of high intensity at a wavelength (red light at 620 nm in the initial experiments [13]) that penetrates into the eye, which is not a very appealing prospect for the patient.

3.9.2 Optical Coherence Tomography (OCT)

The solution to the high power requirement of the nonlinear detection is to use linear detection, combined with property of laser light to be »coherent« and to make interferences [14]. No »black box« is needed anymore in Figure 3.7b. As the mirror M is scanned back and

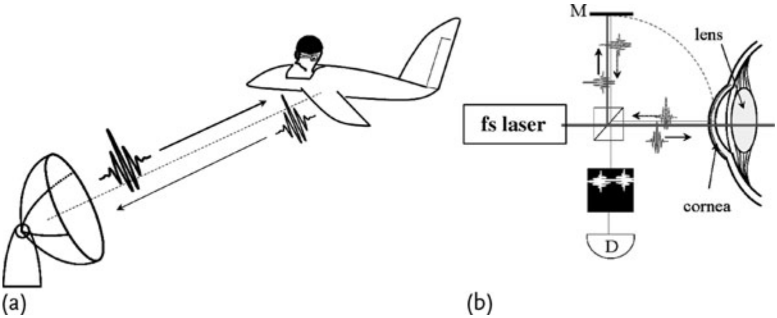


Figure 3.7 (a) The radar emitter sends a few cycles of electromagnetic waves in a nanosecond pulse towards a target in the sky. The distance to the target is determined from the measurement of the time it took the pulse to make the »round trip«. (b) The same technique applied to the measurement of the eye. It is now a fs pulse from a mode-locked laser that is sent to reflect off the various interfaces within the eye. The pulse length (pulse duration $\times c$) is shorter than even the thickness of the epithelium (membrane in front of the cornea). The time of flight measurement is performed as a pure optical coincidence method: the »black box« only detects a signal if the »reference« and »signal« (from the eye) pulses arrive at the same time. Please find a color version of this figure on the color plates.

forth over a few μm, if an interface of the eye is located at the same distance as the average position of the vibrating reference mirror, the beam from the eye and from the reference will interfere successively constructively (maximum signal on *D*) or destructively (minimum signal on *D*), creating an alternating signal on *D*. If there is no reflecting interface in the eye, at the depth corresponding to the average position of the reference mirror, there will be only a constant background detected on *D*. A schematic representation of OCT as it applies to the imaging of the retina is shown in Figure 3.8a. There is no need for the source to be an ultrashort pulse, as long as it is a source with the same »incoherence« as an ultrashort pulse. The light from the source is sent through fibers, via a 50/50 fiber splitter, to a reference and a signal arm. At the end of the signal arm, a collimating lens, followed by an *x*–*y* scanning mechanism, an optical system to bring the scanned beams into focus onto the retina. At the end of the reference arm, a mirror oscillates back and forth, with an amplitude equal to the coherence length of the source. At each half cycle of the mirror motion, the backscattered light from a layer from the eye makes a succession of constructive/destructive interferences with the pulse reflected from the reference arm. The range over which the interference occurs is ap-

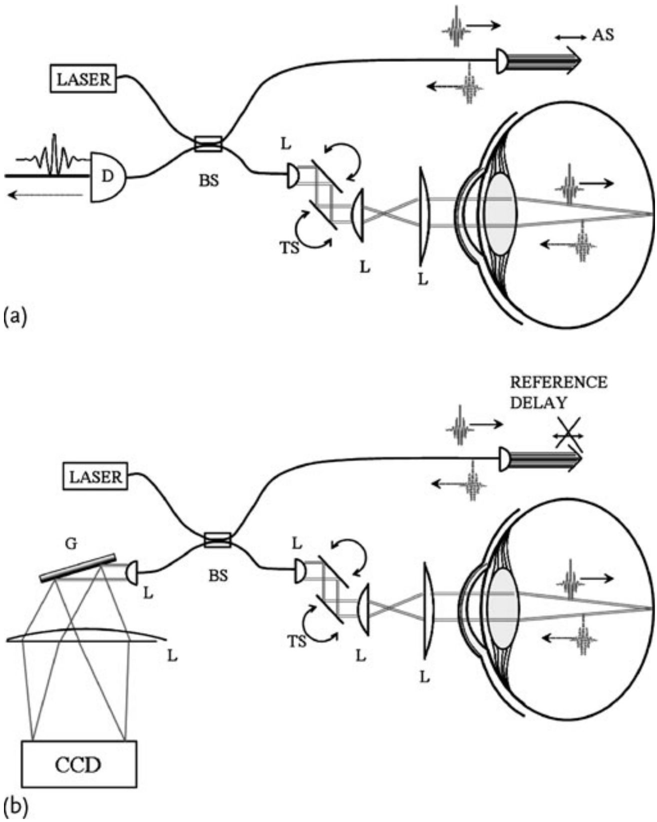
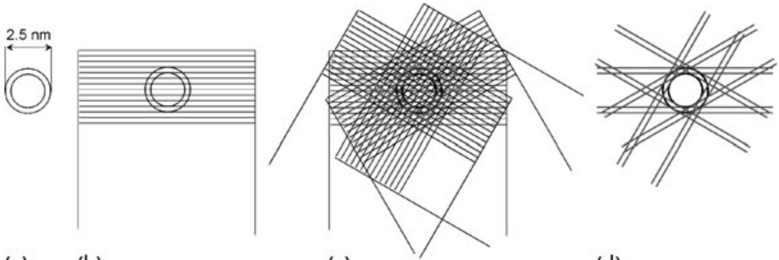


Figure 3.8 (a) Typical set-up for optical coherent tomography. The source is either an ultrashort (femtosecond) pulse laser or a low coherence semiconductor source, coupled to a fiber which is divided into two arms at the beam splitter BS. A scanning retroreflector AS at the end of the reference arm returns a signal back towards the beam splitter BS. The other fiber arm is collimated by the lens L, given a transverse scanning (in *x* and *y*) by the scanner TS, before being sent to the eye by a set of lenses *L*. The backscattered radiation from the eye is mixed with the reference signal in the detector *D*. (b) Since information obtained by scanning is equivalent to a spectrum, the retroreflector of the reference delay can be left fixed, and a single shot spectrum recorded by a CCD is substituted to the scanning information. G is a grating to produce the spectrum. Please find a color version of this figure on the color plates.

proximately the length of the pulse (if ultrashort pulses are used as a source), or equivalently, the coherence length of the radiation (if white light, or a light emitting diode, or a laser diode of low coherence are used as a source).



(a) (b) (c) (d)

Figure 3.9 Successive steps of tomographic reconstruction. (a) The object under investigation. (b) One-dimensional scanning. (c) Scanning from four different directions. (d) The planes that define the object. Please find a color version of this figure on the color plates.

While the resolution of the depth can be of the order of a few μm, the transverse resolution is much coarser. An innovative technique has been found to restore to the transverse direction the exquisite longitudinal (depth) resolution provided by time domain reflectometry. The technique consists of adding angular scanning to the transverse scanning. To realize the power of this method, called tomographic reconstruction, let us consider the problem of visualizing a membrane organized in a sphere of 2.5 nm diameter (Figure 3.9a). A longitudinal scan is performed first, with a transverse resolution of 10 nm and a depth resolution of 0.2 nm. The result is four larger returns corresponding to the four interfaces normal to the beam (Figure 3.9b). Next, a longitudinal scan is performed from another angle. Then another one … The result of four illuminations is shown in Figure 3.9c. After a sufficient number of angles of illumination, the object is defined by an envelope of tangents to the object (Figure 3.9d). Even though the transverse resolution was 10 nm, the final transverse reconstruction after angular scanning is 0.2 nm.

There is more information that can be extracted from the set-up of Figure 3.8a. The scattering from moving blood cells in the retina will be Doppler shifted. This Doppler shift will result in a phase shift of the interference recorded on Detector *D*, which can be determined by recording the signals in phase and in quadrature with the motion of the reference mirror [15].

Speed in data acquisition is essential in capturing images »in vivo«. An interesting improvement on the system of Figure 3.8a is sketched in Figure 3.8b. The scanning of the reference arm is eliminated. Instead, a spectrum is recorded on a CCD of the correlation between the reference and backscattered signals [16]. It can be demonstrated that the spectrum recorded on the CCD contains the same information as the correlation between the reference and signal that was obtained by scanning in Figure 3.8a, but without the need for scanning. The Doppler information itself is also carried by the spectrum. The arrangement of Figure 3.8b enables a larger speed of data acquisition, because the spectrum can be acquired in a single shot, rather than the mechanical reference mirror scanning of Figure 3.8a.

The spatial resolution is limited to a few optical waves, depending on the pulse length or the coherence length of the source. One might wonder whether this is the ultimate resolution possible. As will be presented in Chapter 5, the laser itself has a precision that can beat the wavelength limit. What is contemplated in the section on intracavity phase interferometry, is a futuristic extension of Figure 3.8 where the laser cavity, instead of being the black box at the top left corner of the figures, extends and includes the reference mirror and the object under investigation. As the Doppler effect provides a frequency $\Delta\nu_D$ proportional to a flow velocity v, scaled by the light frequency ν ($\Delta\nu_{\mathrm{D}} = \nu(v/c)$), the intracavity phase interferometry provides a frequency $\Delta\nu_{\mathrm{IPI}}$ proportional to a position or elongation (ΔL), scaled by the light frequency ($\Delta\nu_{\mathrm{IPI}} = \nu(\Delta L/L)$).

3.9.3 Wavefront Sensing

Lasers have helped considerably in quantitatively analyzing the aberration to be corrected. We have seen that the laser light is a coherent wave, characterized by a wavefront which is the surface normal to the rays. The plane wavefront of a collimated laser beam should be transformed into a spherical one by reflection or transmission through a perfect lens. The Shack–Hartman sensor is an instrument that measures the shape of the laser beam wavefront surface and can, therefore, analyze the exact transformation brought by the eye, which is information that can be used to predict the exact ablation to be brought to the cornea. The Hartman–Shack sensor consists of an array of microscopic lenses (typically 200 μm side), focused onto a CCD array. A collimated plane wave creates a two-dimensional dot pattern of equally spaced dots. The departure from that equally spaced pattern can be used to determine the exact shape of the wavefront, as it differs from a perfect plane wave.

References

1 Jelinková, H., Dostálová, T., Nemec, M., Koranda, P., Miyagi, M., Shi, K.I.Y.W., and Matsuura, Y. (2007) Free-running and Q-switched Er:YAG laser dental cavity and composite resin restoration. *Laser Phys. Lett.*, doi:10.1002/lapl.200710062.

2 Boulnois, J.L. (1986) *Lasers Med. Sci.*, **1**, 47–66.

3 Jelinková, H., Pasta, J., Nemec, M., Sulk, J., and Koranda, P. (2008) Near- and midinfrared laser radiation interaction with eye tissue. *Appl. Phys. A*, doi:10.1007/s00339-008-4618-8.

4 Gross, G., Lucas, J.H., and Higgins, M.L. (1983) Laser microbeam surgery: ultrastructural changes associated with neurite transection in culture. *J. Neurosci.*, **3**, 1779–1993.

5 Achauer, B.M. and Kam, V.M.V. (1987) Argon laser treatment of telangiectasia of the face and neck: 5 years' experience. *Lasers Surg. Med.*, **7**, 495–498.

6 Neuman, R.A. and Knobler, R.M. (1990) Venous lakes (Bean–Walsh) of the lips–treatment experience with the argon laser and 18 months follow-up. *Clin. Exp. Dermatol.*, **15**, 115–118.

7 Ashkin, A. (1997) Optical trapping and manipulation of neutral particles using lasers. *Proc. Natl. Acad. Sci. USA*, **94**, 4853–4860.

8 Guck, J., Ananthakrishnan, R., Moon, T.J., Cunningham, C.C., and Kas, J. (2000) Optical deformability of soft biological dielectrics. *Phys. Rev. Lett.*, **84**, 5451–5454.

9 Diels, J.C. (1976) Efficient selective optical excitation for isotope separation using short laser pulses. *Phys. Rev. A*, **13**, 1520–1526.

10 Tenland, T. (1982) *On Laser Doppler flowmetry, methods and microvascular applications*, PhD Thesis, Linköping University, Department of Biomedical Engineering, S-581 85 Linköping.

11 Diels, J.C. and Fontaine, J.J. (1983) Imaging with short optical pulses. *Opt. Laser Engin.*, **4**, 145–162.

12 Diels, J.C., Fontaine, J.J., and Rudolph, W. (1987) Ultrafast diagnostics. *Rev. Phys. Appl.*, **22**, 1605–1611.

13 Diels, J.C., Rudolph, W., and Fontaine, J.J. (1987) Optical radar using femtosecond light pulses, in *Proc. Ernst Abbe Conf. Jena 1987*, EAC, Friedrich Schiller Universität Jena, Jena, Germany, vol. EAC.

14 Huang, D., Duker, J.S., Fujimoto, J.G., Lumbroso, B., Schuman, J.S., and Weinreb, R.N. (2010) *Imaging the Eye from Front to Back with RTVue Fourier-Domain Optical Coherence Tomography*, Slack Inc., Boston.

15 Yazdanfar, S., Rollins, A.M., and Izatt, J.A. (2000) Imaging and velocimetry of the human retinal circulation with color doppler optical coherence tomography. *Opt. Lett.*, **25**, 1448–1450.

16 Leitgeb, R.A., Schmetterer, L., Drexler, W., Fercher, A.F., Zawadzki, R.J., and Bajraszewski, T. (2003) Real-time assessment of retinal blood flow with ultrafast acquisition by color doppler Fourier domain optical coherence tomography. *Opt. Express*, **11**, 3116–3121.

4
Lasers in Industry

4.1 Laser Machining

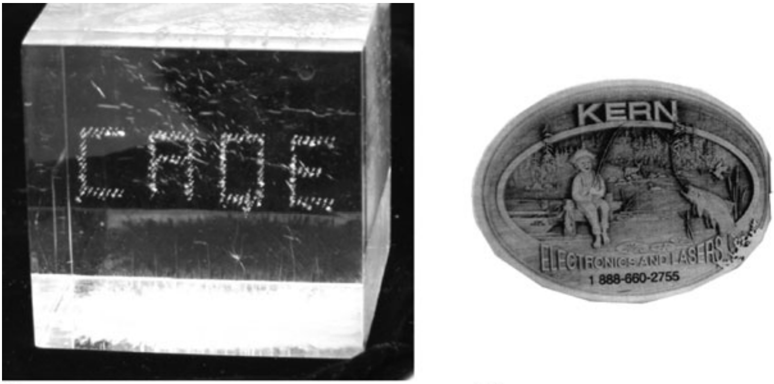
Lasers have come to cover a huge palette of macroscopic and microscopic applications. Under macroscopic, one implies welding, cutting, marking, surface treatment, and so on. Microscopic applications include micromachining, microdrilling, microassembly, and precision marking. The first applications to see the light of day were on sheet metals. Other applications followed, as it became clear that the laser provides a good return despite a relatively large investment.

4.1.1 Marking

The laser offers the cowboy a more sophisticated tool than the red-glowing iron to mark the cows of his herd. Other objects than cows need marking, such as serial numbers on metallic parts or bar codes on any commercial product. Contrary to the glowing iron stamp of the ranch, laser marking is not limited to soft tissue. The laser beam can be used to mark any surface, such as metal, plastic, ceramic, glass or wood, of any surface state. There is also little thermal load on the object to be marked (especially compared to the hot iron stamp). The writing speed can reach several m/s. Using computer controlled deflectors, the marking does not require the fabrication of masks or stamps. It can be done on the surface or inside transparent materials. Figure 4.1a shows the marking of what was the »Center for Applied Quantum Electronics« at the University of Texas, Denton, in 1987. The marking was made with a Q-switched Nd:glass laser focused inside the plastic block.

A particular type of marking is engraving. Surface material is removed with a focused high power laser, such as a CO_2 laser. The advantages of using a laser is the absence of tool bit wear, no »dead

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels



(a) (b)

Figure 4.1 (a) Initials of the Center for Applied Quantum Electronics written with a Nd:glass laser focused in a block of plexiglas (a farewell present to one of the authors in 1986). (b) Wood engraving made by the CO_2 laser.

time« if the tool bit has to be replaced, a better spatial resolution, and the possibility of creating complex patterns, even three-dimensional. Typical commercial instruments use a CO_2 laser of 10–100 W such as presented in Section 1.4.2.1 and achieve a resolution of the order of 10 lines/mm. An example is shown in Figure 4.1b.

4.2 Laser Cutting/Drilling

Lasers have become the preferred tool for sheet metal and foils. A laser vaporizes and melts the foil or sheet without applying any deforming force on it. As the plane to be sliced is moved transverse to the focused beam, the molten or vaporized matter is blown away with a neutral gas. The precision of the cut varies with the mode of irradiation, which is a parameter that can vary in huge proportions. The continuous laser typically provides cuts with a precision of 100 μm. Pulsed lasers can provide a precision of 10 μm. The mechanism by which the material is ablated is thermal, in the range of pulse duration from continuous to picosecond. The mechanism of femtosecond pulse ablation is nonthermal: the atoms are ionized by multiphoton absorption and the strong repulsive forces of positive ions make the molecules fly apart (»Coulomb explosion«). Femtosecond lasers have not taken a sizable portion of the market for industrial applications and will not be discussed more in this context.

For thermal ablation, the laser pulse should be long enough to significantly heat the sample. The coupling of the laser onto the material may be increased at the tail of the pulse, due to the preheating of the pulse leading edge. There are a number of parameters to be considered to optimize the process: pulse length, pulse shape, pulse repetition rate, and velocity of the material. Solid state lasers pumped by semiconductor lasers are widely used. Two oppositing solutions are being implemented to address the problem of heat dissipation faced by high power lasers. High power fiber lasers have a narrow diameter and the heat can be extracted radially. The other extreme is the thin disk laser, where the gain crystal having the shape of a penny, efficient heat removal is achieved over the large area. A pulse duration from 200–1000 ns and a repetition rate from 10–100 kHz provides flexibility to optimize the laser cut. Laser cutting/drilling is particularly attractive for highly brittle materials such as ceramics and semiconductors which are difficult to machine by other techniques.

4.2.1 Laser Welding

As opposed to electrical arc welding, the melting of material required for welding is not limited to conducting metals. Welding of metals use typically pulse durations between 100 μs and 20 ms and welding velocities of the order of m/min. Power densities of up to 1 MW/cm^2 are required for metals and of the order of 10 000 W/cm^2 for plastics. These techniques also allow the bounding of very dissimilar materials (junctions of polymer/metal, elastic plastics with rigid ones, and so on).

4.2.2 Lasers to the Rescue of Cultural Treasures

Lasers are increasingly used to clean buildings and statues and are replacing more destructive techniques such as sand blasting. A particularly challenging cleaning operation has been the cleaning of reliefs of the Acropolis of Athens blackened by pollution. The laser property mainly exploited is the absorption by the pollution of selected wavelengths. The wavelengths selected for this operation were that of the Q-switched Nd:YAG laser at 1064 nm and its third harmonic at 355 nm. Accurate intensity control was required to remove the pollution without damaging the structure. At 1064 nm, the damage threshold for the black crust covering the relief is about 0.8 J/cm^2, while damage to the marble will occur above 3.5 J/cm^2. Irradiation between these two values ensures self-limiting removal of the encrustation without damage to the marble. A 20–30% proportion of third harmonic radiation prevents a discoloration and yellowish tinting of the marble that otherwise occurs when only infrared radiation is used [1].

Lasers have also been applied to the even more delicate task of painting restoration. Here again, it is the wavelength selectivity that is exploited in eliminating degraded contaminated varnish from the surface of painted works of art. That varnish absorbs strongly in the UV (at wavelengths less than 300 nm). At the wavelength of the krypton fluoride laser (248 nm) only a thin superficial layer is absorbed, most of the time leaving a 10 μm thick layer of intact clear varnish to protect the painting, when the removal is made with nanosecond pulses. In the cases where the varnish layer is too thin or absent (wall paintings or Asian art), the nanosecond excimer laser is not the ideal tool for restoration. This is the case where femtosecond laser pulses are considered, because the interaction is through multiphoton excitation rather than thermal excitation. Comparative studies have been made of the etching rate of various varnishes with femtosecond and nanosecond pulses [2]. Femtosecond pulses at 800 nm required high energy densities ($> 2\ J/cm^2$) and produced melting and cracks. Femtosecond pulses at 248 nm had the lowest etching rate per pulse (which is desirable) of 0.5 μm/pulse at 200 mJ/cm^2 irradiation. The femtosecond etching rates increase more smoothly with increased energy density than with nanosecond pulses of the same wavelength, which implies a better resolution and control.

4.3 Cutting the Forest

A saw, a planing tool, a scraper, ... are all wood cutting tools taking away chips of material until the final shape is achieved. They are neither delicate nor discriminating, and one can feel that they must hurt the wood cells as badly as the occasional finger they snap off. These tools leave crushed and broken wood cells. The tree will occasionally get its revenge by putting a hard node in front of the tool, sometimes defeating the tool. One thought early enough to use the CO_2 laser as an alternate cutting tool. The advantages are that no sawdust is created, complicated profiles can easily be cut, no reaction force is exerted on the workpiece, and there is no tool wear. Unfortunately, the CO_2 laser did not bring a great improvement of surface quality. The effect is akin to using a torch to cut wood. The CO_2 laser is a beam of heat and it leaves behind burned surfaces and unpleasant smells. The effect of high power, continuous, shorter wavelength lasers (Nd:YAG laser at 1064 nm or the argon ion laser at 514 nm) is similar: burning is the sensation left on the wood (as well as on the human skin). Is this finally an area where the laser does not find its place? The proverb »where there is a will there is a way« may apply, or more appropriately »where there are $$$ there is a way«! We have already mentioned in the case of eye ablation for LASIK that ultrashort (femtosecond) laser pulses interacted with tissues in a nonthermal manner. The same applies to wood cutting, except that it takes more energy to cut a wooden board than to remove a layer of a few μm depth from a cornea. Tests have been performed with a large femtosecond laser/amplifier system [3] (over several million times more energy per pulse than the laser used in ophthalmology). Figure 4.2a shows the layer of planed maple wood surface after a conventional planing. It is to be noticed that the cells are crushed and broken. This is to be contrasted by the femtosecond laser cut, which leaves a remarkably smooth and clean cut, as shown in Figure 4.2b. The cells are left undamaged and an excellent surface quality can even be seen under 10 000× magnification (Figure 4.2c).

4.4 Nanostructure with Lasers

Some readers might still remember those days of writing and rewriting homework with pencil and eraser. Now with computers on hand it is an easy task to use the »back space« and rewrite again and again without any trace of previous words. It is hard to extend this ability from the virtual world to the real one; how to fix a broken piece (or mend a broken heart?) or undo a scratch is still challenging. Focusing laser light, as we saw in Section 4.1, can create localized damage. In free space the focal spot of the laser is limited by the wavelength, and it can be reduced to $1/n$ of the wavelength in a material with

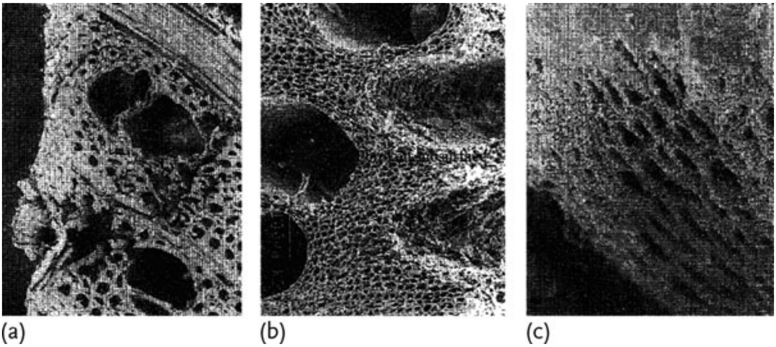


Figure 4.2 (a) Cut through maple wood with standard (planing) tool. (b) Cross-section of oak wood cut by an intense fs laser. (c) Maple wood cut by an intense fs laser, magnified 10 000× (courtesy of See Leang Chin, Laval University, Quebec [3]).

index of refraction »n«. Although wavelength seems to be the limiting factor, structures that are two orders of magnitude smaller than the wavelength are created by focused laser light. One can use laser light to create well defined structures (*waveguides*) on the material. The structure generated on the material enhances the transmission of the light. This can be understood as the material choosing as its war strategy the line of least resistance to the incoming beam.

An example realized with the output of a commercial laser is shown in Figure 4.3. The 50 fs output of a Ti:Sapphire laser at 100 kHz repetition rate is focused on a fused silica substrate with lenses of 0.45 and 0.65 numerical aperture (N_A) [5]. The energy is deposited in a small volume and plasma is generated. For a certain pulse energy between 200 and 1000 nJ, a clean pattern is generated with linearly polarized light. The lines shown in Figure 4.3 are separated by $\lambda/2n$, where »λ« is the wavelength of the light in vacuum and »n« is the index of refraction of fused silica (about 1.45 for 800 nm light). Figure 4.3a, b present different cross-sections of the pattern, taken with an atomic force microscope (AFM). The thickness of each line was carefully measured with a scanning electron microscope (SEM) to be less than 10 nm. The structure can extend tens of microns inside the sample and can be scanned as well across the sample by moving the focused light. The direction of light propagation »k« is set to the »z«-axis of the coordinates, the direction of scan »s« is along the »y«-axis, and the light (linear) polarization direction is along the »x«-axis. The structure goes as deep as tens of microns in the sample. Note that light is

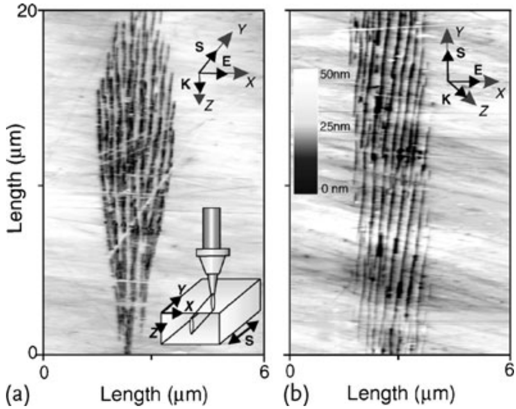


Figure 4.3 Atomic force microscope image of a laser modified region. (a) Cross-section of nanostructure formation in the XZ plane shows the depth of the structure. (b) Cross-section of the structure on the top surface (XY) plane shows the periodicity of the planes formed perpendicular to the light polarization and spaced by $\lambda/(2n)$ (courtesy of Ravi Bhardwaj [5]).

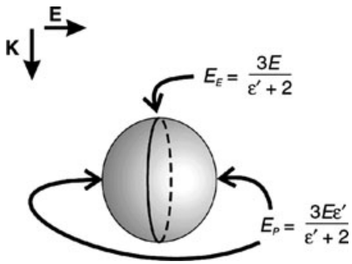


Figure 4.4 Schematic showing the local field enhancement outside a nanoplasma. K denotes the direction of propagation of the laser beam and E the electric field. E_E and E_P are the local fields found at the equator and poles of the sphere, respectively, for an overall field E (courtesy of Ravi Bhardwaj [5]).

absorbed, as the structures are formed due to the nonlinear process (Section 1.11)[30] identified earlier as stimulated Raman scattering [4].

So far it was all about experimental focusing conditions. The exciting part is that, as the linear light polarization is rotated in the XY plane, the structures are modified to have planes perpendicular to the new light polarization axis. It is not an instantaneous effect, taking a few hundred shots for the structure to be rewritten. It is a smart guess to think that no such structure would be formed with circular

30) About 50% of the light is absorbed for 200 nJ input pulse energy.

polarization. This guess is indeed correct, as confirmed in the laboratory.

How and why are these structures formed? The plasma generated by the laser light forms a bobble as shown in Figure 4.4. The field distribution is not uniform around the bobble, because the symmetry is broken with light polarization.[31] The plasma density generated is less that the critical density $\epsilon' < 1$ in Figure 4.4. The field in the equator E_E is larger than the fields at poles E_P. At half the critical power the field at the equator is about twice the field at the poles. This may seem not a large difference, but in a nonlinear multiphoton interaction, it leads to a structure grown perpendicular to the field polarization and along the equator of the initial bobble [5].

References

1 Frantzikinaki, K., Panou, A., Vasiliadis, C., Papakonstantinou, E., Pouli, P., Ditsu, T., Zafiropulos, V., and Fotakis, C. (2007) The cleaning of the Parthenon west frieze: an innovative laser methodology, in *Proc. 10th International Congress on the Deterioration and Conservation of Stone, ICMOS*, Sweden.

2 Pouli, P., Paun, I.A., Bounos, G., Georgiou, S., and Fotyakis, C. (2008) The potential of UV fentosecond laser ablation for varnish removal in the restoration of painted works of art. *Appl. Surf. Sci.*, **254**, 6875–6879.

3 Naderi, N., Lagacé, S., and Chin, S.L. (1999) Preliminary investigations of ultrafast intense laser wood processing. *Forest Prod. J.*, **49**, 72–76.

4 Brueck, S.R.J. and Ehrlich, D.J. (1982) Some applications of picosecond optical range gating: stimulated surface-plasma-wave scattering and growth of a periodic structure in laser-photodeposited metal films. *Phys. Rev. Lett.*, **48**, 1678–1682.

5 Bhardwaj, V.R., Simova, E., Rajeev, P.P., Hnatovsky, C., Taylor, R.S., Rayner, D.M., and Corkum, P.B. (2006) Optically produced arrays of planar nanostructures inside fused silica. *Phys. Rev. Lett.*, **96**, 057404.

6 Jackson, J.D. (1975) *Classical Electrodynamics*, McGraw-Hill, New York.

31) The field distribution is calculated by satisfying the boundary conditions [6].

5
Laser Time Capsule

5.1 Introduction

Perhaps the most spectacular performances of the laser in terms of »precision« are in the time and frequency domain. In Section 1.7 we introduced the basic nature of an ultrashort pulse, methods of pulse compression, as well as ultrashort pulse generation through »mode-locking«. A first part of this chapter contains a brief overview of some applications related to ultrashort pulses themselves. The impact of the laser pulse is here mostly in the *time* domain and is related to ultrafast dynamics of laser–matter interaction. Digital communication is still limited in speed by electronics and the frequency of the waves that carry the information. Purely optical communication with femtosecond pulses has the potential to bring the communication speed from GHz to the tens of THz. There are numerous applications of ultrashort pulses that require particularly high power in order to reach optical electric field strength exceeding the intraatomic fields. These applications will be left for Chapter 6 that follows.

The last part of the present chapter is dedicated to applications intrinsic to the continuous train of pulse generated by a mode-locked laser. The emphasis is then on *frequency*: the spectrum of the continuous train of pulses is a comb of frequency teeth, which is reaching an accuracy and precision unequalled in any other field. The applications range from fundamental physics (are the physical constants of nature really constants, with no drift whatsoever?) to astronomy and to numerous aspects of metrology.

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

5.2 Ultrashort Pulses in Microscopy

Progress in biology, chemistry, and physics have been intimately related to the ability of visualizing ever smaller objects. Microscopy has caused a revolution in many aspects of science, from physics to biology, manufacturing, electronics, and the medical field. The laser and nonlinear optics have brought more than incremental improvements, leading, for instance, to 3D imaging of the eye by *o*ptical *c*oherence *t*omography, as we saw in Section 3.9.2. Microscopy is, as its name indicates, limited to $\approx$ μm, appropriate for bacteria and cells, but not viruses or nanostructures. The wavelength has long been a resolution barrier to optical imaging. New techniques are emerging to image objects with electromagnetic waves, on a different scale. As objects become smaller, the dynamics become faster as well. A technique to improve the resolution in imaging is nonlinear fluorescence microscopy.

The exciting photons produce transitions to a band of excited states in a fluorescing molecule. The excitation decays to the bottom of that band, from where there is a transition to the ground state with emission of the fluorescent photon. In conventional fluorescence spectroscopy, the fluorescence signal is proportional to the irradiating light intensity. As illustrated in Figure 5.1a, the fluorescence will be nearly uniform over the focal volume. In the case of two-photon fluorescence for instance, the excitation is proportional to the square of the exciting radiation, as we saw in Section 1.11.3. Therefore, the excitation (and the resulting fluorescence) is confined to a smaller portion of focal volume. Hence the spatial resolution is increased. Another advantage is the improved penetration depth. In the case of multiphoton excitation, the attenuation of the irradiation beam starts only in the part of the focal volume where there is substantial multiphoton excitation. In the case of single photon fluorescence as in Figure 5.1a, the light is attenuated as soon as it enters the sample. For a large density of fluorescing molecules, the emission at the focal spot can even be less intense than at the entrance of the medium [1].

In a laser scanning microscope, either the laser focus is scanned across the sample, or the sample is scanned while the laser focus is stationary. The reconstruction of high resolution three-dimensional images is possible. Nonlinear microscopy is not limited to n-photon fluorescence. Third harmonic microscopy has also been demonstrated. Here also, an ultrashort pulse is focused by a microscope objec-

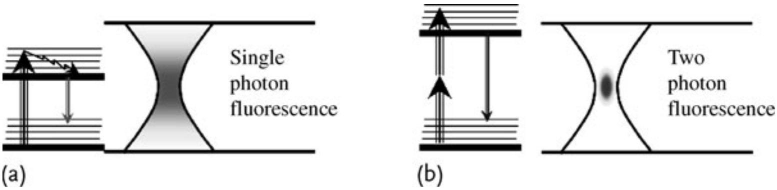
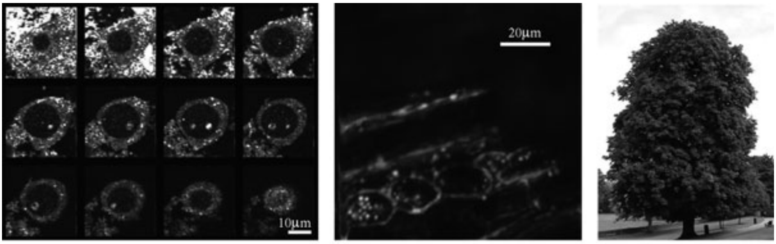


Figure 5.1 (a) Conventional fluorescence (single photon) microscopy. If the fluorescing material is uniformly distributed in the sample, the entire spectral volume will emit fluorescence radiation. (b) In the case of two-photon fluorescence, the fluorescence is confined to the center of the focal volume. Please find a color version of this figure on the color plates.

tive through the sample. Some third harmonic (see Section 1.11.1) of that radiation is generated, collected by another microscope objective and separated with filters from the fundamental radiation. The advantages highlighted in Figure 5.1 still apply. As compared to conventional microscopy that probes the linear absorption or the linear refractive index, the contrast in nonlinear microscopy is based on the nonlinear properties of individual molecules. Harmonic generation is very sensitive to structural changes like symmetry breaks in crystals, local field environments and dopand concentration in solids. Nonlinear microscopy through harmonic generation is a type of »coherent microscopy«; the harmonic that is generated is a coherent pulse, similar to the pulse that was sent to generate the harmonic. As a result, the phase and polarization of the generated signals are prescribed by the same parameters of the exciting radiation, but also by the geometric distribution of radiating molecules, their symmetry, and their physical properties. Incoherent microscopy instead involves the generation of signals with random phases, which are generally emitted randomly in all directions. The various multiphoton absorption techniques are included in this category, where the signal that is produced is incoherent fluorescence.

The resolution of a microscope, in particular an ultrashort optical microscope, can be defined in terms of many different criteria. The effective three-dimensional size of the interaction volume is one of these. This interaction volume is determined by the focusing properties of the microscope (its numerical aperture, N_A), the wavelength of the excitation light, and also the order of the nonlinearity of the interaction.



(a) (b) (c)

Figure 5.2 (a) Third harmonic generated picture of sections of a live neuron (courtesy of http://www.weizmann.ac.il/home/feyaron/index.htm, 2 March 2011). (b) Two-photon fluorescence of horse chestnut bark. From http://www.uni-muenster.de/Physik.AP/Fallnich/Forschen/NichtlineareMikroskopie.html, June 2011. (c) A picture of the horse chestnut. Please find a color version of this figure on the color plates.

Two examples of nonlinear microscopy are reproduced in Figure 5.2. Sections of a live neuron are shown in Figure 5.2a as an example of third harmonic generation microscopy. Two bright nucleuli are visible inside the dark nucleus sections of a live neuron. Two bright nucleuli are visible inside the dark nucleus. The example of two-photon excited fluorescence is that of cut through horse chestnut bark. The latter naturally contains aesculin, which is a fluorescent dye of the coumarin family, which naturally occurs in horse chestnut. The latter typically fluoresces blue light when excited by UV radiation. The image (Figure 5.2b) clearly displays the cell structure and the distribution of aesculin within the cells when exiting the bark cells by two-photon absorption of 100 fs pulses from a Titanium:Sapphire laser at 780 nm.

5.3 Communication

5.3.1 Introduction

A straight line of sight communication is definitely older than the laser. Once upon a time children did not ask for a walkie-talkie for Christmas, but were happy to improvise with an old tin can as a microphone, a tin can as receiver, and a string spanned between the two cans as the communication medium. It is all wave communication: from the spoken words, to the vibration of the air exciting the bottom of the tin can, communicating its vibration to the stretched string. The sound travels as a longitudinal wave to the bottom of the receiver can, which communicates its vibration as a sound wave propagating in air. It did not take long after the discovery of the laser before the string was replaced by an He-Ne laser beam. The electro-optic effect mentioned in Section 1.5.3.3, by which an electric field applied to a crystal changes its index of refraction, is used to replace the tin can. A microphone transforms the sound wave into voltage, which is amplified and applied to the electro-optic crystal. The laser beam sent through the crystal carries a phase modulation proportional to the sound wave. At the reception, the wave can be demodulated, for instance by beating with another oscillator (another laser), in a similar manner to radio wave transmission. Unfortunately, one could only find disadvantages with respect to radio wave communication. Some spy agency, however, found that the laser be could be used as means to eavesdrop remotely on conversations, using the Doppler effect discussed in Section 3.8.3.1. A laser is beamed on the window of an office, which vibrates with the sound waves of the conversations inside. The vibrations Doppler shift the beam, which is backscattered by the window, collected, and mixed with the original beam in a detector just as in Figure 3.6a. The signal from the detector directly carries the sound perceived by the window. Here again, it is not the best or most discrete means of spying. The East Germans had more success listening to the Bundestag conversation from the top of the St. Marien-Krankenhaus in Berlin with microwaves. Does this mean the end of the line for lasers in communication? As we have entered the digital age, the properties of ultrashort laser pulse gives them a clear edge in ultrafast communication.

5.3.2 Soliton Communication

In digital communication, each alphameric character is represented by a string of pulses. We will assume »return to zero« communication, where the signal returns to zero between each pulse. The »soliton«, as discussed in Sections 1.7.3 and 1.7.5.1, maintains its shape over long distances, as an equilibrium is set between a nonlinear index of refraction (intensity dependent) and the dispersion of a fiber. The stability of the soliton makes it attractive for communication over very long distances, for instance across oceans. Here the emphasis is more on reliability, stability, and fidelity of the information, than on speed. Because of the long distances involved, pulses of the order of ps are generally used.

5.3.3 Multiplexing

There is an unavoidable disconnect of three orders of magnitude between the minimum pulse duration that electronic circuits can provide and the shortest optical pulses that can be generated. With 10 fs optical pulses, the »clock rate« of a communication system could be 100 THz! How could this extreme speed be exploited, while the electronically supplied information is only at 10 GHz? The solution is in multiplexing, or putting all signals in parallel. Two approaches are possible: wavelength multiplexing and time multiplexing.

5.3.3.1 Wavelength Multiplexing

In wavelength multiplexing, the electronic signals – represented by a succession of »0« and »1« – that come from difference sources, are each used to modulate a beam at a different wavelength (Figure 5.3). All these different channels are sent simultaneously into a fiber. At the receiver end, the various wavelengths are separated again (»demultiplexing«) and sent to detectors which will restitute the same electronic signal at each of the original channels.

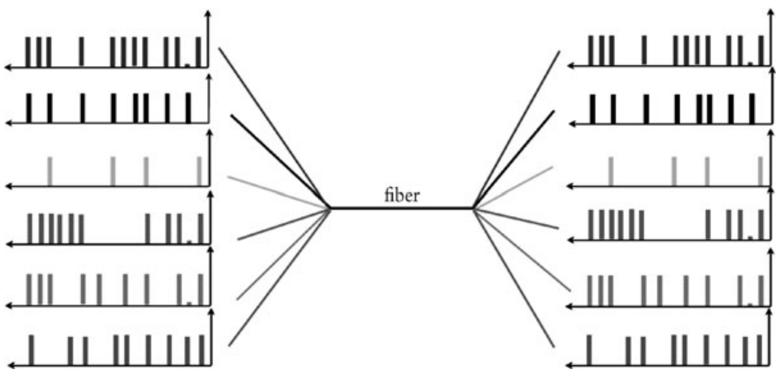


Figure 5.3 The principle of wavelength multiplexing. Several words (pulse strings) from various sources modulate a difference color channel in a fiber. Filters (resonators) are used at the detection to separate the different wavelength, hence restituting the individuality of each channel. Please find a color version of this figure on the color plates.

The number of channels is limited by the number of wavelengths that can be inserted in the bandwidth of the gain medium. For a given bandwidth of the gain medium, the number of channels is equal to that bandwidth divided by the bandwidth required by a single signal pulse. The faster the clock rate (which is the frequency of the signal if every signal was a »1«), the shorter the individual pulse needs to be, the broader its bandwidth, and the lesser the number of channels available. It is clearly impossible to take advantage of the shortest pulse that the broad bandwidth of the gain medium has to offer.

5.3.3.2 Time Multiplexing

To illustrate how time multiplexing can operate, let us consider a clock signal at 12 GHz. At that frequency, a 12 bit word covers a time interval of 1 ns. A typical mode-locked laser will generate pulses shorter than 80 fs. It is thus possible to squeeze a 12 bit word within a time span of 1 ps. The clock rate with fs pulses can be 1000 times faster than with electronics. The 80 fs pulse corresponds to a bandwidth of 6 THz, considerably larger than the bandwidth of any electronic instrument. This very large bandwidth can be exploited if each 12 bit word from up to 1000 independent channels is compressed into a string of 12 fs pulses spanning 1 ps, and if all these compressed channels are put back to back in an optical beam sent from an emitter to a receiver. The string of pulses that is beamed towards a receiver contains in 1 ns the first word of all the 1000 electronic channels, as sketched in Figure 5.4. »Time demultiplexing« at the reception consists in separating each of the successive ps signals and expanding the $<$ 1000 12 bit fs words in similar electronic words at a 12 GHz clock rate, and addressing them to the appropriate channel.

There are interesting methods of optics that make time multiplexing possible [2]. Optical signals behave in time just as optical beams in space. An optical system (in space) with lenses can make a magnified (as in a microscope) or reduced real image of an object. Similarly, an optical system (temporal) can make an expanded time sequence or a compressed time sequence of a time dependent signal. This is called the space time analogy [3]. The broadening of a beam as it propagates through air (diffraction – see Section 1.2.3) is the equivalent of the broadening of a pulse as it propagates through a fiber. The action of a lens is to modify the profile of the wavefront in space. The time equivalent is phase modulation, such as occurs in the Kerr effect (Sec-

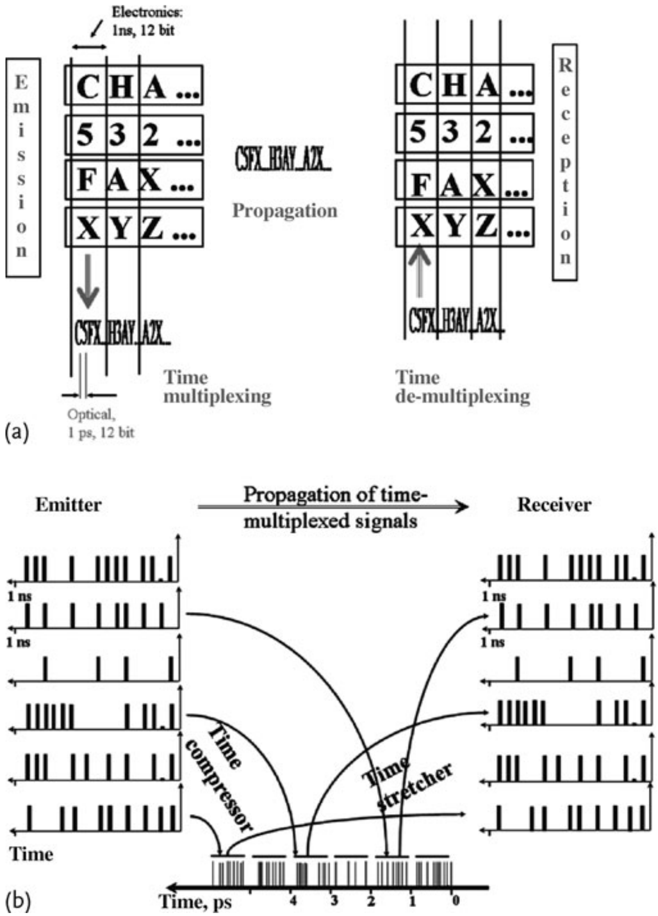


Figure 5.4 Principle of time multiplexing. (a) each 12 bit electronic word from different channel covers approximately 1 ns. Optical methods exist to compress this word 1000 times, so that it covers only 1 ps. Therefore, up to 1000 channels can be put back to back and transmitted. At the reception side, the reverse process has to occur. (b) pulse representation of the same.

tion 1.7.3). There are numerous electronic and optical means to impart a large phase modulation in time (the equivalent of a microscope objective).

The time multiplexing scenario sketched in Figure 5.4 has the space analogy shown in Figure 5.5. A short focal distance lens placed far away from the object will produce a real image, which is reduced in size and inverted. The real image of the successive channels will be

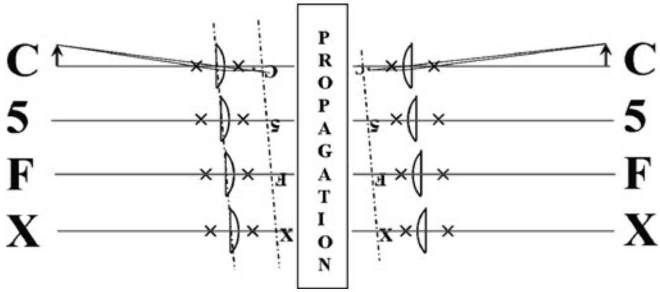


Figure 5.5 Space equivalent of time multiplexing.

displaced respectively to each other if the object–lens distance is incremented a little from one channel to the next. At the reception, the reduced real images are magnified to their original size by a similar lens system, with the focal point of each lens close to the real image to be magnified. In the time picture, the long propagation distances are replaced by temporal dispersion. The hardware producing the largest temporal dispersion is a grating. The temporal equivalent of the lens is a phase modulator.

An alternative method to transform a single fs pulse into a string of 12 bit string of pulses covering 1 ps is the »pulse shaper« of »frequency synthesizer« discussed in the next section.

5.4 Frequency Combs

Any string instrument, violin, guitar, or piano, emits some sort of frequency comb. Playing one of these musical instrument amounts to broadcasting a well defined combination of acoustic frequencies, controlling the relative amplitude – and even to a certain extent the phase – of all these emitters. We have seen in Section 1.9 that the mode-locked laser emits a comb of optical frequencies with rigourously equal spacing. With the mode-locked laser, we have moved from the 20+ strings of the sitar to 10 000 000 sharp frequency (optical) notes. The difference, as the book title indicates, is in the »precision of light«, as well as the very high frequency of optical waves. Would it be possible to »play the piano« with all the keys represented by this vast amount of notes and extract a wonderful melody? Accurate control and measurement of such an extraordinary large raster of frequencies has been achieved, as will be detailed in Section 5.4.3.

Methods of generating extended frequency combs, and how they can be locked to time frequency standards are presented in Section 5.4.1. Applications of such accurate combs are in fundamental physics, astronomy (Section 5.4.2), and metrology (Section 5.4.4).

5.4.1 Creating Extended Frequency Combs

Up to the era of the laser, the meter was defined by a block of quartz in the »bureau des poids et mesures« – the French equivalent of NIST (National Institute of Standards) – kept at standard temperature and pressure. The »meter stick« had a length of 1 m with 1000 graduation marks spaced by 1 mm. With the frequency comb, the »tick marks« are the wavelength. As we saw in Section 1.9, when the carrier to envelope offset (CEO) is set to zero, an integer number of wavelengths (larger than 1 million) defines the »coarse« tick marks (distance between successive pulses).

The meter definition was replaced in favor of a wavelength standard: the meter in the new SI system is defined as 1 650 763.73 wavelengths of the orange-red emission line of the krypton-86 atom in vacuum. An equivalent definition is that the meter is the length of the path traveled by light in vacuum during a time interval of 1/299 792 458 of a second. Other visible emission lines have comparable accuracy and stability, such as a hyperfine component of an iodine transition near 532 nm, or the He-Ne laser new 3.39 μm stabilized by a CH_4 cell, or an Ytterbium ion transition at a frequency of 688 358 979 309 312 Hz $\pm$ 6 Hz.

One method to have an absolute calibrated frequency comb is to lock one tooth of the comb to a calibrated atomic emission line and to lock the repetition rate to a RF standard such as a rubidium or cesium clock, as sketched in Figure 5.6a. The 9 631 770 Hz ground state hyperfine transition in cesium-133 is the internationally recognized definition for the second. The disadvantage of this method is that the error in determining another optical frequency N teeth away is $N\Delta f$, where Δf is the error bar on the radio frequency.

A more accurate method, sketched in Figure 5.6b, is to stabilize two modes of the comb to a pair of atomic emission lines, for instance the cesium D1 line at 335 THz (895 nm) and the fourth harmonic of a

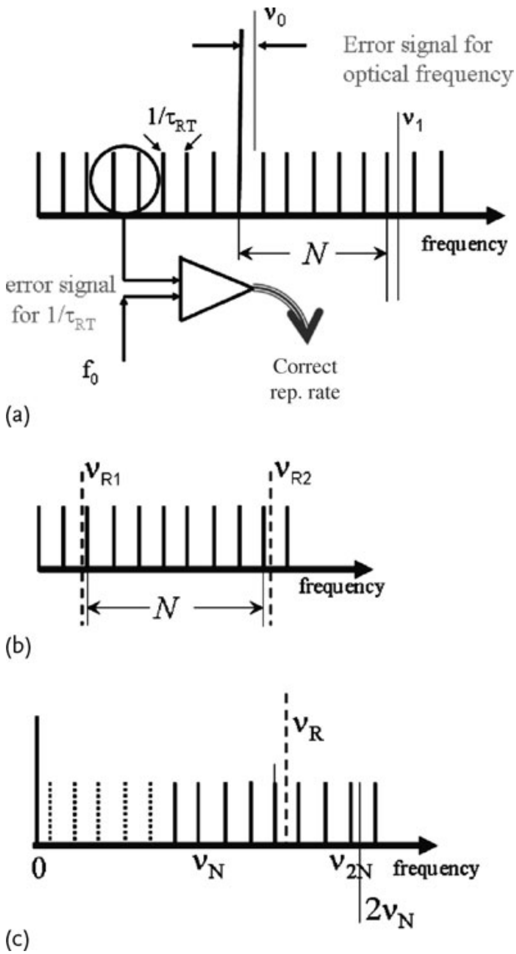


Figure 5.6 Stabilization methods of a frequency comb. (a) Control the repetition rate by locking one tooth of the comb to a calibrated line at ν_1 and the spacing between two modes to a RF atomic clock. (b) Lock two modes of the comb to two reference lines at ν_1 and ν_2. (c) Lock on mode of the comb to an optical reference ν_R and measure/stabilize independently the carrier to envelope offset (»self-referencing technique«).

CH_4-stabilized 3.39 μm He-Ne laser [4]. The disadvantage is complexity, since it requires two optical standards.

A third method (Figure 5.6c) that requires only a single optical standard is to lock a tooth of the comb to an optical standard and measure/stabilize the CEO through a »self-referencing« technique.

That self-referencing technique is sketched in Figure 5.6c. It requires a train so short that the pulse spectrum is broad enough to include one mode ν_N at the low frequency side and a mode of double that frequency ν_{2N} at the high frequency side. However, if the pulse train does not start at zero frequency, but at the CEO f_0, the double of the low frequency mode is $2\nu_N$, which differs from the mode frequency ν_{2N} precisely by the CEO frequency f_0. Having thus determined the CEO frequency f_0, a single optical standard at ν_R suffices to completely and accurately characterize the frequency comb. The difficulty in this last method is that it requires extremely short pulses, of the order of 5 fs. Such pulses have been generated by Ti:sapphire lasers [5]. A method has been devised to extend the frequency combs through nonlinear effects, by simply propagating them through specially manufactured fibers. The rigorous mode spacing of the original comb is preserved if the pulses launched into the fiber have a duration of less than 100 fs. The fiber used include »microstructured fibers« [6], tapered fibers [7] and so-called »highly nonlinear dispersion shifted (HNLF) fibers« [8].

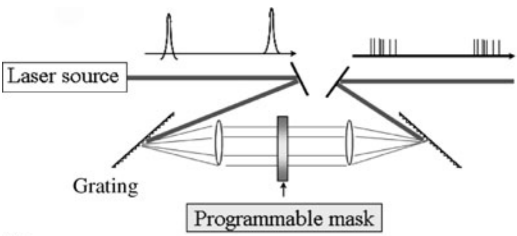
5.4.2 Femtosecond Pulse Trains to Probe Our Universe

The frequency comb truly illustrates the precision of light: with good optical standards, any optical frequency can be measured with this ruler in frequency with an accuracy better than one part in 10^{17}. One might wonder whether there is any use anywhere for such an accuracy? The answer is somewhere in the fundamentals of our understanding of our world and of basic physics. There are a lot of physical parameters in our physics world believed to be immutable, such as the electron charge, the dielectric constant of vacuum, Planck's constant, and the speed of light. But are they? Physics is not about believing or not believing whether these constants are real, but about observing facts. It is not possible to go back in time to measure all these quantities and verify that they had the same value. However, there is a »magic number«, a dimensionless combination of these sacred quantities, that could be probed in the past. This number, the »fine structure constant α«, is the ratio of the square of the electron charge, to the product of Planck's constant h by the speed of light and twice the dielectric constant of vacuum ϵ_0. There are countless physical meanings for α. We will cite only one: the ratio of the energy it takes to force two repulsing electrons to come from infinity to a small distance d of each other, divided by the energy $h\nu = hc/\lambda$ of the photon of wavelength $\lambda = 2\pi d$. The fine structure constant is responsible for the relative frequencies of emission and absorption lines of elements. Given a hypothetical value of α, theorists can calculate emission and absorption spectra. These spectra are compared with the spectra of the light from very distant quasars that has been absorbed by gas clouds. The red Doppler shift of these spectra provides information on how far in the past the matter that is probed is situated (up to 13.8 Gyr, the age of the Universe), and the relative position of the spectral lines provides, compared to the calculation, the value of the fine structure constant at that time [9]. The results indicate a smaller fine structure constant some 10 billion years ago of $0.999\,995\times$ the present value. Other measurements indicate a $4.5 \cdot 10^{-8}$ relative change 2 billion years ago. If there was a constant drift of the fine structure constant, it would be between a 10^{-16} and 10^{-18} fractional change per year. Present stabilized frequency combs are zooming in onto this level of accuracy, and measurements of a drift of the fine structure constant may emerge in the near future.

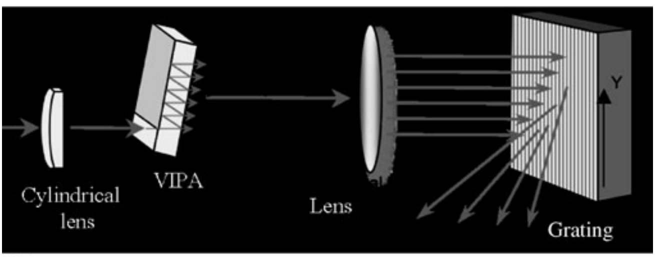
5.4.3 The Giant Keyboard

5.4.3.1 Pulse Shaping

Before discussing the manipulation of the individual tooth of a comb, let us see whether a particular signal in time can be created through manipulation of the spectrum of an ultrashort pulse. Producing a controllable signal in time, by manipulating a set of frequencies, is a technique that has started before the notion of the »frequency comb«. We saw in Figure 1.20 in Section 1.7.1 that any optical pulse is made of a combination of various pure frequencies. The shorter the pulse, the larger the range of optical frequencies that are contained in it. Starting from an ultrashort pulse, one uses any device that decomposes the pulses in its individual frequency components and manipulates each of them, changing its amplitude and/or phase. The controllable signal in time or »synthesized waveform« is obtained by recombining the individual notes, the reverse process that split the pulses in its frequency components. This pulse shaper [10, 11] is as sketched in Figure 5.7. There are two essential elements: one that creates a display of the light frequency (or wavelength) versus space and the other that manipulates the spectral components that have thus been separated. A simple device to display the wavelength is a prism. It is a common occurrence to observe the display of colors when the light from the sun is decomposed by a prism. However, the separation of the difference wavelengths or optical frequencies provided by a prism is not sufficient to clearly separate the different spectral components of a pulse. The next best separator is a grating, essentially a reflecting block of metal in which fine parallel grooves have been traced, separated by a little more than a wavelength. A grating is what was used in the first »pulse shapers« as sketched in Figure 5.7a. The frequency components of successive pulses from the laser are spread in the plane of the figure. A »mask« that provides either difference opacity at different points (amplitude mask) or different index of refraction (phase mask) is used to modify the spectrum of the pulse. The individual components of the spectrum are recombined with a



(a)



(b)

Figure 5.7 (a) A standard pulse shaper. A first grating displays the spectrum of each pulse of a pulse train onto a programmable mask. The mask manipulates the spectral components in amplitude and phase. The transformed spectral components are brought back together by a second grating. Each pulse of the original train has given birth to a sequence of pulses, controlled by the mask. (b) Combination of a VIPA and a grating to isolate every single tooth of a frequency comb (courtesy of Scott Diddams [12]). Please find a color version of this figure on the color plates.

second grating, exactly the reverse process that had spatially separated the frequency components of the original pulse with the first grating. »Programmable masks« can be purchased, which are »liquid crystals« between arrays of electrodes on which voltages are applied to change either the index of refraction or the polarization of the transmitted light. When placed between polarizers, the change in polarization becomes a change in intensity of the transmitted light. With proper programming of the mask, any pulse shape can be generated by this technique, provided that it is longer than the original pulse. For instance, if the mask consists of a series of equally spaced dark lines, the spectrum transmitted will be a series of spikes equally spaced in frequency or a »mini-frequency comb«. We saw in Section 1.9 that a series of equally spaced frequencies (in phase) make up a pulse train, of repetition rate equal to the frequency spacing of the teeth of the comb. As sketched in Figure 5.7a, an appropriately applied pattern of electric signals – for instance the digital word mentioned in Section 5.3, can be imprinted on a time sequence of femtosecond pulses.

5.4.3.2 Comb Manipulation

The grating provides a linear display of the frequencies, which can be played upon like a piano keyboard to create the desired beat in time. However, the grating is not sufficient to separate each of the 1 000 000 teeth of the frequency comb generated by a fs mode-locked laser. One has to make use of a second dimension, as the organ keyboard is made of a series of piano-like keyboards. That type of optical instrument with a huge (in terms of the number of keys) keyboard has been realized, with the combination of a grating and a plane parallel glass plate with appropriate reflection coatings. The device is sketched in Figure 5.7b. The combination of a cylindrical lens and a thin ($\approx$ 100 μm) plate of glass is called a virtually imaged phased array or VIPA [13]. VIPA has the advantage over diffraction gratings that it separates the various wavelengths (or optical frequencies) 10–20 times more effectively than a typical grating. The right-hand side of the glass plate is coated to have a reflectivity of $\approx$ 95%. The left-hand side is totally reflecting, except for a small totally transmitted window in which the beam is launched through a cylindrical lens. As with the grating, different wavelengths are transmitted at different angles and are collimated by a lens onto a grating. The disposition of

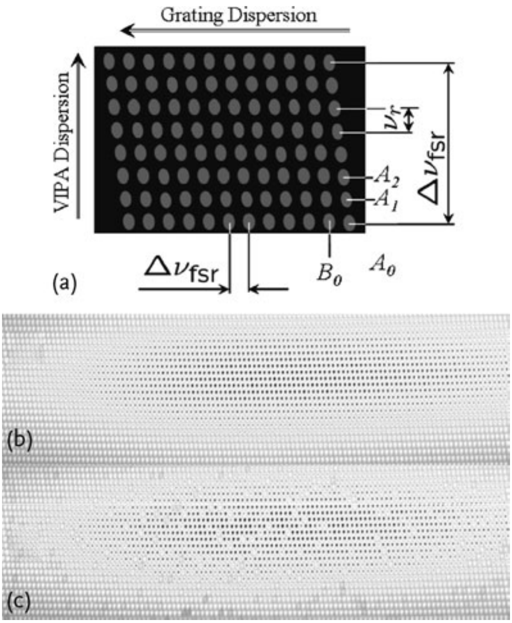


Figure 5.8 VIPA.

the various frequency components of the frequency comb [12, 14] is sketched in Figure 5.8a. Along the vertical axis (y), the successive dots are the impact of the individual modes (separated by ν_r) on the CCD, as they are separated by the VIPA. Like any Fabry–Pérot resonator, VIPA can only provide information over a certain range $\Delta\nu_{fsr} = N\nu_r$. The point A_0 in Figure 5.8a corresponds to a tooth of the comb of frequency ν_0. Successive teeth of the comb will be represented at $A_1, A_2, \ldots, A_{N-1}$. However, the tooth corresponding to the frequencies $\nu_0 + m\Delta\nu_{fsr}$, with $m = 1, 2, \ldots$, would again be at position A_0, in the absence of grating. The deflection of the grating has as effect to shift on the CCD spots corresponding to increasing frequency to the left, so that the frequency $\nu_0 + \Delta\nu_{fsr}$ falls on B_0, distinguishable from A_0.

One application of the VIPA sketched in Figure 5.7b is to provide a »keyboard« of a huge number of »notes«, such that when inserted in the shaper of Figure 5.7a every tooth of the comb can be accessed.

Another application is simple spectroscopy. A portion of the VIPA display of a frequency comb is shown in Figure 5.8b. A cell containing iodine has been inserted in the path of the beam to generate the display of Figure 5.8c. The missing dots indicate absorption at the frequency corresponding to the missing tooth. This is not different from conventional spectroscopy, except for the extreme frequency resolution, since this »spectrometer« is capable of resolving differences in frequency at the electronic level rather than the optical level. This spectroscopy also has extreme accuracy if the frequency comb has been locked to a frequency standard.

5.4.4 Reaching Beyond the Wavelength

The applications presented in this chapter pertained to the utmost accuracy in time that can be achieved with lasers. Being a length standard through the wavelength, one should expect that laser beams can be exploited to measure displacement and lengths. The applications in metrology are so numerous that a separate chapter will be devoted to them.

The near perfection of the laser output itself makes it very sensitive to any perturbation. As an example, if we consider only the propagation of the frequency comb of zero CEO shown in Figure 1.33b, the velocity of pulse envelope will generally be different from that of the carrier. As a result, the CEP will change; a change that can be exploited to monitor the properties of the medium traversed. These properties can be influenced by magnetic and electric fields, the linear motion of the transparent medium traversed, rotation, and so on. Hence, the large number of sensing applications, which, in general, involve the propagation of the laser through some device that will convert the quantity to be measured in a phase or amplitude change of the light (Chapter 8).

Highest sensitivity can be achieved if this change in CEP is exploited inside the laser itself, as will be analyzed in more detail in Section 8.2.2. These sensing applications are *local*, that is, the object to be measured has to be in the proximity of the laser. The possibility offered by high power pulses to project high intensities at distance through filaments, leads to a new type of remote sensing. Propagation of these high power beams is discussed in Section 7.1. The specific application to remote sensing will be the object of Section 7.1.5.

References

1. Zipfel, W.R., Williams, R.M., and Webb, W.W. (2003) Nonlinear magic: multiphoton microscopy in the biosciences. *Nat. Biotechnol.*, **21**, 1369–1377.
2. Diels, J.C. (2005) Method and apparatus for femtosecond communication, United States Provisional Patent Application. Docket Nb.1863.049US1; UNM-676.
3. Kolner, B.H. and Nazarathy, M. (1989) Temporal imaging with a time lens. *Opt. Lett.*, **14**, 630–632.
4. Udem, T., Reichert, J., Holzwarth, R., and Hänsch, T. (1999) Absolute optical frequency measurement of the cesium D_1 line with a mode-locked laser. *Phys. Rev. Lett.*, **82**, 3568–3571.
5. Ell, R., Morgner, U., Kärtner, F.X., Fujimoto, J.G., Ippen, E.P., Scheuer, V., Angelow, G., Tschudi, T., Lederer, M.J., Boiko, A., and Luther-Davis, B. (2001) Generation of 5-fs pulses and octave-spanning spectra directly from a Ti:sapphire laser. *Opt. Lett.*, **26**, 373–375.
6. Ranka, J.K., Windeler, R.S., and Stentz., A.J. (2000) Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm. *Opt. Lett.*, **25**, 25–27.
7. Birks, T.A., Wadsworth, W.J., and Russel, P.S. (2000) Supercontinuum generation in tapered fibers. *Opt. Lett.*, **25**, 1415–1417.
8. Nicholson, J.W., Yan, M.F., Wisk, P., Fleming, J., DiMarcello, F., Monberg, E., Yablon, A., Jorgensen, C., and Veng, T. (2003) All-fiber, octave-spanning supercontinuum. *Opt. Lett.*, **28**, 643–645.
9. Webb, J.K., Murphy, M.T., Flambaum, V.V., Dzuba, V.A., Barrow, J.D., Churchill, C.W., Prochaska, J.X., and Wolfe, A.M. (2001) Further evidence for cosmological evolution of the fine structure constant. *Phys. Rev. Lett.*, **87**, 091301.
10. Weiner, A.M., Heritage, J.P., and Kirschner, E.M. (1988) High resolution femtosecond pulse shaping. *J. Opt. Soc. Am. B*, **5**, 1563–1572.
11. Weiner, A.M. (2000) Femtosecond pulse shaping using spatial light modulators. *Rev. Sci. Instrum.*, **71**, 1929–1960.
12. Diddams, S.A. and Hollberg, L. (2007) Molecular fingerprinting with the resolved modes of a femtosecond laser frequency comb. *Nature*, **445**, 627–630.
13. Shirasaki, M. (1996) Large angular dispersion by a virtually imaged phased array and its application to a wavelength demultiplexer. *Opt. Lett.*, **21**, 366–368.
14. Xiao, S., McKinney, J., and Weiner, A. (2004) Photonic microwave arbitrary waveform generation using a virtually imaged phased-array (VIPA) direct space-to-time pulse shaper. *Photon. Technol. Lett.*, **16**, 1936–1938.

6
Light in Matter

The interaction of light and matter is sensed through seasonal changes, the heating of a pond by sunlight, and the growth of plant leaves. The energy of the photons is transferred to molecules in air and water, and the transfer of energy manifests itself in increase of particles velocity, and therefore heat. The transfer of energy is like adding hot water to cold water: high energy water molecules collide with slower ones (low energy), and after a while an equilibrium is reached. In the case of heating with sunlight, the transfer of energy is through absorption. Since photons have no mass, they do not collide like water molecules. When a molecule absorbs a photon, the excess energy leads to a higher vibration state or an increase in linear velocity. The excess energy is then distributed among other molecules.

The mutual interaction of light and matter goes beyond warming a pond of water. In a low-energy phenomenon such as the *photoelectric effect*, a photon of energy matching the work function of a conductor expels a free electron, that would be measured as a current. Historically, the knowledge of a discrete energy gap helped us to discover that photons individually have discrete energy (Section 1.1.2). A finer interaction, such as *photosynthesis*, has kept biologists, physicists, and chemists busy for a long time. Sunlight is the fuel for the magical green engine that synthesizes simple molecules such as carbon dioxide into more complicated ones like sugar, that store energy.

Can we imitate a plant? Is there a way to monitor and control chemical reactions? Molecules are formed and dissociated. The formation and dissociation of molecules are through chemical bonds, where electrons play a key role. The atomic-molecular and optical (AMO) physics studies matter–matter and light–matter interaction in atoms and molecules, with the aim to extend it to larger biological molecules. Laser light can induce a reaction and also monitor it (i.e., a change in the molecular system such as bond stretching is imprinted on an op-

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

tical pulse). As we have seen in Chapter 5, coherent waves as small as a few cycles have been generated in laser cavities. There is a double advantage of using short pulse lasers: time resolution and high intensity.

As the time resolution reaches the femtosecond scale, we are able to watch and control the electronic motion that takes place within molecules. How do we take a picture of these fast electronic events? What carries the information for these fast motions? The laser pulse that is used as the time stamp perturbs the system in a way that either itself or other photons, or even electrons carry the information in their phase, frequency or, in the case of electrons, in their velocity distribution. In this chapter, we are more focused on the interrogation of electrons and generated photons or the energy deposited by the intense light. In Section 8.2, we look instead at the imprint on the optical pulse itself.

The *coherent* interaction of light with atoms and molecules led us to control and measure of motions in an *attoseconds*[32] time scale. It takes 24 as for electrons in the hydrogen atom to make a full orbit around the nucleus. Interaction of short laser pulses with atoms and molecules leads to another class of photon emission. As a result, attosecond pulses are generated which are not due solely to laser designs such as described in Chapter 1. The coherent ride of the electrons and excitation of atoms and molecules with light must be carefully considered. The coherence of light is transferred to an electron that interacts coherently with matter, thereby generating short light pulses that cannot be created in optical cavities. Here, matter (electrons) acts like a frequency multiplier for the initial photon. This interaction can also be viewed as collision between particles. In a high laser field an electron is carried away from its parent with the laser field. This electron is accelerated with the field and can achieve extreme energies. The collision of those high energy electrons with the atoms serves various fields of study. Attosecond pulses are photons generated as a result of this recombination, while other products are high and low energy electrons. For a heavy nucleus and at higher intensities, laser-induced nuclear reactions might occur.

32) 1 as is 10^{-18} s. In the physics community, when a time less than a femtosecond is resolved, the class of attosecond phenomena has started.

The precise timing of light pulses is exploited to watch chemical reactions and electron dynamics in atoms and molecules. Laser pulses are also used to orient molecules in space. In Section 3.8.2 the photon's force is applied to confine and move particles in defined directions. Laser pulses can slush the electrons inside a molecule. Electrons are not necessarily uniformly distributed and neither is the photon wave (see polarization 1.2.2). The relative orientation of the electron orbital[33] with respect to the light polarization leads to a torque that would align the electron orbital (and as a result the molecules) with respect to the field.

In this chapter (Section 6.2) we see how the coherent interaction of light and matter results in surfing electrons on a light wave. With precise engineering of the wave the accelerated electron can be used for new light generation, particle acceleration, and laser-induced nuclear reaction. Lasers are used in nuclear fusion, since laser pulses can be added coherently to create the intensity needed for initiating a reaction confined in time and space. Laser cooling is an unexpected application of lasers, in contrast to most applications of lasers which are in energy deposition and heating. For laser cooling, with a proper choice of energy level and light frequencies, the emitted photon energy exceeds that of the absorbed photon, hence a net loss of energy for the material, which is then cooled [1].

This chapter discusses using laser properties as completely as possible, simultaneously exploiting the energy, the coherence, and the frequency structure. Although these applications do not have the visibility of the supermarket scanner, they make a tremendous contribution to our control and understanding of the universe.

6.1 Attosecond Science

While most of all the laser properties studied in Chapter 1 revolved around the photons, it was barely mentioned that these photons are generated from electron absorption in gain media. Driving electrons with applied fields had been practiced for a century in electronic cir-

33) An electron orbital is defined as the distribution of electrons (halo of electrons) around the atom nucleus. It is obtained by solving the Schrödinger equation of motion for the probability presence of the electron. The orbitals of atoms are named s, p, d, . . . , and for molecules σ, π, . . .

cuits and machinery. Since laser light is an oscillation of the electric field, the same driving can be performed with laser fields. The optical field is definitely more precise than the voltage difference imposed by a capacitor, since we can engineer pulses in time and space with various frequency components and spatial distribution.

A neutral atom can be decomposed to its loosest electron and the rest (positively charges) of the atom, which includes the nucleus and the remaining electrons. This electron is attached to the remaining atom and molecule, due to Coulomb attraction, and stuck in a potential well. The electron sits in this well like a birdie in its nest. The *ionization potential* of an atom is the energy required to hold the loosest electron to the positive nucleus, or the energy needed to release it. It is the worm's energy that has to be fed to the little bird to give it the strength to escape from the nest. It is higher for the ionized atom, because the charged particle holds the remaining electrons more tightly. In the presence of a high electric field (such as caused by an intense laser pulse), the potential well is distorted. It is similar to the nest being tilted by a high wind. Fortunately, the classical birdie will not fall out of the nest, being kept still by the rim of the nest. In quantum mechanics however, there is a chance for the little bird to fall out of the tree by passing through the barrier of the nest – this is called tunneling. For the electron, there is also a chance (*probability*) for an electron to pass through the barrier of the deformed well through a *tunneling* process. This probability increases with the laser field. As we will see in Section 8.1.1.5, light itself can also »tunnel« through a barrier.

6.1.1 The Three Step Model

The linearly polarized laser field displaces the electron and takes it to a journey on its shoulder, speeds it up, and like a slingshot (see Figure 6.1a) throws the electron back. It is amazing that a simple intuitive picture for this event [2, 3] named the *three step model* can explain the basics of this phenomena. In this model, a complicated atom or molecule is simplified to an electron and the nucleus. At rest, the electron oscillates around the nucleus and, in the view of the outside word, is stuck deep down a potential well (see Figure 6.1b). The laser electric field distorts this potential by its force »$-e.E$« and adds the term »$-e.E.r$« to the total energy of the system. The position »r«

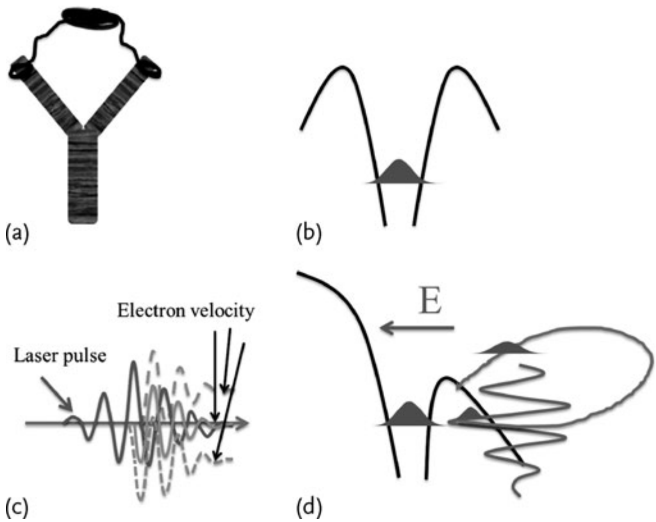


Figure 6.1 (a) A laser pulse takes the electron and accelerates it just like a slingshot taking a stone. For the light photon of 800 nm, the electron wavelength after this acceleration is only between 10 to 0.3 Å. (b) The electron in an atom or molecule is held in a potential well by Coulomb attraction to the positive nucleus. Although in quantum mechanics, contrary to classical physics, a particle has a chance to pass a barrier beyond its energy, the probability of this event is negligible when the particle is at rest. (c) With the high electric field of the laser the atom is ionized and the electron oscillates with the laser field. The three curves on the right side represent three different moments of ionization, which will lead to different acceleration and ultimate speed of electron. The trajectory of the electrons with applied laser field is calculated by classical physics. (d) The ejected electron travels with the laser field and may return and recombine with its parent ion. Please find a color version of this figure on the color plates.

is the distance of the electron distribution from the center of nucleus. The light electric field opposes – hence reduces – the attractive force between electron and the remaining atom. In other words, the Coulomb potential is distorted (see Figure 6.1d) and an electron has a high chance of leaving the atom and tunneling through (*step 1*).

The electron now is called a free electron. As it moves away from the center, the attractive force between electron and remaining atom, inversely proportional to the square of the distance (i.e., $\propto 1/r^2$) is reduced, but the electron is not completely »free«: it is forced to follow the laser field. Since a wave changes sign after half a light period, for a linearly polarized light, the same field that pulled the electron away is going to push it back. The electron's journey with the light pulse is *step 2* of the process.

For the returning electron *step 3* or recombination takes place. Note that just as with a slingshot with a stone, the electron can acquire a lot of energy, ranging from 1 to 10^3 eV in a noble gas atom with an IR laser field. This high energy electron generates a high energy photon or creates electron–electron collision.

This model is simple enough to be understood by anyone with some basic knowledge of field, charge, and classical motion of particles. However, deep down, the simple picture shelters many interesting details about light–matter interaction. In step 1 the process of ionization can be *multiphoton*, *tunneling*, or *above barrier*. Here again a theory that was not initially made to apply to a laser field, and was supposed to explain the ionization through a strong continuous (DC) field [4], is stretched to predict the probability and mechanism of the ionization phenomena with alternating high laser fields at frequencies of 10^{14} Hz.

6.1.1.1 Step 1: Ionization or Tunneling

There are two distinct mechanisms by which the electron can escape the atom or molecule. By absorbing several high energy photons, the electron can pop out of its well like the chick can escape from the nest after swallowing a few high energy pills. This mechanism relates more to the particle nature of light. At the other extreme, when the period of the light is long (low photon energy), the potential is slowly distorted to let the electron escape by tunnel effect, as the slow, persistent wind tilts the nest to reduce the barrier holding back the bird. Tunneling dominates over photoionization (multiphoton) when the light electric field »E« is large relative to the depth of the well of the ionization potential »I_p«, and applied for a long time (large light period $T = 1/\nu$). It is therefore not surprising that a »Keldysh parameter« [4], proportional to $\nu\sqrt{I_p}/E$, has been defined to mark the vague transition between tunneling and multiphoton ionization. Values of less than 1 for this parameter correspond to large fields and low frequencies of light, with respect to the depth of the well. Considering the tunnel image in space (Figure 6.1b) low values of the Keldysh parameter correspond to slow and deep distortion of the well, so that the electron can tunnel out, and the ionization is called »*tunnel ionization*«. If the electric field of the light changes rapidly (high

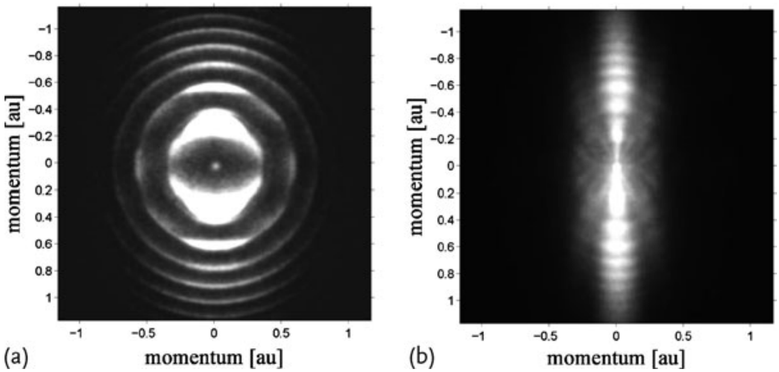


Figure 6.2 A means to monitor the ionization in high field is by measurement of the ejected electron momentum in three dimensions. The electron momentum is represented in atomic units where 1 corresponds to the velocity of the electron in a hydrogen atom. The *x*-axis corresponds to the direction of propagation and the *y*-axis to the light polarization. The 3D image is projected in two dimensions in the measuring apparatus of velocity map imaging. (a) Multiphoton image of the electrons from argon with 400 nms linearly polarized laser light. (b) Tunnel ionization image of the electrons produced in argon with 800 nm linearly polarized laser light.

optical frequency), the electron bounces back and forth in the well as if it is ionizing in a vertical channel. The angular distributions of the ejected electrons are different, as seen by direct electron momentum imaging from argon with 400 and 800 nm lasers of linear polarization (Figure 6.2), showing a clear transition between multiphoton and tunneling. The rings seen on the picture are »above threshold ionization« (ATI) [5] rings. These are due to the electrons that are above the barrier but still close to the ion and can absorb more photons that are needed to overcome the barrier. Photons have well defined energy and, since there is no way to absorb half a photon, these rings are well separated by the light photon energy. The separation of the rings is related to the photon energy of light, which is nature's way to provide a calibration for the image.

6.1.1.2 Step 2: The Path of the Ejected Electron

The ejected electron follows the laser field by the classical force »$-e.E$«, just as the stone travels with the elastic on the slingshot. The laser light changes its sign at each half period, implying that the electron that was carried away is forced to come back. During the travel time, the electron is accelerated and ends up with a final velocity that is a function of the moment of ionization (Figure 6.1c). The path and final velocity of the electron are strongly dependent on the moment of ionization. Because the amplitude of a linearly polarized electric field oscillates, the probability of ionization is not the same at all times. In most cases, the ionization occurs at the peak field. The electron that ejects before the peak value has no chance to return back: by the time the field changes sign the electron is already too far from the ion. Electrons ejected at and after the peak each have a different path. The ones leaving closest to the peak have a larger travel path than those ejected closer to the sign reversal point of the field *short and long trajectory*. For a near-infrared laser at field strength of 10^9 V/cm, the total excursion of the electron reaches several tens of angstroms, which is beyond the size of the molecule. Under the influence of the alternating field $E\cos(2\pi\nu t)$ of linearly polarized light, an electron undergoes a periodic motion, with its velocity changing at each period $1/\nu$. To this periodically changing velocity or »quiver motion« is associated the kinetic energy $U_p = (e^2 E^2)/[4m * (2\pi\nu)^2]$. This energy is known as *pondermotive potential*. For a single carrier frequency laser, the maximum energy that the electron can acquire is $3.2\,U_p$.[34)]

6.1.1.3 Step 3: Recollision

The last step is *recollision* for the electrons who can make it back to the ion.[35)] The returned electron can have a range of energies and different accumulated propagation phases (because of different travel paths). The result of the collision also varies. (i) Elastic backscattering of the electron results in emission of highly energetic electrons. (ii) An electron may recombine with the ground state and emit a high energy photon. The photon generation is known as »high harmonic generation« (HHG). The highest energy photon has the maximum $3.2\,U_p$ pondermotive energy, plus the energy of the ionization potential I_p. (iii) It may knock off another electron from inner shell and cause a double ionization (»*nonsequential double ionization*«). (iv) Inelastic collision and transfer of energy to bound electrons.

34) This is enhanced by using a chirped pulse laser.

35) That is for linear or slightly elliptical polarization, since in circularly polarized light the field changes its oscillation direction continuously so that the ejected electron never has a chance to return back. In this case, the ejected electron always receives an acceleration perpendicular to its linear motion. It is interesting that with a change of polarization we can simply avoid recollision.

As poets and painters may see and present the event of »a sunset« in their own individual way, scientists from various background have their own interpretation. For a collision physicist with memories of neutron and ion collision in targets, high field ionization is a miniature accelerator (see Section 6.2). An electron is accelerated by the laser field to high velocities and upon return it is all *collision physics*. This includes elastic collisions or the billiard ball bounce of the electron against the ion and inelastic collisions with transfer of energy to a photon or an electron. A scientist with a quantum optics background may see it as an *interference* of the electron wave floating on the laser field, with a remaining wave inside the ion. Above threshold ionization of the electrons and high harmonic generation of photons with discrete energy difference is the result of this interference. The traveling electron is coherent with the remaining electron. In quantum mechanics language part of the wavefunction has left the atom and part of it is still inside, waiting for the return of the passenger. The superposition of the wavefunction of the traveling electron with that of the bond electron results in dipole oscillation; a charge oscillation that results in photon emission.

The details of these processes and mathematical description of these events can be found in review papers [6, 7] and references therein.

6.1.2 Application of Attosecond Science

In the evolution of science, there are efforts that may result in a single isolated paper over a lifetime, and there are times that the pick hits the oil well and there follows a nonstop gush of scientific discoveries. Attosecond science is one of these miraculous oil wells. To name a few scientific applications, we will look at molecular *alignment* with short pulses, analyze the ionization process, image molecular orbitals, drive currents inside atoms, and watch the evolution of chemical bonds.

6.1.2.1 Molecular Alignment

Laser pulses rotate polarized molecules. The strength of this force depends on the shape of the electronic-orbital in molecules and its positioning with respect to the laser field. As a result of this interaction the laser field pulls the electron orbital into its plane of polar-

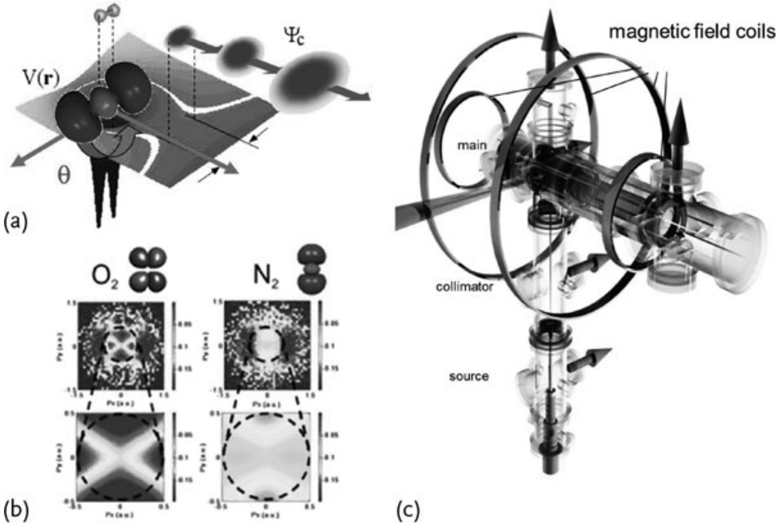


Figure 6.3 (a) Tunneling with high laser field. The ejected electron from the tunnel carries the information about the orbital that it left. (b) Recording of the momentum distribution of aligned and anti-aligned molecules is used to produce a normalized image of the electron orbital. The image recorded of low energy tunneled electrons with the highest electronic orbital calculated for nitrogen and oxygen is in agreement with the image of direct electrons [9]. (c) A schematic of a COLTRIM to synchronously record the momentum of the ejected electrons and ions. The source is the gas jet that moves up in the picture to meet with the laser (the red light from the left) at its focal spot. After the reaction the charged products are guided to their proper recording device. The high voltage bias separates the ions from electrons. The magnetic coil on the COLTRIMS overpowers the earth magnetic field and extends the travel time of electrons. COLTRIMS are made of various chambers to separate the interaction and detection procedures (courtesy of Andre Staudte and Moritz Meckel). Please find a color version of this figure on the color plates.

ization. Quantum mechanics suggest that the rotational energy levels are discrete. Having discrete energy levels results in a rotation of the molecule with a characteristic revival time.[36] The revival can be seen as a common period of a series of pendulums with proportional lengths. There is a common multiple among the periods at which the pendulums comes back to the same spot. In a simple diatomic molecule like N_2 the electronic orbital is pulled towards the laser field.

For a long enough pulse around 100 fs of 800 nm light, the molecular orientation comes to alignment with the laser field. This push

36) For example, nitrogen has 8.4 and oxygen has 11.6 ps as revival time.

towards the field starts the pendulum of rotation. The sample comes back to the same orientation after 8.4 ps from the »prompt« alignment with the laser field. This is a necessary tool for studying light matter interaction, because the alignment and orientation of a molecule is set with a laser pulse and can be studied with a probe laser in the absence of any perturbing field; so called *field free alignment*.

6.1.2.2 Watching the Ionization from a Molecule

Countless research programs have been devoted to the understanding of the dynamics of chemical reactions and the inner structure of molecules and atoms. In one example the detailed process of ionization from an HCl molecule was investigated. It was shown that in high field ionization the probability of removing an electron from the hydrogen side is higher than at the chlorine pole of the molecule. Having a highly polarized HCl atom that is mostly shown as H^+Cl^-, the result of the experiment was unexpected [8].

The challenge is to expand these observations to larger molecules to understand the dynamics of charge transfers and chemical reactions. Another experiment [9] was to image the electron orbitals in oxygen and nitrogen by measuring the distribution of momentum of the ejected electrons (step 1). Cold target recoil ion momentum spectroscopy (COLTRIMS) is a device to monitor light–matter interaction by recording the time and position (therefore the momentum) of ions and electrons generated in the high intensity laser focal spot.

6.1.2.3 Molecular Breathing

The information about the molecule is carried away in the photon(s) of high harmonic generation, as well as in the recolliding electron. Simultaneous imaging of the geometric and electronic structure of a molecule, as it undergoes a chemical reaction, can be recorded by monitoring the photons (high harmonic generation) generated from recombination of the electron to its parent ion (step 3).

Since the electronic orbital is strongly affected by the separation between the molecules, a temporal shift of less than an attosecond of high harmonic generation is documented between stretched and compressed geometry of diatomic molecule Bromine [10].

6.2 Lasers in Nuclear Physics and Accelerators

As we saw in Section 1.2.1, any matter in physics has some energy characteristics. If the matter is excited at energies matching a level structure the resonance is induced. The resonance can be sharp as in atomic structures, or broad and vague as in the solids in Chapter 4. In this section we consider very high intensities of tightly focused light. For the applications considered in this section, the synchronization of events, essential in the case of attosecond generation, takes a backstage role in favor of maximizing the *energy deposition*.

The unique *coherence* property of the laser results in a well collimated beam and high quality focus. The photons have temporal and spatial coherence and as they are brought together they constructively interfere, which is why a high intensity spot is created. A typical Q-switched Nd:YAG laser produces pulses of 10 MW intensity in 10 ns. A bright flash of white light, with a loud »BANG« is produced by focusing this pulse in air. This effect is called »avalanche breakdown«: at the laser intensity of the order of 1 TW/cm^2 reached at the focus, a few lone electrons are accelerated by the field of the pulse, to a sufficient energy to ionize molecules of air, creating electrons that are in turn also accelerated, etc... Much higher intensities are achieved with ultrashort pulses. It is shocking that a commercial (amplified) Ti:sapphire of a few tens of femtosecond duration and millijoule energy, once focused to a 30 μm spot, creates intensities that exceed those at the sun's surface (about 10^{15} W/cm^2). The sun is right there in the laboratory, but there should be no worry that the building might melt down: the high intensity is confined geometrically and in time. Surprisingly, the ultrashort pulse is much more discrete than its nanosecond counterpart. The reason is that there is not enough time in less than 1 ps for the avalanche process. Nevertheless, the multiphoton ionization does make itself heard and seen. Instead of the bright flash of white light and the very loud noise, the focused millijoule pulse produces only a little crackle, a small streak of purple light, and some colors that can be seen on a screen. These are indications for the experimentalist that the laser operates with short pulses and high energy.

The race to get higher intensity lasers is not just to set a record, it is also for cracking up higher energy processes. Some of the physical processes with their associated intensity are listed in Figure 6.4. Helium is ionized at laser intensities of the order of 3×10^{14} W/cm^2. When

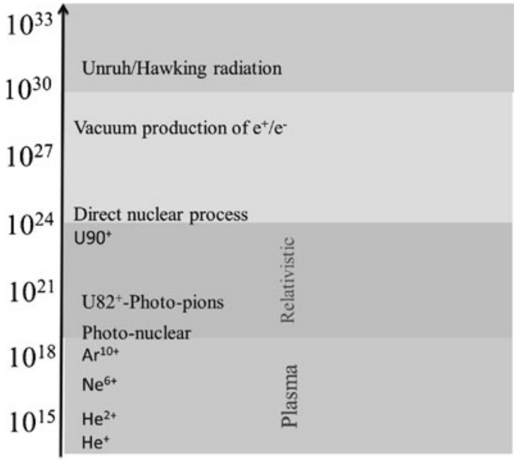


Figure 6.4 Selected events occurring at high laser intensity. This graph is just for presentation and the threshold values for the events are not exact.

the first electron is removed from an atom, the balance between positive and negative components is lost. The positive charges, having gained a majority, pull the electrons tighter, and it takes more effort to ionize more. In a sense, atoms are not like gamblers who are more drawn into games after losing a sum of money with a hope to win. If an atom loses an electron, it will hold to the remaining ones much tighter. Higher laser fields are necessary to tilt the Coulomb potential (Figure 6.1) in order to release another electron. Stripping *all* the electrons of neon occurs at 10^{17} W/cm^2. For a heavier atom like argon removing all 10 electron requires intensities of 10^{18} W/cm^2. Between 10^{18} and 10^{19} W/cm^2, photon-induced nuclear reactions are possible. The production of the first elementary particle, the *pion*, takes place around 10^{21} W/cm^2. At a very high intensity of 10^{28} W/cm^2 electron–positron pair or *pair production* (Figure 6.5) from the vacuum is possible.

Of the photonuclear effects, nuclear fission, or laser-induced fission was observed from uranium at the VULCAN laser facility in 1999. The uranium nucleus has the shape of the rugby ball. For the uranium isotope 238, the short-range attractive nuclear force balances the repulsion of 92 protons to give the nucleus its prolate deformation. For such a big molecule the excess of energy from a photon or incident neutron results in vibration or rotation of the nucleus. The vibration results in an increase of average distance between nucleons. The short-range (attractive) nuclear force is strongly dependent on the average distance between nucleons, while the (repulsive) balancing Coulomb force is less affected by the increased average distance. Once the balance is broken, it is hard to keep the nucleons together: two main fragments and a few evaporated neutrons and gamma rays are generated. A person walking with free hands will keep his/her balance, but one carrying parcels with every tooth and finger like a Christmas tree will tip over and drop his/her loose companions. Fission of uranium produces fragments with mass numbers about 95 and 140 corresponding to the neutron magic numbers of 50 and 82. The way to monitor the fission is normally by detecting characteristic gamma rays emitted by this process.

In nuclear industry both fast and slow neutrons are used to induce fission. Other nuclear probes like protons, electrons, deuterons, alpha particles, heavy ions, electrons, muons, and gamma rays also ignite the fission. With terawatt (10^{12}) and petawatt (10^{15}) lasers on hand, a light source can be used alongside (or perhaps replace) an accelerator for nuclear studies. Accelerators are limited by electric breakdown at fields of about 20 MV/m, when electrons are torn from the atom in the accelerator's support structure. A 100 J energy in a picosecond pulse, using a parabolic mirror, is focused to a few μm^2 regions. In this small area an intensity of 10^{20} W per square centimeter is reached. Electric fields of the order of 10^{11} V/cm are generated along with a huge alternating magnetic field close to 10^9 Gs, which is only 1000 times smaller than the magnetic field of a typical black hole. In Section 6.1 we saw how a laser pulse tears the atom and accelerate electrons. In the late 1970s it was noticed [11] that highly accelerated electrons could be generated by focusing light into a plasma medium.

As seen in Section 6.1 light pulses create high energy electrons. In a low density target the motion of the electrons is mainly due to the laser field. In a dense material, however, a laser pulse sets up a high electrostatic wave within a plasma by displacing the negatively charged electrons with respect to the heavier positive charges. This displacement creates an accelerating field in which electrons oscillate at speeds close to the speed of light. Electron energies of over 200 MeV can be created in this way.

In a target with high atomic number Z, the accelerated electrons slow down and emit high energy photons as gamma radiation. The

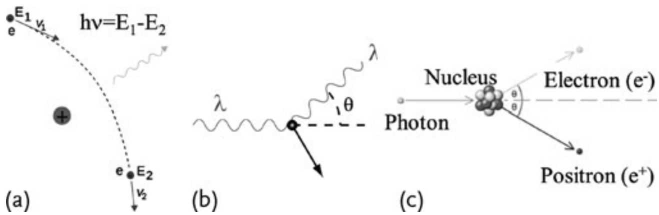


Figure 6.5 (a) Bremsstrahlung radiation or braking radiation of an electron. The electron trajectory is affected by the positive charge of the nucleus. This energy loss due to the deceleration of the electron is transferred to a photon in the x-ray and gamma ray range. (b) Compton scattering, the high energy photon is deflected by collision with electrons in matter. The photon energy is reduced (its wavelength is increased) and the energy difference is given to the electron. (c) Pair production, when a light photon has high enough energy to produce an electron and a positron pair (= 2 × 511 keV), a photon can be annihilated and be replaced by matter. The excess energy is given as kinetic energy to the electron and positron going in opposite direction to conserve the momentum. Please find a color version of this figure on the color plates.

process of this gamma radiation is called »*braking radiation*« or in its original German »*Bremsstrahlung*«. In Figure 6.5a an electron is decelerated and deflected in the vicinity of a charged particle. In physics, the law of conservation of energy is a hint to solve most problems. The difference in the energy of the electron goes to a high energy photon radiation which fits in the x-ray or gamma range. x-ray tubes are based on the *Bremsstrahlung* phenomenon where electrons accelerated through an applied voltage hit a high atomic number sample, and the deceleration of these electrons leads to continuous x-ray spectra. The Bremsstrahlung process applies to deceleration of any charged particle that has an energy larger than its rest mass ($E = mc^2$). Since the electron is lighter than ions and protons, this phenomena is mostly applied to electrons.

There are three major phenomena of light–matter interaction, which are recognized by their characteristic energy: the *photoelectric effect, Compton scattering,* and *pair production*. Low energy photons around the visible wavelength (electron volt) are in resonance with energy gaps of metals. In the photoelectric effect the discreteness of photon energy was observed by recording the current of the electrons that jumped through the energy gap. If the energy gap or the work function is discrete, so must be the photon energy.

In *Compton scattering* the x-ray or gamma ray photon scatters from an electron. The photon needs to have an energy comparable with the rest energy of the electron, that is, around 511 keV. When the energy of the photon and electron are comparable, the particle nature of the light shows up in this interaction, as if a collision is taking place between balls on a pool table (not exactly the same, because collisions on a pool table are elastic). As a result of transferring its energy to the electron at rest, the electron receives this recoil energy, the photon energy is reduced, and the light wavelength is changed from λ to λ':

$$\lambda' - \lambda = \frac{h}{mc}\left(1 - \cos\left(\theta\right)\right). \tag{6.1}$$

The light is deflected to an angle θ after this collision. The larger the deflection angle, the more energy is transferred to the electron. When light acts as a particle, the particle acts like a wave too. The right-hand side of the equation has »m« as the mass of the electron and h/mc has the dimension of the wavelength, which is why it is called the *Compton wavelength* of the electron.[37] This electron can be further accelerated with the laser field.

When the photon energy is high enough to host a positron and an electron (note that the photon has no charge so it can only be transformed to species of zero total charge), it can annihilate and give birth to matter (a positron and an electron) following the conservation of mass and energy $E = mc^2$. The threshold of the formation of electron–positron pairs is at a laser intensity of 10^{28} W/cm^2. It is exciting to realize that matter can be produced out of laser light focused into a small focal spot. It suggests a vision of the universe formation out of a tiny focal spot on the order of the light wavelength!

What is the limit in the highest achievable intensity with laser pulses? As the energy of the laser goes up it ionizes the material and damages objects upon illumination. The critical *quantum electrodynamics* QED field of $E_s = m^2c^3/e\hbar = 1.32\,\text{V} \times 10^{16}\,\text{V/cm}$ [12] represents a field value at which the photon is annihilated and an electron–positron pair is created in vacuum. As mentioned in Section 1.8, this critical field is such that it accelerates an electron over the distance equal to the Compton wavelength λ_c to the energy at rest of the electron mc^2. It is thus defined by the relation: $eE_s\lambda_c = 2mc^2$. At this field one expects to see the photons transferred to matter, so there

37) The Compton wavelength of the electron is 2.43×10^{-12} m.

could be no light with higher fields.[38] It was a heated debate and a paradox to consider fields of that strength. The simulation shows that when using multiple pulses, the threshold for such a reaction is reduced to fields 100 times smaller. Optical intensities of the order of 5×10^{25} W/cm^2 (corresponding to $0.01\,E_s$) are sought in projects of extreme light infrastructure ELI and x-ray free-electron lasers XFEL. As laser fields accelerate electrons (Section 6.1) up to relativistic velocities, the accelerated particles emit hard photons that, in turn, produce a new electron–positron pair. This pair production with lasers was observed before the turn of the century in SLAC [13].

If a laser can be strong enough to burn any material and create an electron–positron pair in vacuum, how could it ever exist in a cavity? What is the gain medium for such a source? The answer is based on what we have learned about laser coherence used in achieving a tight focal spot (Section 1.6.2), stretching and compressing a pulse in time (Section 1.8.2), and the coherence of a pulse train (Chapter 5). The laser beam can be expanded to tens of centimeters and at the point of interaction reduced to micron size. The size change from 5 cm diameter to a micron focal spot results in 50 000 times enhancement of the intensity. Pulses can be stretched in time about 10 000 times and even more. For a given energy that stretching means reducing the peak power by the same factor. To avoid most damage to optical components, the instantaneous field has to be kept lower than a threshold. Stretching the pulse in time is a convenient way to keep the components of a laser system safe. The last tool at hand is to use multiple lasers and synchronize their oscillation to acquire a coherent superposition of pulses, a difficult task since each laser has its own world. The laser cavity size, pump laser intensity and a fly flapping its wings would affect the phase of the laser oscillation under the envelope and so will be the superposition of the pulses.

Petawatt lasers are the class of lasers that is able to deliver powers of 10^{15} W in short bursts of optical pulses.[39] One example of this class

38) Theoreticians now consider fields higher than this value. With further developments on QED, the Klein paradox is resolved and the electromagnetic Lagrangian is valid at arbitrary field strength.

39) To keep things in perspective, the total average (gas, electricity, etc.) power consumption of the United States in 2005 was about 3 TW (3.34×10^{12} W).

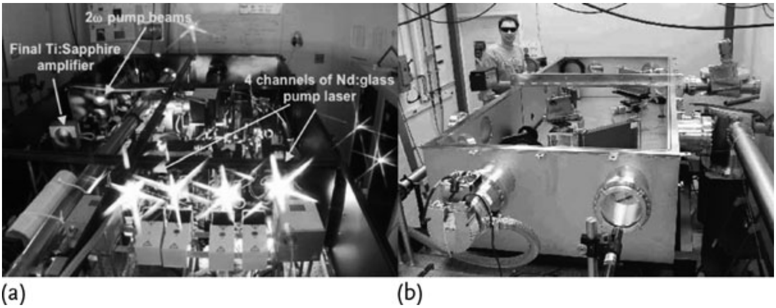


Figure 6.6 (a) A picture of the HERCULES Laser from the FOCUS project of the University of Michigan (courtesy of Anatoly Maksimchuk). (b) The four-grating compressor to reduce the pulse to 30 fs (courtesy of V. Yanovsky).

of lasers is the HERCULES petawatt laser at the University of Michigan, which reaches 10^{23} W/cm^2 by focusing about 15 J of 30 fs pulses to a diffraction limited focal spot of one micron. A picture of this system is shown in Figure 6.6a. The four bursts of purple light are from the flash lamp pumped Nd-YAG rods. The pump laser has two stages of amplification. The frequency-doubled output of the first stage (the green light in Figure 6.6a) is used for pumping the 2.5 cm diameter Ti:sapphire amplifier, while the unconverted infrared light is injected into the second stage of the pump laser for further amplification. The frequency-doubled output of the second stage is used for pumping of the booster (5 cm diameter) amplifier of the HERCULES laser. The pump laser has a quasi-flat-top beam profile that was achieved at 0.1 Hz repetition rate.

The HERCULES laser design (Figure 6.6a) is based on chirped-pulse amplification with removal of the amplified spontaneous emission (ASE) noise after the first amplifier. Special care has been given not to amplify unwanted spontaneous radiation of the laser (Section 1.2) instead of the stimulated radiation. Two cross-polarizers are used to reduce the radiation from amplified spontaneous emission (ASE) to a background of less than 10^{-11} of the laser power. The output pulse of the 12 fs pulse of the laser is preamplified in the two-pass preamplifier to the microjoule energy level. The clean microjoule energy pulse is stretched to about 0.5 ns by the stretcher, based on a modified mirror-in-grating design. The whole laser is designed to be fifth-order dispersion-limited over 104 nm bandwidth. The high-energy regenerative amplifier and cryogenically cooled four-pass amplifier bring the pulse energy to an energy level of one joule with nearly diffraction-limited beam quality. Two sequential two-pass-Ti:sapphire amplifiers of 2.5 cm and 5 cm beam diameter, respectively, raise the output energy to a value approaching 20 J. The booster two-pass amplifier uses an 11-cm-diameter Ti:sapphire crystal (red light in Figure 6.6a). In order to suppress parasitic oscillations the side surface of the crystal is covered with a thin layer of index-matching thermoplastic coating doped with organic dye absorbing at 800 nm. The compressor design to reduce the pulse width to 30 fs is shown in Figure 6.6b.

6.3 Laser Cooling

May be one of the most surprising applications of the laser is *laser cooling*. Most of the applications that we have considered so far deposit the energy of the laser in a structure or material (Chapter 4) for ablation and modification in a cell (Chapter 3) or to impinge upon an atom or a molecule (Section 6.1). No matter what the scale of the interaction, the energy of the photon resulted in heating or accelerating particles. Here we look at a peculiar application of lasers in cooling materials, which can be extended into solids. This application is based on radiation pressure (Section 3.8.2) of light. This refrigeration of matter can be applied in vacuum and can thus operate in space.

The momentum kick that an atom receives from a photon is quite small and a typical velocity change is of the order of 1 cm/s. However, by exciting a strong atomic transition, it is possible to scatter more than 10^7 photons/s. The gain linewidth for an interaction is not a delta function (Section 1.2.1). The strength of the interaction is reduced as the frequency is detuned from its resonance value. Having atoms in motion (for a temperature »T« and an atom with mass »m« moving in three dimensions $kT = 3/2mv^2$), each one sees the light at a slightly different frequency due to a Doppler shift.[40] When the laser light is tuned to be lower than the atomic resonance, the atoms moving against the laser light see the frequency of the light closer to the resonance value and have stronger interaction than those moving along the direction of the laser light. The particles in the laser beam experience a scattering force (Section 3.8.2) along the propagation direction

40) The Doppler shift is $\Delta\nu_{\text{Doppler}} = v/c \times \nu_{\text{laser}}$ where »v« is the velocity of the atom, »c« is the speed of light, and ν_{laser} is the frequency of laser light.

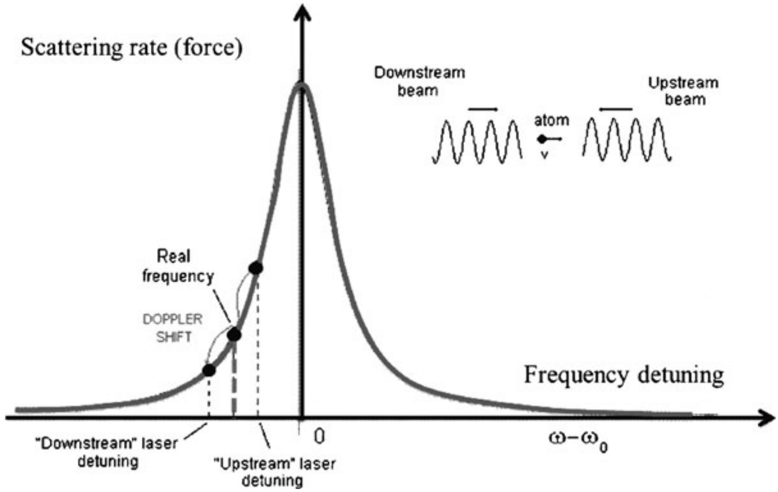


Figure 6.7 The scattering rate profile as a function of frequency detuning $\omega - \omega_0$, where ω_0 is the resonance frequency and ω is the light frequency. An atom moving upstream with respect to the laser field sees the light frequency upshifted by $\nu + \Delta\nu_{\text{Doppler}}$ and the one moving downstream sees the frequency down shifted $\nu - \Delta\nu_{\text{Doppler}}$. When the laser light is tuned below the resonance, the atom moving against the laser field has higher interaction with light and receives a kick (scattering force) opposite to its propagation direction.

of light. Therefore, the atoms moving upstream from the laser field will receive a kick against their direction of motion. The slowed down atoms experience cooling.

The laser cooling process needs to be extended to atoms moving in opposite direction with a counter propagating laser beam. Six laser beams confine the motion of the atom in three-dimensional space. The cooling solely based on the radiation pressure of light can reduce the target temperature to 100 μK. Indeed, when one uses Doppler cooling there is a residual motion of the atoms that one cannot get rid of. Whenever an atom absorbs or reemits a photon, it acquires an additional momentum in a random direction: even if the Doppler cooling is improved the atoms will keep moving a little.

In a magneto-optical trap laser cooling is combined with a slow modification of a magnetic trap. The potential well is modified with a magnetic field, so that the higher energy atoms with larger values of dipole moment can leave the well and the cooler ones stay inside. With this evaporative cooling method temperatures of micro Kelvin are attained.

References

1 Sheik-Bahae, M. and Seletskiy, D. (2009) Laser cooling in dense atomic media. *Nat. Photonics*, **3**, 680–681.

2 Lewenstein, M., Balcou, P., Ivanov, M.Y., L'Huiliier, A., and Corkum, P.B. (1994) Theory of high-harmonic generation by low-frequency laser fields. *Phys. Rev. A*, **49**, 2117–2132.

3 Corkum, P.B. (1993) Plasma perspective on strong-field multiphoton ionization. *Phys. Rev. Lett.*, **71**, 1994.

4 Keldysh, L.V. (1965) Ionization in the field of a strong electromagnetic wave. *Sov. Phys. JET*, **20**(5), 1307–1314.

5 Agostini, P., Fabre, F., Mainfray, G., Petite, G., and Rahman, N.K. (1979) Free–free transitions following six-photon ionization of xenon atoms. *Phys. Rev. Lett.*, **42**, 1127–1130.

6 Krausz, F., and Brabec, T. (2009) Attosecond physics. *Rev. Mod. Phys.*, **81**, 163–234.

7 Brabec, T. and Krausz, F. (2000) Intense few-cycle laser fields: Frontiers of nonlinear optics. *Rev. Mod. Phys.*, **72**, 545–591.

8 Akagi, H., Otobe, T., Staudte, A., Shiner, A., Turner, F., Dörner, R., Villeneuve, D.M., and Corkum, P.B. (2009) Laser tunnel ionization from multiple orbitals in HCl. *Science*, **325**, 1364–1367.

9 Meckel, M., Comtois, C., Zeidler, D., Staudte, A., Pepin, H.C.B.H., Kieffer, J.C., Dörner, R., Villeneuve, D.M.., and Corkum, P.B. (2008) Laser-induced electron tunneling and diffraction. *Science*, **13**, 1478–1482.

10 Wörner, N.J., Bertrand, J., Kartashov, D.V., Corkum, P.B., and Villeneuve, D.M. (2010) Following a chemical reaction using high-harmonic interferometry. *Nature*, **466**, 604–607.

11 Tajima, T. and Dawson, J.M. (1979) Laser electron accelerator. *Phys. Rev. Lett.*, **43**, 267–270.

12 Fedotov, A.M., Narozhny, N.B., Mourou, G., and Korn, G. (2010) Limitations on the attainable intensity of high power lasers. *Phys. Rev. Lett.*, **105**, 080402.

13 Burke, D.L., Horton-Smith, R.C.F.G., Spencer, J.E., Berridge, D.W.S.C., Bugg, W.M., Shmakov, K., Weidemann, A.W., Bula, C., McDonald, K.T., Prebys, E.J., Bamber, C., Boege, S.J., Koffas, T., Kotseroglou, T., Melissinos, A.C., Meyerhofer, D.D., Reis, D.A., and Ragg, W. (1997) Positron production in multiphoton light-by-light scattering. *Phys. Rev. Lett*, **79**, 1626–1629.

7
High Power Lasers (Tazer/Teaser)

As we saw in Chapter 1, »high power« is a different concept for people of different disciplines. In this chapter we look at what is perceived as high power for common mortals; lasers that can inflict some damage at a distance and are not bigger than what is commonly found in university research laboratories. These have a whole range of applications, from remote sensing to lightning protection to military applications and even »crowd control«.

7.1 Filaments

A »filament« is the name given to a high intensity submillimeter feature in a broader beam of infrared [1] or UV [2] radiation, as it was seen to drill a minuscule hole on any target such as a mirror or metal put in its path. Filaments are sometimes confused with bright light created from breakdown in air, which is just dense plasma (see Section 6.2). One of the main features of a filament that can be used for its definition is that its size is confined to a small dimension over a long distance. As we saw in Section 1.6.1, even though a laser is referred to as having the best collimated beam, it diverges, reaching 1.4× its size over the Rayleigh distance. A filament is a light beam that retains its size for distances much longer than the Rayleigh length. A complex combination of plasma effect on radiation, phase front, and polarization is the source for this feature. Upon observation of filaments, researchers became excited about its promising application to guide light and transport optical energy over long distances. However, they got more than they bargained for: another puzzle of nature to scratch their heads about.

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

7.1.1 The Filament Fighting for Its Existence

We saw in Chapter 1, Section 1.7.5.3, that a laser beam of sufficient intensity can create its own waveguide, even in air. The mere existence of filaments, as self-guided beams, has been the object of controversy since shortly after the invention of the laser; a controversy that continues to this day.

In the good times of the Cold War, there was a hot debate between a Russian and American scientist. The Russian scientist [3, 4] explained filamentation as a balance between a nonlinear lensing effect (nonlinear index of refraction increasing proportionally to the intensity), and an index of refraction decreasing proportionally to the square of the intensity. As we saw in Section 1.7.5.3), the former effect would cause the beam to focus to a point, but the latter effect would take over close to the focus and maintain a stable beam (or filament) radius. His eminent US colleague countered that filaments do not exist, but are just an illusion created by the fact that, as the intensity increases along a pulse, the self-focus recedes towards the source [5]. To explain this point of view, a pulse has been divided in slices of increasing intensity in Figure 7.1b. As the pulse intensity increases along the leading edge of the pulse, it will start to focus, reaching a focal point at the extreme right of the picture. The next slice of the pulse being of higher intensity will focus at a shorter distance. The fourth slice corresponding to the peak intensity will focus at the shortest distance. There is thus a spot of highest intensity that travels along the center of the beam, giving the illusion of a filament. In transparent solids such as glass, that intensity spike is sufficient to shatter the material, leaving a string of beads of broken glass inside the optical component, which has the appearance of filaments. This explanation of the damage caused in solids by pulses of nanosecond duration is generally accepted. That is not to say that the Russian theory was incorrect.

Somewhere in the middle between the Cold War warriors, a French scientist proved the existence of filaments, creating visible self-induced waveguides with a continuous laser beam [6]. The material used was a suspension of minuscule (4 nm diameter) spheres in a transparent liquid. The nanospheres were either plastic (latex) spheres in water, of oil droplets maintained in a stable configuration in a mixture of soap, alcohol, and water (microemulsion). If the nanoparticles have an index of refraction higher than the liquid, it

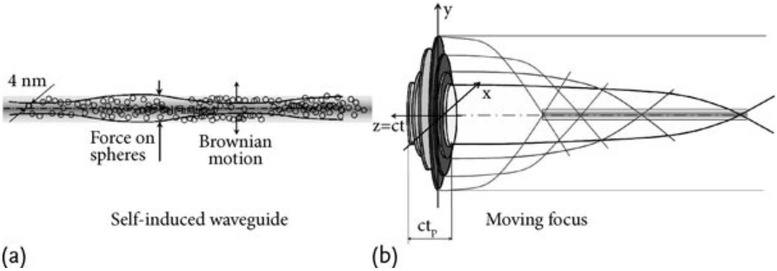
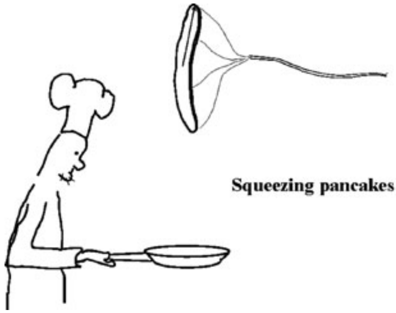


Figure 7.1 Comparison of the moving focus model and true self-induced waveguide. For the moving focus, successive slices in intensity reach a focus at a different point along the beam axis, giving the illusion of a filament. True self-waveguiding is observed in suspensions of nanospheres, which tend to aggregate in the most intense part of the beam (on the axis in the case of the figure). As the particles accumulate on the axis, they increase the average index of refraction of the suspension and create a lens. The Brownian motion counteracts this effect by dispersing the nanoparticles. Please find a color version of this figure on the color plates.

can be shown that they will migrate towards the center of the beam (see Section 3.8.2). Since they have a higher index than the liquid, the higher concentration will result in an overall higher index of refraction near the beam axis, which creates a lens or an optical waveguide as in Section 1.4.4. The distribution of the nanoparticles inside the liquid will reach an equilibrium, because the aggregation force of the light is countered by the Brownian motion that wants to disperse the spheres.

Scientists do not seem to have paid much attention to that French demonstration, which has been widely forgotten by the filamentation researchers. The controversy has continued to grow between proponents of some version of the moving focus [7, 8] and champions of the self-induced waveguide [9, 10]. How could such a seemingly simple problem have gone unresolved for such a long time? In the case of femtosecond pulses, visualizing an ultrashort – 40 fs for instance – light pulse spread transverselly over several cm, transform itself into a minuscule light bullet is not trivial. The initial light pulse is like an ultrathin pancake, 20 000 μm diameter by 12 μm thickness. How could the best cook imagine squeezing such a pancake into a 50 μm diameter spaghetti? There is no reason to expect that the edges of the



pancake will move towards the axis of the beam and reach the central part at the same time. Not only does that happen sometimes, but it has been observed that the bullet-in-spaghetti is squeezed to be *narrower* than the original thickness of the pancake! Through the filamentation process, a pulse that was only 40 fs in duration was transformed into a 6 fs pulse [11]. The ability to compress high energy pulses has become one important application of filaments. As we saw in Section 6.1, these ultrashort intense pulses are mainly used in research, to create even shorter (attosecond) pulses. There are, however, less exotic applications for these filaments, as we shall see in the remainder of this chapter.

7.1.2 Various Types of Filaments

We saw in the previous section that a moving focus can have the appearance of a filament and that a femtosecond pulse can give rise to a filament where the energy stays confined near the beam axis. Nearly all filament research in the world (up to 2011) has concentrated on filaments created by ultrashort pulses from a Ti:sapphire laser. One exception is the continuous radiation filament [6] discussed in the previous section. Another exception is the UV filament at 266 nm, which involves pulses of 1000× longer duration and energy [12].

Let us quickly review how a filament is generated in air. The index of refraction (Kerr effect) of air is intensity dependent, creating a lensing effect where the intensity is the highest, as is sketched in Figure 1.28. The beam is focused by that self-induced lens, reducing in size and at the same time increasing its intensity on axis, until reaching a very small diameter. There is a minimum diameter at which the intensity on axis becomes high enough to ionize the air, creating a cloud of electrons of density decreasing from the center (beam axis) outwards. Electrons are known to have a negative contribution to the index of refraction. This implies that they create a negative lens, compensating the self-focusing effect. The two opposing effects are the stabilizing effects that make a filament possible.

One might wonder why ultrashort pulses are generally used to create a filament. Could an arbitrary long pulse of sufficient intensity be used? The high intensity electric field of a pulse accelerates the electrons at each cycle. The average velocity of the electron cloud of the plasma increases with successive light periods. This is called plasma heating. In a gas, the temperature is determined by the average velocity of the molecules. It is the average velocity of electrons that characterize the temperature of a plasma. After some time, electrons may reach such a velocity that their kinetic energy exceeds the minimum needed to ionize a molecule. These electrons, upon collision with a molecule, will ionize it, creating another electron, which will in turn be accelerated, and so on. This is called an avalanche process and ultimately leads to a complete ionization of the gas. The time needed to reach the avalanche is inversely proportional to the intensity and to the wavelength. For the UV filament, the intensity is 100 times less than at 800 nm, and the wavelength squared 10 times less. Therefore, a UV filament can exist with a 1000 times longer pulse duration than that of the 800 nm filament and thus carry a much larger energy. This realization led to the generation of filaments with long UV pulses using a Q-switched laser as a source rather than a mode-locked laser [12].

The demonstration of filamentation in the UV is shown in Figure 7.2. The UV pulse is generated from a Q-switched, near infrared (1064 nm) Nd:YAG laser, which is twice frequency doubled to a wavelength of 266 nm. This intense UV beam (nearly 1 J/ns) is focused in a 3 m long vacuum tube. The focused beam is then launched in the atmosphere. Since no solid state or liquid can withstand the focused power of the UV source, a supersonic flow of air is used as a barrier between vacuum and atmosphere (Figure 7.2a). This »aerodynamic window« consists of a narrow nozzle followed by a specially profiled expansion chamber. The shape of that expansion chamber is calculated in such a way as to achieve the pressure distribution shown in the figure. The color coding for the pressure inside the expansion chamber shows a range from 0 to 760 torr (mm of Hg). 5 to 10 cm following

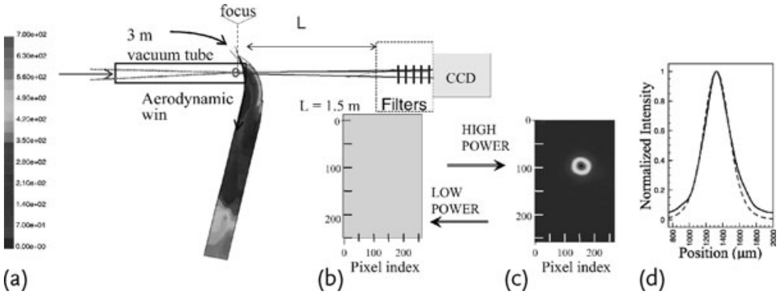


Figure 7.2 UV Filament. (a) A 2 cm diameter high power laser beam at 266 nm is focused through a 3 m long vacuum tube. The focal spot is located 1 to 2 cm in front of the aperture of an aerodynamic window, where a supersonic flow of air serves as seal between vacuum and atmosphere. The various colors inside the expansion chamber of the aerodynamic window indicate the local pressure (from dark blue, 0 torr to red, 700—760 torr). To attenuate the beam without any distortion, a 15 cm diameter mirror at grazing (89°) incidence first reduced the filament intensity by a factor of 10 million. Further attenuation can thereafter be made by simple absorbing gray filters (»neutral density filters«). (b) At low intensity, the beam diverges after the focus, covering the entire aperture of the CCD at 1 m distance. (c) At high intensity, the beam diameter remains constant at 300 μm of the 4 m propagation distance available in the laboratory. (d) Profile of the filament (cross-section through (c)), and theoretical curve (dashed line). Please find a color version of this figure on the color plates.

the nozzle, there is vacuum in the inside bend (dark blue), and atmospheric pressure at the outside curve (red). A 3 mm diameter hole or slot is made for passage of from the region of minimum pressure to the atmospheric pressure side. It should be noted that the transition from low pressure (200 torr, light blue) to atmospheric pressure (red) takes places over a distance of only a few mm. The aerodynamic window is operated continuously by a compressor providing a pressure of 8 kg/cm^2 with a flow of 150 dm^3/s. This somewhat complicated arrangement has the advantage to prove unequivocally, that when a filament is observed, it is unequivocally the result of a balance between self-focusing and defocusing. Indeed, a moving focus cannot take place, since the beam is focused in vacuum to a point before the interface vacuum–air. At a distance L from the window, varying from 0 to 4 m, the beam or the filament is linearly attenuated, before being observed with a CCD. The linear attenuator consist first in a large mirror at grazing incidence (89°) followed by neutral density filters. Because of the grazing incidence, the high intensity of the filament is spread over a relatively large area (150 mm × 0.6 mm), thereby preventing laser damage that would otherwise occur. At a distance L of more than 1 m, and at low power, the beam covers completely the viewing area of the CCD, as shown in Figure 7.2b. At maximum power, the pattern on the CCD is a round spot of 300 μm diameter, at any distance between 0 and 4 m (longest distance available in the laboratory) [12] (Figure 7.2c)

7.1.3 Remote Sensing with Filaments

Filaments ionize molecules of oxygen and nitrogen, creating positive ions and electrons. The positive ions of oxygen and nitrogen fluoresce. It is that fluorescence that is at the origin of the Aurora Boreal, with the oxygen ion fluorescing in the green (557.7 nm) and the red (630 and 636 nm), and nitrogen in the UV (337 nm) and blue (391.5, 428.3, and 470.9 nm). These colors do not have the spectacular appeal of the Aurora Boreal and go unnoticed, except for researchers attempting to analyze and visualize the filaments. A considerably more spectacular radiation of the filaments is what is called the conical emission. The name is inspired from the fact that this emission makes a small angle with the axis of the filament. The relation between spectrum and angle is shown in Figure 1.27 of Section 1.7.5.3. This narrow cone of light is an ideal white light source for spectroscopy. The exact mechanisms giving rise to this display of colors is still the object of heated debate.

Researchers have not waited to understand the phenomenon before applying it, and it is fair to say that excitement over filaments started with a simple experiment of remote sensing of the atmosphere [13, 14]. A filamenting laser was beamed to the sky and the spectrum of the light backscattered was recorded as a function of time. The principle is the same as in Figure 3.7a, except that there is no airplane scattering back the light, but dust, water droplets, and other particles in the atmosphere. Another difference is that not only the round trip time from the laser to the particle and back is recorded, but also the full spectrum of the radiation. For a given time delay (that translates into a given altitude), the spectrum shows absorption lines characteristics of the pollutants encountered in the light path. The three-dimensional set of data (backscattered intensity versus distance and wavelength) is sufficient to determine the composition of the atmosphere along the direction of the laser beam. Adding two dimensions – by scanning the direction of the laser beam – can lead to a complete volumetric mapping of the atmosphere. This first application of filamentation was able to detect backscattering from an altitude of 13 km, which led numerous readers to the wrong conclusion that stable filaments could propagate over such a distance. It is the white light (conical emission) beamed by the first few meters of propagation of the filaments that was backscattered by clouds and particles, and recorded by gated photon counting technique after a delay of up to 43 μs (the delay corresponding to a distance of 13 km).

7.1.4 Remote Sensing by THz Spectroscopy

The white light produced by a high power filamenting beam has an astounding wide spectrum, ranging from UV to mid-IR. More surprising even is the generation by filaments of radiation of THz frequency[41] (in the range of 1–30 THz), corresponding to a wavelength range of 10–300 μm. This wavelength range is extremely interesting for spectroscopy and imaging.

THz radiation traverses porcelain and leather, and is absorbed by water. Spectroscopy in the THz range can identify molecules, for instance through their rotation and vibration spectrum. The large water vapor absorption of THz radiation makes this type of radiation useless for remote sensing. Filaments exhibit a remarkable ability to generate pulsed THz waves through an optical nonlinear process. A filament can thus be used as a remote source of THz radiation. Techniques are being developed by which another filament can be used for remote detection. The dream is to exploit the range of filaments to transport at a large distance a source and detector of THz. The distance between the remote source and detector can be optimized to enable imaging and spectroscopy with best resolution and sensitivity.

7.1.5 The Filament Competing with Sniffing Dogs

The remarkable sniffing sensitivity of dogs have has made them valuable auxiliary of law enforcement personal in the detection of explosives. The limitation is distance: the nose has to come within »sniffing distance« to the suspect object. Instead of relying on a »dog shield« for protection from material liable to explode, it would be de-

41) $1\,\text{THz} = 10^{12}\,\text{Hz}$.

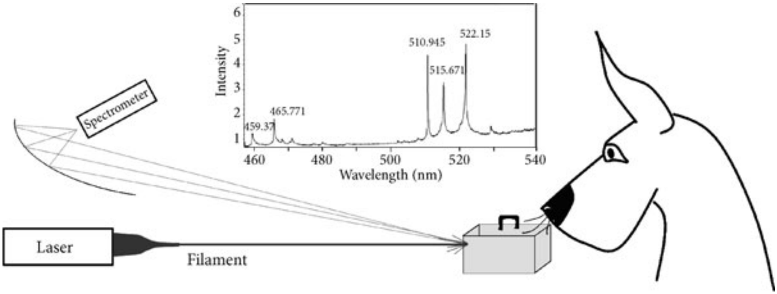


Figure 7.3 Is there an alternative to the sniffing dog to detect some suspicious substance on a suitcase? It would be nice to be able to shoot a filament on the suitcase, collect the light emitted by the plasma plume created by the filament with a parabolic mirror, and send it to a spectrometer. With 800 nm filaments, such an experiment has been performed and can identify the material from which the suitcase is made.[42] The spectrum shown has been taken in this fashion for a polystyrene target (from [15]).

sirable to have remote optical detection of dangerous substances. Filaments offer this possibility because they are able to project a high intensity at hundreds of meter distances.

When a filament hits a target, it vaporizes and ionizes some of the material. The plume of material is sufficiently excited to emit radiation, with some wavelengths that are characteristics of the material that was vaporized. A large parabolic mirror can collect that radiation and concentrate it on a spectrometer. It is hoped that the analysis of the spectrum leads to an accurate identification of the material. The technique is called laser-induced breakdown spectroscopy or LIBS. Figure 7.3 shows an example of a spectrum that can be remotely detected when a 800 nm filament impinges on a solid, in this case polystyrene. The useful information contained in such a measurement is the narrow spectral lines at specific wavelengths, due to molecular transitions, as indicated in the figure, that can be used to identify the target. However, the IR filaments also produce a broad continuum of light, which was exploited in Section 7.1.3 as a spectral lamp for probing the atmosphere, which is detrimental for laser-induced breakdown spectroscopy. Indeed, the conical emission is partly responsible for the broad continuum observed as a pedestal to the ray spectrum of Figure 7.3. Only partly, because the impact of a high intensity femtosecond pulse on molecules creates a strongly

42) Only the surface of the suitcase is detected by this method. To observe the content, THz spectroscopy is required.

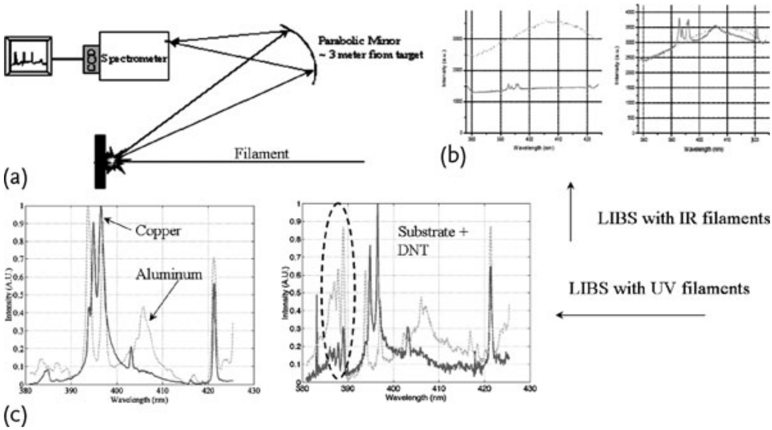


Figure 7.4 Comparison of laser-induced breakdown spectroscopy with UV and IR filaments. (a) Experimental setup. (b) Comparison of the spectrum of Al and Cu, with and without a film of DNT, through irradiation by a IR filament. No new spectral feature appears. (c) Comparison of the spectrum of Al and Cu, without (left) and with a film of DNT. Spectral lines characteristic of CNT are clearly identified. Please find a color version of this figure on the color plates.

ionized plasma, and the ionized molecule undergoes what is called a »Coulomb explosion«, decomposing it into unrecognizable fragments. Rather that identify a bulk solid, copper or plastic, it would be considerably more useful to be able to identify a thin film or residue left by an explosive substance. The UV filament at 266 nm [12] has two considerable advantages over the IR filament for remote sensing. There is no conical white light emission associated with these filaments. With the longer pulse duration of the UV filament (ns), there is no »Coulomb explosion«, but a vaporization of the molecules, and partial dissociation in large fragments that have a characteristic spectrum. Figure 7.4a illustrates how remote laser-induced breakdown spectroscopy is performed. The filament hits the target. The radiation of the plume is collected by a parabolic mirror and focused onto a spectrometer. Data of laser-induced breakdown spectroscopy performed with UV are shown in Figure 7.4c (left) bottom picture (from [16]). The target was either a block of copper (solid red lines) or aluminum (dotted green lines). A comparison is made for the bare substrate, or the substrate covered with a thin film of DNT. The thin layer of DNT (ammonium perchlorate was also tested) was produced by evaporating a drop of ethanol solution of DNT on the metal.

Characteristic spectral lines of DNT are clearly seen in the spectral region below 390 nm indicated by the dashed ellipse) on copper or on aluminum substrate. The same experiment was performed with 800 filaments in exactly the same condition [16]. The results shown in Figure 7.4b does not show any spectral feature due to the thin film of either DNT or ammonium perchlorate. The continuum and spectral lines of copper fluctuate from shot to shot, but in each case overpower the weaker emission than could be attributed to the thin deposit on the metal.

7.2 Laser-Induced Lightning

7.2.1 Lightning

These days, despite centuries of scientific scrutiny, it is fair to say that a basic understanding of lightning, and means to control it, are still lacking. Yet, it is a natural phenomenon with important consequences. In the United States alone, about 20 million flashes hit the ground, causing forest fires and property damage. From 1940 to 1991, the National Weather Service of the United States indicated that an average 163 deaths per year are reported [17]. The cost to the US utilities amounts to $ 1 billion annually in lost revenues and damaged equipment. It is also the cause of costly delays of rocket launches into space. For example, during the Apollo 12 launch of 1969, lightning was responsible for temporally disrupting certain vital electronics on the spacecraft. In 1987, an Atlas Centaur 67 rocket carrying a communication satellite was struck, altering the flight control computer's memory so extensively that the vehicle was destroyed [18]. Would it be worth the effort to try to control lightning? Any golfer would answer in the affirmative: lightning has made golf one of the deadliest sports [19].

With his famous experiment with a kite, Benjamin Franklin established the connection between lightning and electricity. As the legend puts it (Figure 7.5), kite, wire, and operator made a perfect lightning rod. However, the lightning rod is not the foolproof device that it is cracked up to be. Most often[43] the cumulonimbus cloud itself is a

43) Famous counterexamples are the lightning storms in the sea of Japan, where the bottom of clouds can be positively charged [20].

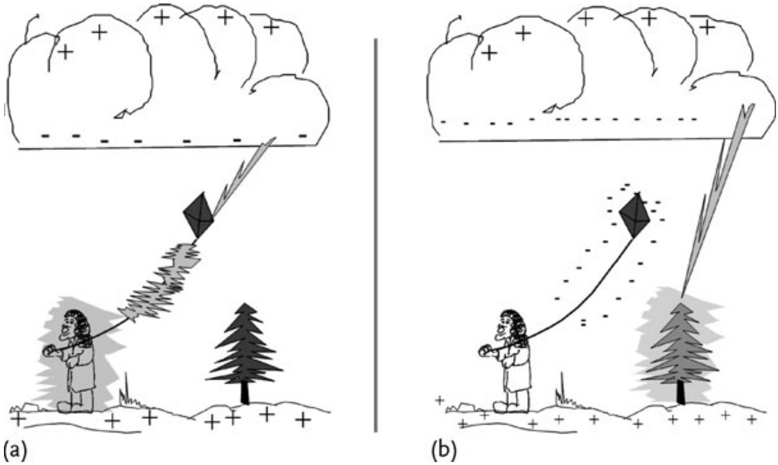


Figure 7.5 (a) How Benjamin Franklin is said to have discovered the connection between lightning and electricity. The combination of kite and metallic wire is the equivalent of a tall lightning rod. (b) Space charges provide a shield for the lightning rod, reducing the probability of strike on the tall conductor.

giant capacitor with the bottom charged negatively, and the top of the cloud positively. The ground itself has a positive polarity in the presence of the negatively charged bottom of the cloud. The atmosphere between cloud and ground is a good insulator, but it is not perfect. There is a small background of ions, free electrons created by ionization either from cosmic rays, or local field enhancement at sharp objects. This background becomes particularly intense in the presence of an electric field. Most of us will have experienced the hissing sound near high voltage installations: this is called the corona. The free electrons that are created are attracted by the positive charges, creating a negatively charged mantel or shield. This shield reduces the effectiveness of the lightning rod (Figure 7.5b). Standing with a needle in your hand, pointing towards a thundercloud, will not guarantee that you will be »zapped«. Space charges shield any conductor put in the atmosphere, reducing the probability of a strike along the conducting path.

7.2.2 Lightning Protection

Is there no hope of protecting our village church from the wrath of thunderstorms? The lightning rod should be put in place so rapidly as not to give time for the space charges to come in place. This

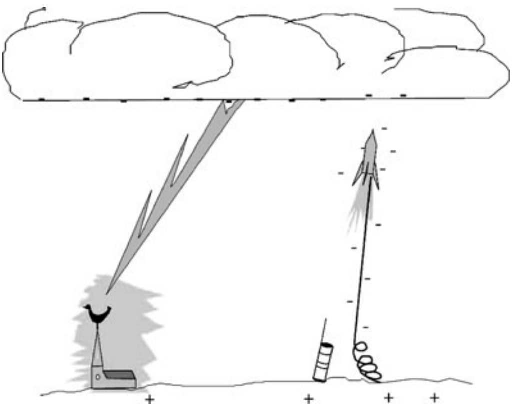


Figure 7.6 Sensors monitor the electric fields under a thundercloud. At the instant that an imminent strike is detected, a rocket is launched towards the developing flash, trailing a conducting wire. There is, however, a possibility that space charges shield the rocket, to the dismay of the rooster guarding the local church.

has led to the idea of the wire trailing rocket to trigger lightning. A small missile carries at its base a spool of thin wire that unwinds in flight. A rocket is fired towards a thundercloud, trailing the copper wire, as sketched in Figure 7.6. The speed of the rocket is of the order of 100 m/s. Unfortunately, the »shielding« electrons are even faster, traveling at 350 m/s.[44] The wire trailing rocket is a good research tool, having a success rate of 50–70% when fired in the right direction, at the instant that a lightning strike is in formation. When successful, the result can be spectacular, as witnessed by the picture of Figure 7.7. A first lightning flash follows the copper wire and creates a path of least resistance in the air. As the wind displaces and deforms the conductive path, successive strokes of the same flash occur within a fraction of second. Even as a research tool, the wire trailing rocket has its shortcomings. For instance, the glow from the vaporized copper wire will interfere with the spectral analysis of the lightning. This is not the ideal tool for the protection of golfers or rock concert audiences: what goes up must come down …

A modern Zeus, able to bend the power to thunderstorms to his will, has yet to appear. There is, however, hope that the laser will one day be a tool capable of diverting lightning. The challenges are, how-

44) That is assuming a local accelerating field of 50 kV/m and an electron mobility in air of $\mu_e = 7 \times 10^{-2}\,\text{m}^2/(\text{Vs})$.

Figure 7.7 Rocket triggered lightning. A first stroke follows the copper wire trailing the rocket. Successive strokes follow the conductive path blown away by the wind (from [21]).

ever, nonnegligible and so far there have been numerous unsuccessful attempts since the 1970s [22]. There was a series of attempts with CO_2 lasers in the early 1990s in Japan [23]. Such high power lasers can produce a plasma in air, but they produce at best a dotted line in the sky, rather than a continuous linear path of ionized air. For a long wavelength laser such as the CO_2 laser, it is the electric field of the laser itself that produces the ionization. In the time of an optical cycle, the electrical field of the laser itself is sufficient to accelerate a lone electron to the ionization potential of oxygen or nitrogen, ionizing it, creating in the process another electron that will be accelerated. This is called an avalanche process. In a few optical cycles of the laser, all the molecules of air will be ionized. This ionized volume is totally opaque to the laser light that produced it, and the laser cannot propagate further than the point it ionized. It is like constructing a complex robot whose first task is to turn itself off.

7.2.3 Laser Filaments to the Rescue

The solution to this problem is to use filaments [24], in the UV [21, 24] or in the near infrared [25]. As discussed above in Section 7.1, they create a weakly ionized trail over a long distance. While the CO_2 laser produced a conductivity as good as a metallic wire over a very short distance, the filaments provide a low conductivity over a long distance. Not only is the resistance of the filament generated wire high, but the wire itself is short lived. The electrons liberated by the ionizing filament attach to the oxygen molecule in a time of the order of nanoseconds, to form negatively charged oxygen ions. Because these ions are much bigger and slower than the electrons, the resistance of the filament wire increases a thousand fold. It takes a long time (tens of microseconds, which is an eternity in the world of lasers) for a lightning discharge to establish itself over hundreds of meters. By that time, some electrons will have attached to oxygen, others will have recombined with the positive ions created when the electrons was ejected, and the air will have become a near perfect insulator again!

There is, however, light at the end of the tunnel, with a scheme that has been proposed but not yet implemented [26, 27]. First, a high power laser (either UV, which can be nanosecond in duration, or near IR) sends a pulse towards the thundercloud; a pulse that will become a filament (Laser 1 in Figure 7.8a). The high power short pulse leaves a »plasma trail« of free electrons and positive ions behind (shown in light blue in Figure 7.8b), which are only going to live for several nanoseconds if nothing is made to save them. In (b), Laser 2 sends a long pulse (more than 10 μs) along the same path as the filament produced by Laser 1. If the wavelength of Laser 2 is short enough (less than 800 nm), the photons have enough energy to kick the electrons out of the negative oxygen ions. This process is called photodetachment, and will maintain a cloud of free electrons in the filament, thereby conserving the channel conductivity.

There are two effects that will subsequently contribute to the increase in density of the channel and its expansion towards the cloud and towards the earth, as sketched in Figure 7.8c. The first phenomenon is a »needle effect«. It is well known that, if a needle is put in a uniform electric field (for instance placed between two plates connected to the positive and negative of a voltage source), there will be a considerably more intense field at the tip of the needle than at any point in the space between the two plates. This is the situation with the filament, the earth (ground electrode), and the base of the cloud (positive electrode). Even if the filament is only weakly

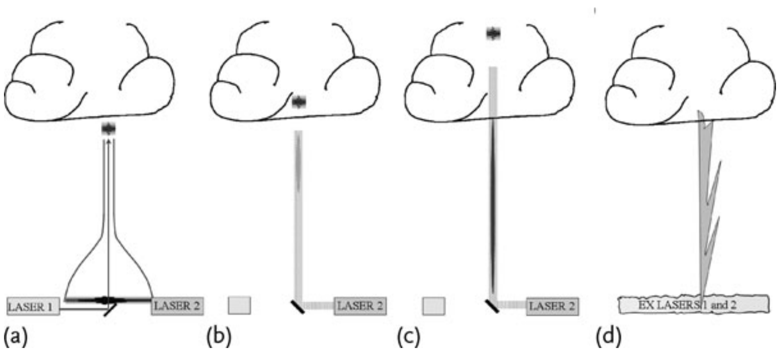


Figure 7.8 Pulse sequence to trigger lightning. (a) A powerful filamenting pulsed laser (Laser 1) is beamed towards a thundercloud. (b) The laser filament has created a weakly ionized needle shaped volume in the sky. Within a nanosecond after the ionizing pulse, a powerful visible laser (Laser 2; wavelength shorter than 750 nm) or a combination of a visible and an IR laser is sent along the path of the filament. The pulse duration of Laser 2 should exceed 10 μs. (c) Under the influence of the electrostatic field between cloud and ground, the needle of electrons expands and increases its density. Finally, as both ends of the needle reach the reservoir of charges that constitutes the cloud and ground (d), the lightning discharge is established.

conductive, the electric field at the tip of the needle is sufficient to accelerate some electrons to such a velocity that, when they collide with air molecules, they will ionize them, creating additional electrons. Numerical simulations [28] have shown that the density of electron increases (implying that the conductivity of air increases) and the »needle« of electrons and ions becomes longer, as sketched in Figure 7.8d. This effect is related to the static electric field between ground and cloud.

The other phenomenon that can increase the channel density is associated with the field of the laser beam that co-propagates with the filament. We have seen that the electric field of a laser can accelerate electrons that have been ionized (Sections 1.8 and 6.1). Even a low intensity beam will have an effect on an electron cloud. At each half period of the laser light, electrons will increase their average velocity. To this average velocity corresponds an average kinetic energy, which can also be translated as a »temperature« of the electron cloud. The increase with time of the average electron energy caused by a constant intensity laser beam is called inverse Bremsstrahlung.[45] The longer the wavelength of the laser, the faster the plasma heats. As the average electron energy increases, more electrons will have enough energy to create other electrons by collision with molecules of air. Ultimately, all the molecules in the needle can be ionized, given a sufficient long irradiation at high enough intensity. Under the combined effect of the static electric field and the field of the long pulse laser, the electron cloud will connect the base of the cloud and the ground, resulting in a lightning discharge.

For successful lightning protection, the lasers should induce lightning at a tenth or twentieth of the natural breakdown field in air. This requires putting several lasers in the field simultaneously, in adverse

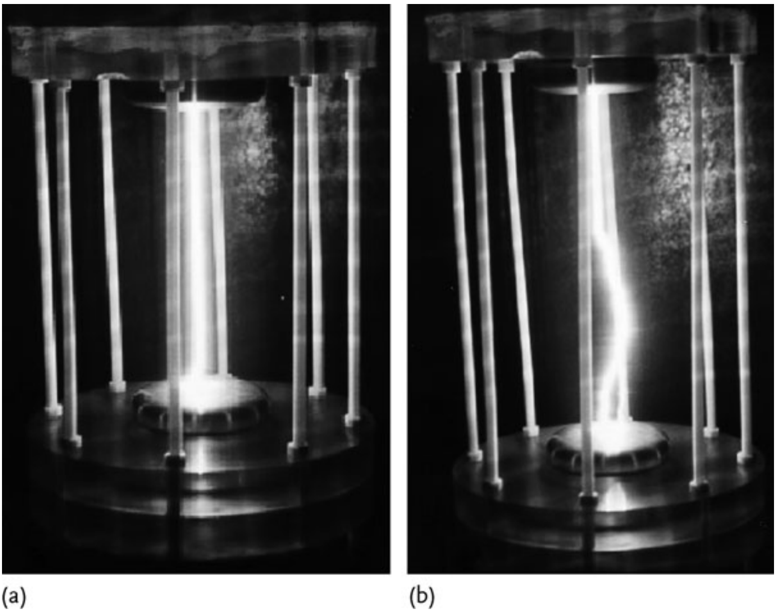


Figure 7.9 Two examples of UV laser-induced discharge with ps filaments at 250 nm. The UV laser passes through two profiled holes in the center of the electrodes. (a) The filament starts near the bottom electrode and the discharge is guided over the full length. (b) The filament starts half way between the electrodes.

45) The name is derived from the opposite effect. As electrons decelerate (»bremsen« in German), they emit radiation (Strahlung in German), hence the name »Bremsstrahlung« for that emission. See Section 6.2.

conditions that most lasers are not built to sustain, and the accurate combination and synchronization of several beams. These tests have not been performed yet. However, laboratory tests [29] confirm the improved laser triggering achieved by associating to the filament a long pulse co-propagating visible laser for photodetachment of O_2^-. These tests were made with the »Teramobile« laser, so called because it produces terawatt pulses (10^{12} W) and is on a mobile platform (a trailer). The pulse duration is $\approx$ 200 fs for a pulse energy of 200 mJ, at the near IR wavelength of 800 nm. With pulses of 100 times less energy in the UV (250 nm) and 1 ps duration, lightning discharge can be triggered at atmospheric pressure at 1/5 of the self-breakdown voltage of air for gap between electrodes of 60 cm, as shown in Figure 7.9. The light is sent through a hole between electrodes, from bottom to top. The discharge is a straight line when the filament starts near the bottom electrode (Figure 7.9a). The guided portion of the discharge is only on the top half of the interelectrode spacing where the filament starts in Figure 7.9b.

7.3 Laser Tazer–Teaser

If laser can make a conductive path in air, maybe this can be exploited for some other means. This section starts like a fairy tale.

Once upon a time there was a leader from a powerful country, supreme leader Foliage,[46] who had a near panic fear of protesters. Any crowd of demonstrators was to be kept 2 miles away from his passage. But that was not sufficient to alleviate his fears. Was there not a better way to get rid of these people who believed that they could gather and shout their opinions in the streets? Machine gunning them? That was not an option – something in the constitution was against that, and also not »politically correct«. Out of the search for a solution was born a powerful agency: the »Nix the troublemaker by any resource« (NTAR) designed to find means to fight crowds, without killing anyone, an action that would have made supreme leader Foliage unpopular. Filaments seemed to offer a first attractive means, and large contracts were given to academic researchers to determine if the pain inflict-

46) This is fiction: any resemblance with any living or deceased person is pure coincidence.

ed by a filament on the skin was sufficient to disperse a crowd. The answer was negative, but the laser-induced lightning inspired another approach: remote »zapping« with high voltage discharge guided by the laser beam. Not only would the protesters be eliminated for the duration of the mandate of the leader, but it would eliminate the worse elements in one stroke: those that are holding hands! Millions of dollars from the agency and private investors were given to private contractors (university academicians were not to be trusted for such research) who devised giant Tesla coils associated with a laser. If it succeeded, it would be a classified information. If it did not, that would be an even higher level of classification …

Should we expect to see every policeman or policewoman armed with a laser tazer gun one day? There would be no advantage over the traditional firearm. The applied voltage and capacitance required to sustain a discharge would need to be much higher than what is used in the electrical chair. In addition, even if incredible progress is made in miniaturization, the weight of the equipment would surely incapacitate the strongest law enforcer. The prospect of having a portable »laser gun« capable of killing an assailant is even more improbable. »Laser guns« are used as target markers in war games. It is better that it stays that way … as a game.

References

1 Braun, A., Korn, G., Liu, X., Du, D., Squier, J., and Mourou, G. (1994) Self-channeling of high-peak-power fs laser pulses in air. *Opt. Lett.*, **20**, 73–75.

2 Zhao, X.M., Rambo, P., and Diels, J.C. (1995) Filamentation of femtosecond UV pulses in air, in *QELS, 1995*, Vol. 16, Optical Society of America, Baltimore, MA, p. 178 (QThD2).

3 Akhmanov, S.A., Sukhorukov, A.P., and Khokhlov, R.V. (1966) Self focusing and self trapping of intense light beams in a nonlinear medium. *Sov. Phys. JETP*, **23**, 1025–1033.

4 Akhmanov, S.A., Sukhorukov, A.P., and Khokhlov, R.V. (1967) Development of an optical waveguide in the propagation of light in a nonlinear medium. *Sov. Phys. JETP*, **24**, 198–201.

5 Shen, Y.R. and Loy, M.M. (1971) Theoretical interpretation of small-scale filaments of light originating from moving focal spots. *Phys. Rev. A*, **3**, 2099–2105.

6 Freysz, E., Afifi, M., Ducasse, A., Pouligny, B., and Lalanne, J.R. (1984) Critical microemulsions as optically nonlinear media. *J. Opt. Soc. Am. B*, **1**, 433.

7 Brodeur, A., Chien, C.Y., Ilkov, F.A., Chin, S.L., Kosareva, O.G., and Kandidov, V.P. (1997) Moving focus in the propagation of ultrashort laser pulses in air. *Opt. Lett.*, **22**, 304–306.

8 Dubietis, A., Gaisauskas, E., Tamosauskas, G., and Trapani, P.D. (2004) Light filaments without self-channeling. *Phys. Rev. Lett.*, **92**, 253903-1–253903-5.

9 Couairon, A. and Mysyrowicz, A. (2007) Femtosecond filamentation in transparent media. *Phys. Rep.*, **441**, 49–189.

10 Loriot, V., Hertz, E., Fauchet, O., and Lavorel, B. (2009) Measurement of high order Kerr refractive index of major air components. *Opt. Express*, **17**, 13439–13434.

11 Hauri, C.P., Kornelis, W., Helbing, F.W., Heinrich, A., Couairon, A., Mysyrowicz, A., Biegert, J., and Keller, U. (2004) Generation of intense, carrier-envelope phase-locked few-cycle laser pulses through filamentation. *Appl. Phys. B*, **79**, 673–677.

12 Chalus, O.J., Sukhinin, A., Aceves, A., and Diels, J.C. (2008) Propagation of non-diffracting intense ultraviolet beams. *Opt. Commun.*, **281**, 3356–3360.

13 Schillinger, H. and Sauerbrey, R. (1999) Electrical conductivity of long plasma channels in air generated by self-guided femtosecond laser pulses. *Appl. Phys. B*, **68**, 753–756.

14 Rairoux, P., Schillinger, H., Niedermeier, S., Rodriguez, M., Ronneberger, F., Sauerbrey, R., Stein, B., Waite, D., Wedeking, C., Wille, H., Woeste, L., and Ziener, C. (2000) Remote sensing of the atmosphere using ultrashort laser pulses. *Appl. Phys. B*, **71**, 573–580.

15 Fisher, M., Siders, C., Johnson, E., Andrusyak, O., Brown, C., and Richardson, M. (2006) Control of filamentation for enhancing remote detection with laser induced breakdown spectroscopy, in *Proc. SPIE*, 6219, p. 621907.

16 Mirell, D., Chalus, O., Peterson, K., and Diels, J.C. (2008) Remote sensing of explosives using infrared and ultraviolet filaments. *J. Opt. Soc. Am. B*, **25**, 108–111.

17 Kithil, R. (1999), National lightning safety institute (NLSI) lightning losses in the USA: Lightning's social and economic costs. http://www.lightningsafety.com/nlsi_lls/sec.html. Last access: December 2010.

18 Christian, H.J., Mazur, V., Fisher, B.D., Ruhnke, L.H., Crouch, K., and Perala, R.P. (1989) The Atlas/Centaur lightning strike incident. *J. Geophys. Res.*, **94**, 169–177.

19 Newcott, W.R. (1993) Lightning – Nature's high-voltage spectacle. *Nat. Geogr.*, **184**(1), 80–103.

20 Miyake, K., Suzuki, T., Takashima, M., Takuma, M., and Tada, T. (1990) Winter lightning on japan sea coast – lightning striking frequency to tall structures. *IEEE Trans. Power Deliv.*, **5**, 1370–1376.

21 Diels, J.C., Bernstein, R., Stahlkopf, K., and Zhao, X.M. (1997) Lightning control with lasers. *Sci. Am.*, **277**, 50–55.

22 Koopman, D.W. and Wilkerson, T.D. (1971) Channeling of an ionizing electrical streamer by a laser beam. *J. Appl. Phys.*, **42**, 1883–1886.

23 Uchida, S., Shimada, Y., Yasuda, H., Motokoshi, S., Yamanaka, C., Yamanaka, T., Kawasaki, Z., Tsubakimoto, K., Ushio, T., Onuki, A., Adachi, M., and Ishikubo, Y. (1999) Laser triggered lightning experiments in field experiments. *J. Opt. Technol.*, **66**, 199–202.

24 Zhao, X.M., Diels, J.C., Braun, A., Liu, X., Du, D., Korn, G., Mourou, G., and Elizondo, J. (1994) Use

of self-trapped filaments in air to trigger lightning, in *Ultrafast Phenomena IX* (eds P.F. Barbara, W.H. Knox, G.A. Mourou, and A.H. Zewail), Springer Verlag, Berlin, Dana Point, CA, pp. 233–235.

25 Kasparian, J., Ackermann, R., André, Y.B., Méchain, G., Méjean, G., Prade, B., Rohwetter, P., Salmon, E., Stelmaszczyk, K., Yu, J., Mysyrowicz, A., Sauerbrey, R., L.Wöste, and Wolf, J.P. (2008) Electric events synchronized with laser filaments in thunderclouds. *Opt. Express*, **8**, 5758–5763.

26 Zhao, X.M., Diels, J.C., Wang, C.Y., and Elizondo, J. (1995) Femtosecond ultraviolet laser pulse induced electrical discharges in gases. *IEEE J. Quantum Electron.*, **31**, 599–612.

27 Rambo, P.K., Schwarz, J., and Diels, J.C. (2001) High voltage electrical discharges induced by an ultrashort pulse UV laser system. *J. Opt. A*, **3**, 146–158.

28 Zhao, X.M., Rambo, P., Diels, J.C., and Elizondo, J. (1995) Effect of oxygen in laser triggering of lightning, in *CLEO, 1995*, Optical Society of America, Baltimore, MA, pp. 182 (CWE2).

29 Mejean, G., Ackermann, R., Kasparian, J., Salmon, E., Yu, J., and Wolf, J.P. (2006) Improved laser triggering and guiding of megavolt discharge with dual ns pulses. *Appl. Phys. Lett.*, **88**, 021101.

8
Laser Sensors

A musician is well aware of the effect of heat and force on his/her musical string. Special care and attention is given at the beginning of a performance to tuning the instruments to the same frequency. Laser light is generated in a resonator like a musical note, but with higher precision. The laser frequency and intensity changes if the resonator is modified. Just as in the case of the musical instrument, the laser also can be »tuned« to the »master diapason«, which, in the case of optics, is a reference frequency provided by an atomic transition (see Section 5.4.1). The absorption of laser light is also modified in a passive cavity (or resonator). Laser can sing and sense the change in their propagating medium. This chapter is about the sensing song of a laser.

8.1 Passive Sensors

The conventional laser sensor is generally based on resonator properties. For the purpose of illustration, let us consider a Fabry–Pérot cavity, that is, a resonator made of two parallel mirrors. Unlike the »laser body« defined in Section 1.3.3, there is no gain medium in the passive resonator discussed in this section. As the light rattles back and forth between the two mirrors, we know that the wave will continuously add to itself if the spacing between the two mirrors is an integer number of wavelengths. It is said that the resonator is at resonance. *Independently* of the mirror reflectivity, the transmission, in the condition of resonance, is always unity, provided that there is no loss or absorption in the space between the two mirrors.

The reflectivity of the mirrors does matter, however: the higher the mirror reflectivity, the longer the (injected) wave circulates in the resonator. Recapping Chapter 1, Section 1.3.3, we have seen that the

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

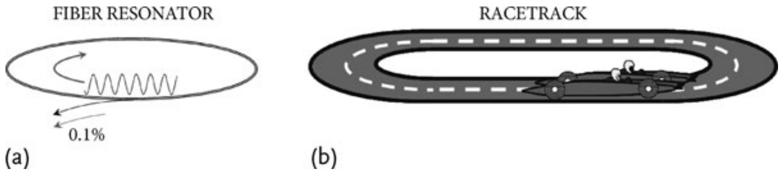


Figure 8.1 (a) A fiber ring resonator, where a counterclockwise circulating wave has been inserted. The wave is resonant with the fiber perimeter, that is, adds in phase to itself at each round trip. The only loss of that resonator is a 0.1% output coupler. It can easily be calculated that a laser intensity put in circulation in the ring will drop to 1/2 of its initial value after 693 round trips. The »Q-factor« of that resonator is the ratio of the »photon lifetime« $693 \times t_{RT}$ to the light oscillation period $T = 1/\nu$ (T is the smallest resolved difference between two waves racing through the ring). (b) Analogy of the racetrack, in which two cars are racing. The analogy of the photon lifetime is the time it takes to empty a gas tank. The smallest resolvable time of arrival difference is the time it takes for the car to move by a wheel diameter. The »Q-factor« definition of the fiber resonator can be used here also. The higher the Q-factor, the smaller the difference in velocity between the two racing cars that can be resolved.

higher the reflectivity, the longer the distance that the laser wave travels between the mirrors (an average of $N_{RT} = 693$ round trips when the mirror reflectivity is 100 and 99.9%). The same applies to a ring resonator, for instance a fiber ring as sketched in Figure 8.1a, where the light loses (as in the previous example of a linear cavity) 0.1% to the external world at each round trip (for instance, through a coupler). It takes a time $t_{life} = 693 \times t_{RT}$ (often called photon lifetime) for the power stored in the ring to drop to half of its initial value. One defines a »quality factor« or »Q factor« of a resonator (any resonator) as the product of the frequency of the radiation ν by the cavity decay time t_{life}.

One may wonder at this point how these considerations relate to sensors. As »resonant« light travels around the ring at the speed of light c/n (where n is the index of refraction of the medium in the ring), it can survive for a time t_{life} only because at each round trip the wave adds constructively to itself. The wave may cancel itself after a few round trips if there is a small change of refractive index causing a change in wave velocity. The smallest change in index of refraction (or in wave velocity) that can be resolved is such that the slower wave lags behind the faster by one light period, after a time t_{life}. This is equivalent to saying that the resonator can sense a change of index of refraction of n/Q.

The situation is analogous to a car race on a ring racetrack (Figure 8.1b). In the latter case, t_{life} is the time that the car can race with a full tank. Let us assume this corresponds to 693 lapses. The analogy of the light period $T = 1/\nu$ is the smallest difference in arrival time that can be resolved. Assuming that the smallest difference between the race cars on the finish line is the diameter D of a wheel (which will be the correspondent of the wavelength in this analogy), the analogy of the light period is $T = D/v$ where v is the car velocity of the fastest racing cars. As in the optical resonator, the smallest difference in velocities between the two cars that can be resolved is such that the slower car lags behind the faster by a wheel diameter after the time t_{life} to cover 693 lapses. This difference is $\Delta v = v \times T/t_{life} = v/Q$, which is exactly the same expression as for the optical ring resonator $\Delta(c/n) = c/(nQ)$. Q for the car analogy is the ratio of the full distance run by the cars to the wheel diameter. For a racetrack of 900 m perimeter, a wheel diameter of 0.6 m, the Q of the racetrack is $693 \times 900/0.6 \approx 1$ million. For a fiber resonator such as in Figure 8.1a of 1.5 m perimeter and a wavelength of 1.5 μm, the resonator Q-factor is 693 million.

Sensors are based on change of wave velocity in the resonator (for instance, by changing the index of refraction) or a change in absorption. The change in absorption is also amplified by the number of round trips. For instance, in our previous example, if the wave is attenuated by 1 ppm (one part per million, which is not measurable) in one round trip, the overall transmission of the resonator we choose as an example, instead of being 1, will be changed by 0.1%, which is quite measurable. The higher the »Q« of a cavity, the more sensitive its transmission will be to a minuscule absorption.

8.1.1 Various Types of Cavities

Resonators can take many different forms. They can be a Fabry–Pérot resonator, or a ring resonator, or a sphere. Surprisingly, the same general trend applies in space as in time. We have seen that the most accurate and precise clock, even over long time spans, ticks at the shortest period (atomic clocks). Similarly, the highest »Q« resonators are not large structures, but microresonators of dimension close to the wavelength.

8.1.1.1 The Raindrop as an Optical Resonator

The first microresonator is as old as the earth and is the major tourist attraction of Belgium: the raindrop. However, the latter had to be exported to sunny New Mexico to gain an understanding of the complex optical phenomena that can occur in a raindrop. An optical ray that is at grazing incidence with a spherical raindrop may be trapped and suffer continuing total internal reflection inside the droplet. The phenomenon has been known for centuries in acoustics and has been exploited in numerous constructions. A famous example is the whispering wall surrounding the Temple of Heaven near Beijing, shown in Figure 8.2a. A whispering voice launched along the wall, can be heard on the diametrically opposite location of the wall, the sound having traveled along the inner wall.

8.1.1.2 Monitoring the Size of an Evaporating Droplet

The first laser sensor based on a microresonator consisted simply of a He-Ne laser, a water droplet, and a detector. In the case of a water droplet [1], the whispering voice can be a He-Ne laser beam, of which a small fraction can be trapped inside the droplet (Figure 8.2b). A resonance condition exists if the droplet perimeter contains an exact integer number of wavelengths, and the radiation can exist for a large number of round trips. Some light will be backscattered in the direction of the incident light. The resonance condition can be ob-

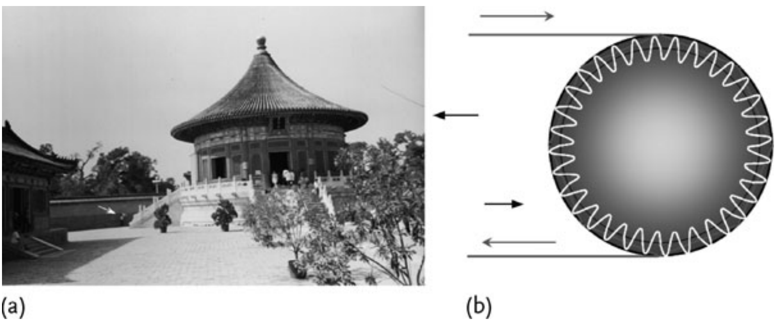


Figure 8.2 (a) The Temple of Heaven near Beijing with the whispering wall in the background. The little umbrella (white arrow) hides a lady whispering to her friend at the diametrically opposite side of the wall, not in sight since he is behind the camera. (b) The whispering gallery mode in a water droplet: a light ray incident from the upper left is trapped and bounces inside the sphere by total internal reflection. Some wavelengths are resonant with the perimeter of the sphere and are trapped for a very large number of round trips.

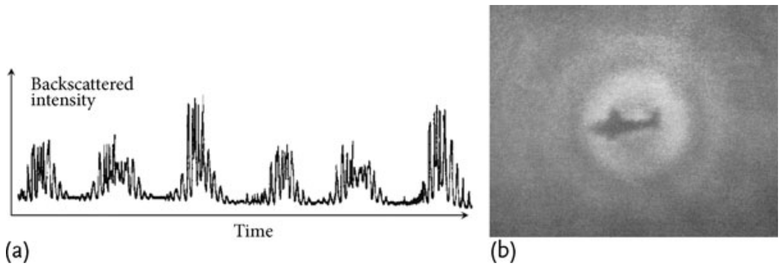


Figure 8.3 (a) Recording of the backscattered light from a single water droplet, as a function of time. As the droplet evaporates, its diameter shrinks, and the light goes to successive resonances with the perimeter of the droplet. Narrow resonance corresponds to the whispering gallery mode resonance: the linewidth and spacing between the peaks indicate at least 100 round trips. (b) Glory seen surrounding the shadow of a plane over a cloud layer (courtesy of Howard Bryant, adapted from [1]).

served by monitoring the light reflected back from the droplet. As the droplet evaporates, its perimeter decreases, going through successive resonances, which are seen as increases in backscattered intensity. These resonances can be used to monitor the diameter of the water droplets, and, eventually, their pollution! Figure 8.3a shows a portion of such a recording. The broad maxima correspond to a difference in perimeter of a wavelength. The grouping of very narrow resonances is more interesting. The successive narrow peaks are separated by 1/100 wavelengths, indicating that they correspond to resonances of 100 cycles.

Sunlight is not monochromatic, but, as all wavelengths are combined, the backscattering results in a well known phenomenon: the glory. The glory was seen mostly in mountains, as a colored ring surrounding the shadow of one's head, projected in a fog bank below. Today, it is most often seen surrounding the shadow of a plane flying above a cloud layer, as shown by the photograph in Figure 8.3b. A complete description of the glory is beyond the scope of this book, since it involves not only the whispering gallery resonance, but also the fact that the backscattering is issued from multiple light »rings« (the annular edge of the droplets), which interfere with each other. The interferences of these rings cause the concentric ring structure of the glory. A complete description of this effect can be found in reference [1].

8.1.1.3 Man-Made Microresonators

There are of course »man-made« versions of the raindrop as resonator. These are crystalline or glass (silica) microspheres, integrated semiconductor microrings/microdisks, silica microtoroids, with Q-factors ranging from 1 million to 10 billion. They are presently a hot topic of fundamental research, with promises of applications in numerous fields. Figure 8.4 shows some examples of microcavities and a list of related research and applications. A discussion of the numerous applications contemplated is beyond the scope of this book. We refer to a few selected citations: for communications [2], plasmonics [3], biosensing [4], quantum optics [5], quantum computation [6], optomechanics [7–9], metrology [10], microwave photonics [11], and narrow linewidth microlasers [12].

We alluded to some mechanical effects of light in Section 1.8. For instance, radiation exerts a pressure on a mirror as it is reflected, a smaller push than that given by a flee crashing onto the mirror. For the photon, the mirror is a huge mass, hence a huge inertia as compared to the photon momentum $h\nu/c$. In Section 1.8 we made the radiation pressure take large values for an exceedingly short time by increasing the laser power to gigantic proportions. Another approach to make the radiation pressure felt is to reduce the size and mass of the mirror that the photons are bouncing off. The microresonator of a high Q-factor increases the number of photons in a confined space, resulting in radiation pressure forces that can be felt by ultralight structures in

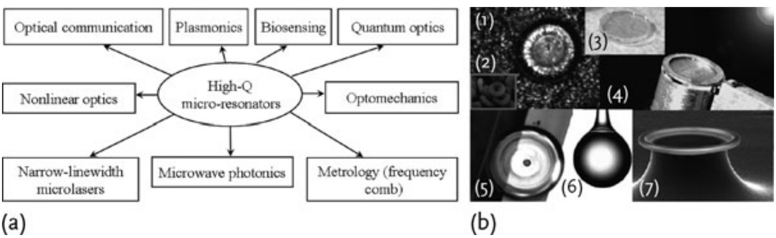


Figure 8.4 (a): fields that are impacted by microcavities. (b) Examples of microcavities. (1) A free silica microtoroid (20 μm diameter) on a silicon chip compared to the size of red blood cells (2), (3) A 2 mm diameter $LiNbO_3$ disk, (4) A prism coupled $LiNbO_3$ microdisk modulator (with the RF ring resonator on top), (5) A free silica microtoroid coupled to a silica fiber-taper, (6) A silica microsphere, and (7) A silica microtoroid on a silicon pillar (courtesy of Professor Mani Hossein-Zadeh of the Center for High Technology Materials at the University of New Mexico).

or near the microresonator. This interaction has led to the new field of »optomechanics«.

8.1.1.4 Micromechanical Forces

The mechanical action of a laser beam is not limited to pushing (as in Section 3.8.2), it can also twist. Circularly polarized light (cf. Section 1.2.2) corresponds to an electric field spinning around the light ray at a rate of the light frequency. Right-circular polarization will spin to the right and left-circular polarization will spin to the left. The photon can be seen as an elementary bullet spinning about the axis of propagation. Rifles use spin-stabilized bullets: the barrel's rifling imparts spin to the bullet as it passes through the bore, a rotation meant to stabilize the bullet in flight. Indeed, we know that angular momentum is conserved, so the spinning motion of the bullet will tend to maintain its axis pointing towards the direction of propagation. As the bullet hits a body, its momenta are exchanged with the target: the linear momentum producing a recoil (the equivalent of radiation pressure $h\nu/c$ for the photon) and the angular momentum producing a torque. The same phenomena of momenta exchanges occur at the source: the gun experiences a recoil when fired and a torque in the opposite direction to that of the spin. The angular momentum L and the kinetic energy K of an object of mass m spinning at a distance r from an axis, at a rate of f turns/second,[47] are, respectively, $L = m(2\pi f)r^2 = m\Omega r^2$ and $K = m(2\pi f)^2 r^2 = m\Omega^2 r^2$. The photon is the ultimate elementary bullet: despite the fact that it has no mass, it has a linear momentum (mv for the bullet) which is $h\nu/c$, and, as any spinning bullet, an angular momentum $h/2\pi$. One may wonder whether the angular momentum of a circularly polarized laser pointer may give some strange sensation to its user. Would it act as a gyroscope, moving the beam sideways when one wants to move the spot downwards? Or would one feel a recoil torque on the laser when turning on the laser? To get a sense of the magnitude of the angular momentum of light, let us imagine a green laser pointer emitting circularly polarized light, as in Figure 8.5a. To the angular momentum $Nh/(2\pi)$ (where N is the number of photons) corresponds the kinetic

47) $\Omega = 2\pi f$ is the angular frequency, in rad/s.

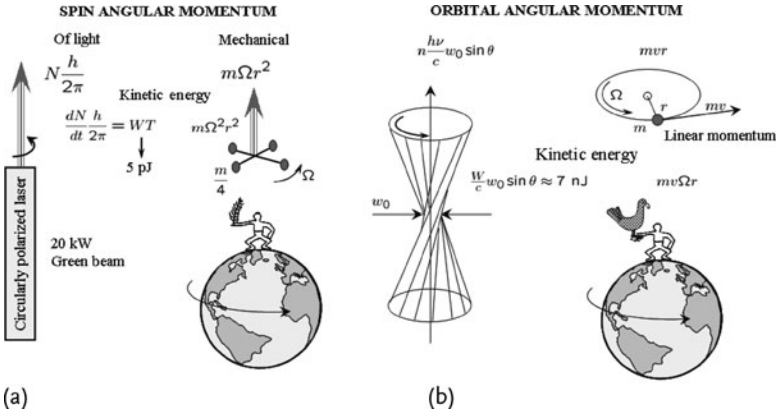


Figure 8.5 (a) What is the angular momentum associated with a circularly polarized green laser pointer of 20 kW power? The angular momentum of the beam is the value per photon ($h/(2\pi)$) times the number of photons N. The kinetic energy, the rate of change of angular momentum, is equal to the product of the laser power W by the light period $T \approx 1.5$ fs divided by 2π. This kinetic energy is that of a 1 g feather on a 1 m arm, spinning at the rate of 1 turn/day! (b).

energy of:

$$\frac{dN}{dt}\frac{h}{2\pi} = \frac{d(Nh\nu)}{dt}\frac{1}{2\pi\nu} = \frac{WT}{2\pi}\,, \tag{8.1}$$

where W is the laser power and $T \approx 2$ fs the period of the laser light oscillation. Even with a laser pointer of 20 kW power (!!), we find that the kinetic energy associated with all the photons spinning in the same direction is only … $5 \cdot 10^{-12}$ J. The mechanical system with the same kinetic energy would be a mass of 1 g, held at arms length (1 m) by a man (or polar bear) standing at the North Pole (hence a rotation rate of $\Omega = (2\pi \text{ rad})/\text{day} = 0.00007$ rad/s). In microresonators where similar powers circulate, that kinetic rotational energy is concentrated in a volume of the order of a μm^3, thus an energy density of 5 J/cm^3, quite sizable for a micromechanical structure.

It is possible to engineer a laser beam with much larger angular momentum by having the rays skewed with respect to the propagation direction, as shown in Figure 8.5b. The envelope of the ray form a hyperboloid, the same as can be obtained by attaching string to two circular bases and twisting the two circles as the bases are pulled apart. The class of beams made of rays that twist around the axis of propagation has been called »Laguerre modes«, which is a different family to the »Gaussian modes«, usually emitted by a laser, that were referred to in Chapter 1. The linear momentum of the photon $h\nu$ has a component $h\nu \sin\theta$ in the plane normal to the propagation axis (which makes an angle θ with the light rays). The linear momentum times the arm w_0 (the radius of the beam at the waist) is an angular momentum, dubbed »orbital angular momentum«, considerably larger than the momentum due to the photon spin. For the example of a 20 kW laser, an angle of 6° and a beam radius of 1 mm, the kinetic energy of such a beam $W w_0 \sin\theta / c$ corresponds to $7 \cdot 10^{-9}$ J. The mechanical correspondent is our North pole experimentalist holding a 1.3 kg bird at arms length, rather than just one feather.

It is not conceivable that the kinetic energy associated with the rotation of a feather rotating about an axis at the rate of one turn/day would be measurable. The »precision of light«, however, is such that the faintest forces are perceived. The minuscule angular momentum of the photon was measured 24 years before the appearance of the first laser by Beth [13]. We saw in Section 1.16 that the polarization of light can be changed from linear to elliptical to circular with birefringent material or wave plates. A half wave plate will change right circular polarization into left circular polarization. In a similar manner as a mirror gets a recoil from the momentum of the light that bounces off it, the half wave plate having switched the direction of rotation of the electric field will experience torsion by reaction. The torque applied by circular polarized light on a wave plate (half wave) that converts it from right circular to left circular was measured by suspending the wave plate on a thin wire, creating a very sensitive »torsion pendulum« [13].

8.1.1.5 Tunneling of Light

The higher the »*Q*« of a microresonator, the more difficult it is for light to escape, but also, the more difficult it is to insert light into it. How can one, for instance, insert light into a perfect toroid such as the one depicted in Figure 8.4b? We saw in Section 6.1 that electrons are trapped in a »potential barrier«, which prevents them from escaping from the atom. The very high electric field of fs pulse can make them traverse this »potential wall«, not unlike Harry Potter traversing a brick wall to go to his train platform. This phenomenon is called »tunneling« in physics and also exists in optics. In optics, tunneling is called »frustrated total internal reflection« or »evanescent wave coupling«.

We saw in Section 1.4.4 that if a light ray is incident on an interface between a medium of high index of refraction n_2 and a lower index n_1 there will be a critical angle of incidence α_{cr} beyond which no light is transmitted and all light is reflected by the interface (hence the name »total internal reflection«). The critical angle is given by $\sin \alpha_{cr} = n_1/n_2$. One would think that interface is an impenetrable barrier. There are different physical phenomena that show this not to be totally the case. One of these is the »tunneling« of the light through the barrier if another interface is approached. Figure 8.6a shows a beam reflected at a total internal reflection interface of a prism. The electric field »leaks« a little through the interface, as sketched by the graph of the field exponentially decaying with distance from the interface. The decaying field on the low index side is called the »evanescent wave«. The penetration depth of the field in the low index medium depends on the angle of incidence, which is largest close to the critical angle. In most practical cases, the evanescent wave does not penetrate deeper than half a wavelength into the low index medium. If an identical prism is approached within range of the evanescent wave, the beam »tunnels« through the double interface, as shown in Figure 8.6b. The transmission factor increases with decreasing distance between the prism (Figure 8.6b), to become 100% when the two interfaces merge (optical contact). In addition to the distance between

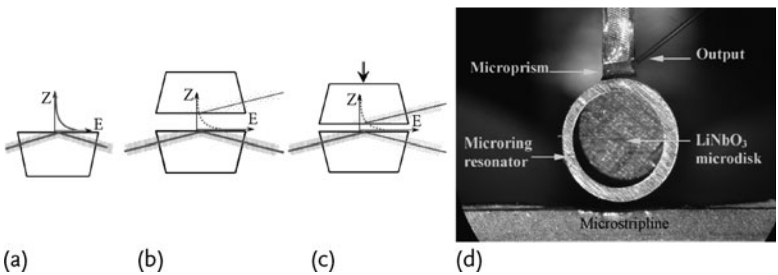


Figure 8.6 (a) Total internal reflection prism. The curve shows the exponential decay in amplitude of the evanescent field as a function of distance from the total reflecting interface. (b) As an identical prism is approached, part of the radiation »tunnels through« the barrier of the interfaces. There is a gradual increase of the transmission (and a corresponding decrease of the reflection) as (c) the prisms are brought closer together, to reach total transmission when they are in contact. This »tunneling« is been used to form continuously adjustable beam splitters [14]. (d) The evanescent wave of a microstripline pumps resonant radiation into the microring. In turn, the intensity in the microring is monitored by letting a small amount tunnel into the microprism (adapted from [11]).

prisms, other parameters affecting the transmission are the polarization, the angle of incidence, and the index of refraction of the prism. It was realized soon after the discovery of the laser that this effect had application in making adjustable beam splitter of relatively high damage threshold [14]. A simple beam splitter can be made by depositing two subwavelength thick layers of chromium on the edges of the interfaces facing each others in Figure 8.6b or c, and applying pressure (with a screw) in the middle of the opposing face of the prism. The elastic bending of the prism (it is elastic, for the displacements are less than 100 nm) brings the two interfaces closer to each other.

Frustrated total internal reflection is the main mechanism used to couple light into and out of microresonators, such as shown in Figure 8.6d. The light is fed into the resonant microring through the evanescent wave from a microstripline. The amount of light circulating in the resonant ring is sampled by tunneling a sampling of the power circulating in the ring into a nearby prism.

8.1.2 Laser Beams to Measure Elongation and Distances

We have seen (Section 3.9) that short pulse lasers can be used as a radar, for three-dimensional imaging of the eye, for instance. These techniques are limited in resolution by the length of the optical pulse rather than the wavelength. Since the meter is defined through the speed of light and the frequency of a laser locked to an atomic standard, one would expect the most accurate measurements of length to be made by a laser. A standard instrument to measure distance with a single frequency laser is the Michelson interferometer, which

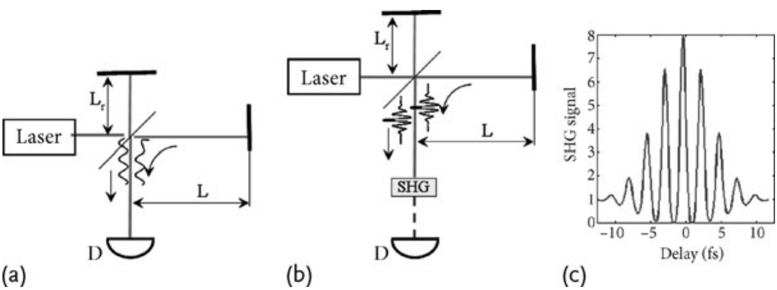


Figure 8.7 (a) The Michelson interferometer. (b) The interferometric autocorrelator to measure distances with a frequency comb. (c) Interferometric autocorrrelation of a 800 nm pulse of 6 fs duration.

is sketched in Figure 8.7a. A detector looks at the reflection of an object, located at a distance L and combines it with the reflection of a reference mirror at a distance L_r. If the distances L and L_r are equal, a bright signal will appear on the detector. If the mirror L_2 is moved by one quarter of a wavelength, the difference distance is then a half wavelength; the two reflections make destructive interference, resulting in a minimum signal on the detector D. Thus any change in distance *within* a quarter wavelength increment can be unambiguously resolved. The difficulty is, however, to determine the number of quarter wavelength differences in the difference $L - L_r$.

8.1.2.1 Frequency Combs to Measure Distances

The solution to resolving the ambiguity of the return signal provided by the Michelson interferometer is to use a frequency comb and apply a technique called »interferometric autocorrelation« [15]. The interferometric autocorrelation consists essentially of a Michelson interferometer such as sketched in Figure 8.7a, but with a nonlinear crystal that doubles the optical frequency as a detector (see Section 1.11.1). The amplitude of the optical oscillation at the doubled frequency is proportional to the square of the amplitude of the oscillation at the fundamental frequency. The detector D detects the intensity of the second harmonic, with the quantity proportional to the square of the second harmonic field. If the electric fields from both arms of the Michelson interferometer are equal, and the difference in optical path $\Delta L = L - L_r$ is zero, the second harmonic field will be proportional to the square of the fundamental electric field entering the nonlinear crystal, or $(2\mathcal{E})^2 = 4\mathcal{E}^2$. The intensity seen by the second harmonic detector being proportional to the square of the field, will be proportional to $(4\mathcal{E}^2) = 16\mathcal{E}^4$. As the optical delay of the reference arm is being changed, there will be successive constructive and destructive interferences of the »reference« and »signal« arms, until the two pulses no longer overlap. From that delay on, the second harmonic intensity will be twice the contribution from each pulse, hence it will be proportional to $2\mathcal{E}^4$. For ultrashort pulses, each individual fringe of the interferometric autocorrelation between the sample and reference position mirrors can be identified without any ambiguity, as shown in Figure 8.7c. The range of the translation of the reference delay does not need to exceed the distance between two successive pulses of the comb! [16]. For a well characterized comb, the position of each successive oscillation of the optical field, within the pulse envelope, is well known from one pulse to the next. It should be noted that this method requires a stabilized frequency comb and is limited by amplitude noise and the dynamic range of the detector.

8.1.3 The Fiber Optical Gyroscope (FOG)

There is a property other than the absorption that is exploited in resonators: the length of the resonator. In a high Q cavity the wave adds to itself over a very large number of round trips. A small change in either the cavity length or the radiation wavelength, and the wave may not add constructively to itself after a large number of round trips, which again implies a loss of transmission. This resonator property is exploited in the fiber laser gyroscope (FOG), which is a ring resonator made with optical fibers.

The FOG is a relatively recent implementation of a century old instrument: the Sagnac interferometer [17, 18]. This device, sketched in Figure 8.8, was presented as a proof of the existence of ether, a fluid medium that would have served as a support for light waves. A sketch of the Sagnac interferometer is shown in Figure 8.8. Since there was no laser source in the days of Sagnac, the source was a filament lamp, spectrally filtered by a Nichol's prism. The light was concentrated on a slit and collimated by a lens, then injected in a ring resonator by a beam splitter B. The light reflected by the beam splitter B went counterclockwise, the transmitted light clockwise in the ring resonator (Figure 8.8a). Both beams returning at the beam splitter B will be interfering. The result of these interferences is observed on a film F. To understand the response, let us approximate the interferometer by a circle (of 33 cm diameter in the experiment of Sagnac). At rest, the length of the resonator is the same for the clockwise and counterclockwise directions, resulting in a bright fringe in the middle of the photographic plate. When the table on which the interferometer is mounted rotates clockwise, the beam reflected by the beam splitter B, circulates counterclockwise, and will see a perimeter P shortened by the amount $\Delta P = v \times t_{\mathrm{rt}} = v \times P/c$ where c is the speed of light, and $v = \Omega R$ the velocity at the periphery of the circle. Since the opposite occurs for the beam circulating clockwise, there will be a difference in optical path between the two beams reaching the middle of the film, amounting to $2Pv/c = 4\pi R^2 \Omega / c$.

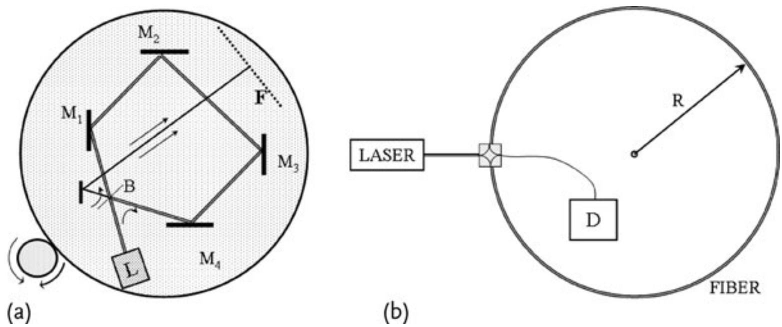


Figure 8.8 (a) The Sagnac interferometer. *L* is the light source, consisting of a filament lamp, a slit, a collimating lens, and spectral filtering. *B* is a beam splitter that injects the light into the interferometer, in both directions (reflection sent counterclockwise, transmission sent clockwise), and extracts the light to make interferences appear on the film *F*. (b) The FOG, which is simply a Sagnac interferometer made with fibers. Instead of a film, the interfering beams extracted from the fiber interferometer are recorded on a detector *D*.

This is a fraction $4\pi R^2 \Omega/(c\lambda)$ of the wavelength, or a phase shift of $8\pi^2 R^2 \Omega/(c\lambda)$. With the Sagnac table rotating at 2 turns/s ($\Omega = 4\pi s^{-1}$), the relative phase shift of the two beams is 0.18, corresponding to $0.18/(2\pi) = 0.029$ of the spacing between two fringes, consistent with the value observed by Sagnac [18]. If the Sagnac interferometer had been a ring laser, instead of measuring a phase shift of 0.03, it would have measured a frequency of $0.03/(2\pi t_{\text{rt}}) = 1.3\,\text{MHz}$. The extreme sensitivity that results from making measurements inside a laser cavity is the subject of Section 8.2.2

It is an interesting point to note that Sagnac had the correct mathematical expressions for the observed interference, yet his experiment was presented as an irrefutable proof of the existence of ether, a theory discarded today. His interpretation was consistent with the existence of a medium (ether) to support the propagation of the waves. The table moving clockwise would drag the ether with it and result in a wave velocity of $c + v$ in our notations. Sagnac argued that the ether had a »whirlpool« motion countercirculating with the table rotation, resulting in an unchanged wave velocity. He subsequently used a fan mounted above the experiment to test the whirlpool effect of air and concluded there was none. If his resolution had been better, he would have found a minuscule fringe displacement proportional to the velocity of air. This effect is called Fresnel drag and will be described in Section 8.2.2.

The Sagnac interferometer enjoyed a huge return to popularity with the emergence of low-loss single mode optical fibers for telecommunication. The sensitivity of the Sagnac interferometer is proportional to its area, which can be multiplied by coiling the fiber (only one loop is sketched in Figure 8.8b). As all passive devices, the measurement is based on an intensity measurement: the intensity resulting from the combination of two beams of the same frequency but different phase. As such, the response is sensitive to the amplitude noise of the laser source. We will see that this is not the case for the active sensors discussed in the next section.

8.2 Active Sensors

It has been recognized since the early days of the laser that intracavity measurements can outperform in sensitivity any measurement performed outside of a laser. We have seen that lasing action requires a delicate balance between the gain and losses of the cavity. Very small intracavity absorption will change this equilibrium and result in a large power change in the laser output. This powerful method is not very widespread, because, with the commercialization of lasers, scientists purchase them as a »black box« that produces light and no longer venture into operating inside the cavity. A laser is not only sensitive to minute changes in losses, but also to minute changes in the optical path between the cavity mirrors. Note that a change in the optical path is not necessarily a change in physical length: it can also be a change in the index of refraction. We have seen that the wavelength of a laser has to match an integer fraction of the cavity perimeter (or twice the cavity length). Since it typically takes 1 million wavelengths to span the cavity length, a change in distance of 1/1000th of a wavelength will cause a relative change in the optical frequency (1/(1000 million)), which is still a frequency of the order of MHz, easily measurable with standard electronics. Intracavity phase interferometry exploits this property.

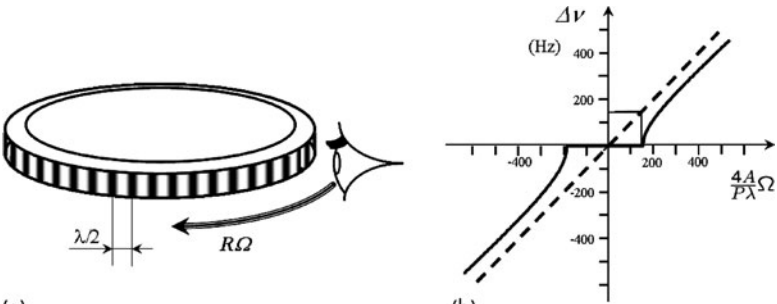
8.2.1 The Active Laser Gyroscope

A laser gyroscope is basically the Sagnac interferometer sketched in Figure 8.8a, incorporating a medium with an optical gain such as to make it a ring laser. Instead of the beam splitter B, which would introduce too many losses, the two countercirculating beams are extracted through one of the cavity mirrors and made to interfere. The response of a laser gyroscope is the Sagnac phase shift divided by the round trip time of the ring laser. From this definition, one immediately concludes that there is one essential difference with FOG: there is no increase in response by »coiling« the laser gyroscope, since the ratio of the Sagnac response to the cavity length remains the same, independently of the number of coils.

One can also understand the response of the laser gyroscope without invoking the Sagnac effect, either in terms of Doppler shift, or by considering the standing wave created by the countercirculating beams, as sketched in Figure 8.9a. Let us consider a circular cavity for simplicity of radius R, in which two beams of the same optical frequency circulate in opposite sense. The detector, or observer, rotates clockwise, around the circle of laser beams at a velocity $v = R\Omega$ (Ω being the angular velocity of rotation). It will see the clockwise beam Doppler-shifted to the red, and the counterclockwise beam Doppler shifted towards the blue. The difference between the two Doppler shifts is the gyroscopic response equal to $\Delta\nu = 2(v/c)\nu = 2R\Omega/\lambda = [4A/(P\lambda)]\Omega$, where ν and λ are the optical frequencies and wavelengths, respectively, and A the area of the laser gyroscope of perimeter P.

An even simpler understanding of the gyroscopic response is by considering that the two circulating beams interfere, making a standing wave pattern all along their path. This standing wave pattern constitutes a nonrotating frame of reference.[48] The observer, in a laboratory framework, rotating with the angular velocity Ω, sees the successive constructive-destructive interferences pass by at a rate $\Delta\nu = (R\Omega/(\lambda/2) = 4A/(P\lambda)$, where A and P are, respectively, the area and perimeter of the laser gyroscope. The sensitivity of the laser gyroscope is characterized by the factor $4A/(P\lambda)$, often called the »scale factor«. A circle is the ideal shape that produces the largest scale factor (the largest A/P ratio). For practical reasons, however, the typical commercial He-Ne laser gyroscope has a triangular cavity, which is a shape that minimizes the number of mirrors. Only recently has gyroscopic

48) There is no violation of any law of physics in having an absolute frame of reference from the point of view of rotation, since rotation involves an acceleration.



(a) (b)

Figure 8.9 (a) In a circular laser gyroscope of radius R, the two circulating beams, of the same optical frequency $\nu = c/\lambda$, make a standing wave pattern. This standing wave pattern is a fixed reference. The detector, or observer, rotating around these interlaced beams, will see successive constructive/destructive interferences, at a rate of $\Delta\nu = R\Omega/(\lambda/2)$, which is the gyroscopic response. (b) With a continuous laser, the response of a real gyroscope is not the ideal straight (dashed) line, but the solid line, showing an absence of response or »dead band« at low frequencies.

response been demonstrated for fiber lasers, giving the possibility of constructing perfectly circular laser gyroscopes [19]. If Sagnac could have made a laser of his 0.165 m radius interferometer, the rotation speed of 2 turns/s would have given him a signal at a frequency of $\Delta\nu = 1.3$ MHz, instead of the barely resolvable phase shift of 0.03 rad.

There are, however, two main challenges that have limited the performances of the laser gyroscope, both related to the difficulty of creating a laser with two independent countercirculating beams. In the brighter regions of interference of the two countercirculating beams (Figure 8.9a), the electric field of the combined waves is twice as large as the field of either circulating wave, hence the intensity if four times larger. This implies that the gain will saturate more, if two beams countercirculate in the laser (bidirectional operation), than if there is only one beam circulating in one direction (unidirectional operation).[49] Therefore, in most cases, the laser will operate in unidirectional mode and there will be no gyroscopic response. Gas lasers are an exception where the two countercirculating beams are not mutually exclusive, which is the reason that commercial laser gyroscopes are He-Ne lasers (continuous gas lasers of shortest wavelength). The second challenge is the requirement that there be no coupling be-

49) A phenomenon generally designated as »mutual gain saturation« and »mode competition«.

tween the two circulating beams. The laser cavity mirrors (as well as any transparent component) will scatter some light from one circulating beam into the other. This causes a phenomenon called »injection locking«: the weak light that is back-scattered from one sense of circulation is amplified and forces the countercirculating beam to have the same frequency, effectively nullifying the gyroscopic response. This creates a »dead band« in the gyroscopic response. An example of a dead band caused by a back-scattering on only 0.000 000 000 022 of the intensity of the incoming beam is shown in Figure 8.9b. The sensitivity to backscattering is so extreme that an active Sagnac interferometer can be used to detect surface defects in optics that backscatter as little as one part in 10^{15} [20, 21]. Two solutions have been implemented to limit the impact of the dead band in commercial He-Ne laser gyroscopes: (i) designing »super mirrors« of ultralow scattering, and (ii) mechanically shaking the laser in all directions to ensure that the operation is never within the dead band. An He-Ne laser and a laser pointer create a bright, visible spot on any surface, including a mirror. The »super mirrors« that have been developed for the He-Ne laser gyroscope have reached such a degree of perfection that the impact of the beam on the mirror is totally invisible. These mirrors are, however, very expensive and fragile (standard cleaning techniques cannot be applied). All commercial He-Ne laser gyroscopes for navigation have mechanical parts that move their operation outside the dead band. This mechanical solution defeats the advantage of the laser gyroscope, which would be to operate without any moving part.

The solution to both the »mode competition« that restricts the active Sagnac interferometer to the He-Ne gain medium and the dead band lies in the use of mode-locked lasers. This solution has given rise to a new field of intracavity phase interferometry presented in the next section.

8.2.2 Two Pulse Waltzing in a Laser Cavity: Intracavity Phase Interferometry

The conventional laser sensor is based on high-Q resonator properties. The inverse of the quality factor Q of a resonator, defined as the ratio of the photon lifetime to the light period, is the ultimate resolution of a phase sensor. This is because as resonant light circulates in a resonator, it can survive for the photon lifetime only because at each round trip the wave adds constructively to itself, which is a condition that is destroyed for a phase shift larger than $2\pi/Q$, the ultimate resolution of a sensor based on a change of index, phase velocity, or resonator length. Instead of increasing the resonator Q through technological marvels (mirrors of extreme reflectivity, lossless waveguides), one can reach the ultimate quality factor by inserting a gain medium, that is, making a laser. Various methods have been devised to exploit the extreme quality factor of a laser interferometer for phase measurement. The difficulty is that the laser will chose to oscillate at the resonant frequency of the oscillator. The solution is to use two lasers in one, that is, with one mode affected by the external parameter to be measured, and a reference mode. The only method to have two noninteracting signals sharing a cavity is to have ultrashort pulses circulating in the resonator, one as a reference, the other as a probe. The probe will be given a phase shift, proportional to the parameter being sensed, per round trip. Two pulse trains issued by this resonator, corresponding, respectively, to the circulating reference and probe, are interfered on a detector. The signal is a *frequency* or beat note, equal to the phase shift/round trip. There are two main advantages to intracavity phase interferometry (i) exploiting the high Q factor of an active laser and (ii) measuring a frequency rather than an amplitude.

To better appreciate the power of intracavity phase interferometry, Figure 8.10 shows a comparison between a Michelson interferometer and IPI, both applied to a measurement of length change, with a mode-locked laser. In Figure 8.10a, a mode-locked laser sends a train of identical optical pulses onto the two arms of a Michelson interferometer, made of a »reference« and »signal« arm. As the length of the signal arm L is varied, the pulses add in or out of phase, resulting in the variation of detected signals (as a function of L) sketched next to the detector D. The sensitivity to length of this arrangement is the ratio of the measured change in detected intensity ΔI to the length change ΔL.

In the case of IPI (Figure 8.10b), the Michelson interferometer is *inside* the mode-locked laser [22], operating in such a way as to have two pulses circulating simultaneously inside its cavity. Some optical device periodically sends one of the pulses into the reference arm and the other pulse into the signal arm. Since these two arms are part of the laser, the pulse circulating in the reference cavity will have a different frequency to the pulse circulating in the signal cavity. The detection is

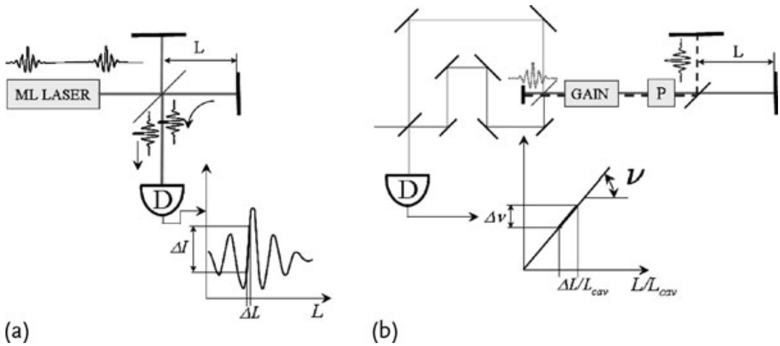


Figure 8.10 Comparison of Michelson interferometry and intracavity phase interferometry. A mode-locked laser is used, producing a train of identical ultrashort pulses. (a) The train of pulses is sent onto a Michelson interferometer. The successive constructive/destructive interferences recorded as the length L being varied give, within a certain range, a change in intensity ΔI proportional to the elongation ΔL. In (b), a similar measurement is performed inside a mode-locked laser cavity in which two pulses circulate. A device (not shown) diverts one of the intracavity pulses upwards towards the »reference arm«, while the other pulse is directed towards the »signal arm« of varying length L. The signal obtained by making the two pulse trains extracted from the laser interfere on a detector has a frequency $\Delta\nu$ proportional to the elongation relative to the cavity length L_{cav}, where the proportionality constant is precisely the optical frequency ν.

made by extracting the pulse trains corresponding to each of the intracavity pulses from the cavity, giving them a relative delay such as to make them overlap on a detector. The detector will record an alternative signal, at a frequency proportional to the difference in optical frequency between the signal and reference. As the length of the signal arm L is being scanned, the measured quantity, which is the recorded *frequency*, will vary linearly. This frequency $\Delta\nu$, generally called the »beat frequency«,[50] is equal to the product of the optical frequency of the laser by the displacement relative to the cavity length L_{cav}: $\Delta\nu = \nu \Delta L / L_{\text{cav}}$. The goal of the measurement is, of course, to determine the small optical length change ΔL from the measurement of the beat frequency $\Delta\nu$: $\Delta L = L_{\text{cav}} \Delta\nu / \nu$. Measurements of changes of $\Delta\nu$ as small as 0.2 Hz have been detected [23], with a laser at an optical frequency of $\nu = c/(1.3\ \mu\text{m}) = 2.3 \cdot 10^{14}$, thus corresponding to an elongation of $\Delta L \approx 10^{-15}$ m $= 1$ fm. One can justifiably look at such a figure with surprise: a femtometer is less than the distance

50) $\Delta\nu$ is called beat frequency or beat note because it results from the »beating« of the two pulse trains on the detector.

between atoms in a crystal, thus also considerably less than the surface irregularities in the best polished mirror. How could the cavity length be defined with much better precision than the surface of the laser mirrors? The answer lies in the fact that the wave surfaces of the laser, after thousands of bounces on the mirrors, take the spherical shape that best matches the curved mirror surfaces.

Implementation of this device is a challenge: it is not particularly easy to design a mode-locked laser where two pulses circulate independently of each other. Despite these challenges, successful systems and applications have been demonstrated and are briefly mentioned below.

Measurement of air currents The laser used in this application is a ring dye laser mode-locked by a saturable absorber jet. The saturable absorber has a double role: that of being the »shutter« that opens itself at every round trip to create the mode-locking. The same saturable absorber also ensures bidirectional operation, with the countercirculating pulses meeting at the location of the absorber. Two counterpropagating pulses meeting in the absorber saturate the latter more efficiently than a single pulse traveling through the absorber (as is the case in unidirectional operation). The first application of intracavity phase interferometry was to measure air flow [24]. It was mentioned that Sagnac unsuccessfully attempted to measure a phase shift due to the flow of an air fan blowing over the interferometer. In the measurement of [24], air was flown through a tube inserted in the cavity, and the beat note recorded as a function of the flow velocity. The observed linear dependence of beat note versus flow rate [24] does not imply that the electromagnetic wave is »carried« by air. The effect is called »Fresnel drag«. As the Sagnac experiment, it was seen as a proof of the existence of ether, the medium assumed to carry the electromagnetic waves. It was theorized by Fresnel [25] that a transparent medium moving along a light beam would »drag« the ether with it. Therefore, the velocity of light c/n (n being the index of refraction) would be affected, a change characterized by a »drag velocity adjustment« v_d proportional to the velocity of the moving medium. The correction term is $v_\mathrm{d} = v(1 - 1/n^2)$, where $1/n^2$ is interpreted as being the ratio of the ether density to the density of the moving medium. The interpretation of Fresnel has long been forgotten, but the expression for the velocity of light in a moving medium remains $c/n + v(1 - 1/n^2)$.

In the ring laser, the beam moving along the air velocity presents a different index of refraction than the countercirculating beam, resulting in a beat note.

Measurement of minuscule scattering In order to have a linear response of the intracavity phase interferometer, there should be absolutely no coupling between the countercirculating pulses. Any backscattering results in a dead band, as discussed in Section 8.2.1. Conversely, the measurement of a dead band can be used to measure minuscule backscattering coefficients. The measurement of Figure 8.9b was obtained by inserting an interface with a backscattering coefficient of $2.2 \cdot 10^{-11}$ at the location of the pulse crossing point. The dashed line, showing an absence of dead band, was obtained by removing the backscattering interface [20].

Various measurements by intracavity phase interferometry Measurements of rotation [26] and magnetic fields [27] have been performed with ring Ti:sapphire lasers. Electro-optic coefficients measurements used linear Ti:sapphire lasers [28]. Sensitive, low power measurements of a nonlinear index of refractions used an optical parametric oscillator [23] in a linear configuration.

References

1 Bryant, H.C. and Jarmie, N. (1974) The Glory. *Sci. Am.*, **231**, 60–71.

2 Hossein-Zadeh, M. and Vahala, K.J. (2008) Photonic RF down-converter based on optomechanical oscillation. *IEEE Photonics Technol. Lett.*, **20**, 234–236.

3 Min, B., Ostby, E., Sorger, V., Ulin-Avila, E., Yang, L., Zhang, X., and Vahala, K. (2009) High-Q surface-plasmon-polariton whispering-gallery microcavity. *Nature*, **457**, 455–458.

4 Armani, A.M., Kulkarni, R.P., Fraser, S.E., Flagan, R.C., and Vahala, K.J. (2007) Label-free, single-molecule detection with optical microcavities. *Science*, **317**, 783—787.

5 Aoki, T., Dayan, B., Wilcut, E., Bowen, W.P., Parkins, A.S., Kippenberg, T.J., Vahala, K.J., and Kimble, H.J. (2006) Observation of strong coupling between one atom and a monolithic microresonator. *Nature*, **443**, 671–674.

6 Ralph, T. and Pryde, G. (2009) Optical quantum computation, in *Progress in Optics*, Vol. 54, pp. 209–269.

7 Hossein-Zadeh, M., Rokhsari, H., Hajimi, A., and Vahala, K.J. (2006) Characterization of a radiation pressure driven optomechanical oscillator. *Phys. Rev. A*, **74**(2), 023813.

8 Hossein-Zadeh, M. and Vahala, K.J. (2010) Optomechanical oscillator

on a silicon chip. *J. Sel. Topics in Quantum Electron.*, **16**, 276–287.

9 Kippenberg, T. and Vahala, K. (2008) Cavity optomechanics: Backaction at the mesoscale. *Science*, **321**, 1172.

10 Del'Haye, P., Schliesser, A., Arcizet, O., Wilken, T., Holzwarth, R., and Kippenberg, T.J. (2007) Optical frequency comb generation from a monolithic microresonator. *Nature*, **450**, 7173.

11 Hossein-Zadeh, M. and Levi, A.F.J. (2006) 14.6 GHz $LiNbO_3$ microdisk photonic self-homodyne RF receiver. *IEEE Trans. Microwave Theory Techn.*, **54**(2), 821–831.

12 Lu, T., Yang, L., van Loon, R.V., Polman, A., and Vahala, K.J. (2009) On-chip green silica upconversion microlaser. *Opt. Lett.*, **34**, 482–484.

13 Beth, R.A. (1936) Mechanical detection and measurement of the angular momentum of light. *Phys. Rev.*, **50**, 115–125.

14 Court, I.N. and von Willisen, F.K. (1964) Frustrated total internal reflection and application of its principle to laser cavity design. *Appl. Opt.*, **3**, 719–726.

15 Diels, J.C., Stryland, E.V., and Gold, D. (1978) Investigation of the parameters affecting subpicosecond pulse durations in passively mode-locked dye lasers, in *Proc. 1st Conf. Picosecond Phenomena*, Hilton Head, South Carolina, pp. 117–120.

16 Ye, J. (2004) Absolute measurement of a long, arbitrary distance to less than an optical fringe. *Opt. Lett.*, **29**, 1153–1155.

17 Sagnac, M.G. (1913) L'éther lumineux démontré par l'effet du vent relatif d'éther dans un interféromètre en rotation uniforme. *C. r.*, **157**, 708–710.

18 Sagnac, M.G. (1913) Sur la preuve de la réalité de l'éther lumineux démontré par l'expérience de l'interférographe tournant. *C. r.*, **157**, 1410–1413b.

19 Braga, A.P., Diels, J.C., Jain, R.K., Kay, R., and Wang, L. (2010) Bidirectional mode-locked fiber ring laser using self-regenerative, passively controlled, threshold gating. *Opt. Lett.*, **35**, 2648–2650.

20 Navarro, M., Chalus, O., and Diels, J.C. (2006) Mode-locked ring lasers for backscattering measurement of mirror. *Opt. Lett.*, **31**, 2864–2866.

21 Quintero-Torres, R., Ackerman, M., Navarro, M., and Diels, J.C. (2004) Scatterometer using a bidirectional ring laser. *Opt. Commun.*, **241**, 179–183.

22 Arissian, L. and Diels, J.C. (2009) Investigation of carrier to envelope phase and repetition rate – fingerprints of mode-locked laser cavities. *J. Phys. B: At. Mol. Opt. Phys.*, **42**, 183001.

23 Velten, A., Schmitt-Sody, A., and Diels, J.C. (2010) Precise intracavity phase measurement in an optical parametric oscillator with two pulses per cavity round-trip. *Opt. Lett.*, **35**, 1181–1183.

24 Dennis, M.L., Diels, J.C., and Lai, M. (1991) The femtosecond ring dye laser: a potential new laser gyro. *Opt. Lett.*, **16**, 529–531.

25 Fresnel, A. (1818) *Ann. Chim. Phys.*, **9**, 57.

26 Lai, M., Diels, J.C., and Dennis, M. (1992) Nonreciprocal measurements in fs ring lasers. *Opt. Lett.*, **17**, 1535–1537.

27 Schmitt-Sody, A., Velten, A., Masuda, K., and Diels, J.C. (2010) Intra-cavity mode locked laser magnetometer. *Opt. Commun.*, **283**, 3339–3341.

28 Bohn, M.J., Diels, J.C., and Jain, R.K. (1997) Measuring intracavity phase changes using double pulses in a linear cavity. *Opt. Lett.*, **22**, 642–644.

9
Future Perspectives

Fifty years ago, nobody in his right mind could have imagined the impact that lasers would have in the near future. More often than not, this device was claimed to be a »solution looking for a problem«. In those days research was supported in a different way. Companies like Bell (AT&T), Philips, and others dedicated large sums of money to the advancement of science. Researchers were not in a »straight jacket« – their survival did not depend on producing something that makes the grass greener or reduces wrinkles. Let the imagination and wisdom span our horizons and increase our understanding of nature, and, voilá, applications emerge. Applications were not the motivation, but the natural result of the learning process. When electricity was found, no one expected that this newly discovered force of nature that powered light bulbs would one day run computers. The laser did lead to applications, more than could be cited in this book. Are we any wiser now to predict the future of lasers? One can always try to draw some lessons from the past.

Laser Development: From Dinosaurs to Bacteria

Most popular in the early years were gas lasers, followed by pumped dye lasers (ion argon lasers). It appears that these lasers are slowly fading into the sunset, to make place for a more efficient, smaller generation of sources of coherent light. Argon ion lasers held for some time the limelight as sources for pumping dye lasers and Ti:sapphire lasers, and entertaining crowds at rock concerts. Contributing to their downfall is their amazing inefficiency. It takes a power source of 480V, 3 phase, 60 A per phase, to power a 20 W laser which can pump a mode-locked dye laser, producing a frequency comb of a few mW average power. Most of the power consumed has to be evacuated in cooling water, involving even more power wasted in heat exchangers. In

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

all, the average power in the dye laser beam resulting from this chain represents a fraction of the order of 1 part in 10 million of the power consumed!

The efficiency of laser chains has increased considerably through miniaturization as well as through the replacement of incoherent pump sources such as flashlamps, arc lamps, by semiconductor lasers. Not only can the wall-plug efficiency of semiconductor lasers exceed 70% [1], but their emission spectrum can be engineered to match the absorption of the laser medium to be pumped. Furthermore, as compared to a flashlamp, the semiconductor laser is considerably more efficient as a pump source because of its directionality. There is a simple physical reason for the extreme miniaturization of lasers. The efficiency will never reach 100%, but can be improved. The higher the power density inside the laser, the more the heat that has to be dissipated. Efficient cooling requires a large surface-to-volume ratio, which, for a given shape, is inversely proportional to the linear dimension. For a given size, the shape can be chosen to maximize cooling. Disk-shaped lasers are playing an increasing role in high-power, small-size lasers. Another shape with larger area-to-volume ratio making huge strides in power capability is the fiber laser. Large arrays of spaghetti will be competing with stacks of pancakes for the ultimate laser power.

What is the limit in laser size? What is the ultimate power? Everything else being equal, laser power is proportional to its size. Mid-size lasers are commercially available and increasingly used for applications in medicine and industry. Seeking laser designs in the two extremes – micro and macro – are the main interests of laser engineers. As for the resonator cavity, the lower size limit is the light wavelength. Micro-resonators are designed in various shapes in the size of a bacteria. It is safe to predict that progress in laser sources will be linked to material development. For instance, progress in the synthesis of cheaper diamond, an ideal heat conductor, will spur the development of a new generation of high power miniature lasers. One major challenge in material development is the creation of solid state lasers at short wavelength, violet and UV. A giant step has been the development of GaN lasers (reaching lasing wavelength as short as 360 nm), not only for purple laser pointers, but for High Definition Digital Video Discs (HDVD) and »Blue Ray«. In most applications involving miniaturization of semiconductor lasers, the laser is just a low maintenance resource, like the ideal husband (?) – a checkbook not to be seen and not to be heard.

As we are seeing the extinction of the medium-size dinosaurs cited above, some super-giants are being hatched, requiring funding on the scale of a continent rather than a single country. The European ELI (»Extreme Light Infrastructure«) project is one example, promising to reach laser powers sufficient to create matter out of light. These megaprojects will be the Tyrannosaur Rex that will slowly gobble up National and International particle accelerator facilities, since the high power ultrashort pulse laser promises to create more compact and efficient particle accelerators.

Silent Lasers?

One can still question the importance of lasers in our daily life. After all, the invention of wheels, light bulbs, and computers were more noticeable than lasers. If we choose to ignore the laser as a scientific tool to explore nuclear and chemical reactions and material processing, we can search for its footprints at home. The silent existence of lasers continues in our CDs, DVDs, HDVDs, *etc*. Quietly, surreptitiously, the laser has squeezed itself into the leading position in one of the biggest markets of our modern society. A walk around the house should reveal many more hidden applications of lasers which may be difficult to trace back to the building components. Bills are printed by laser printers, cell phones and other electronics are made with laser lithography [2] (microfabrication of circuits). It may not be unreasonable to expect lasers to play an increasing role in lighting as well. We are not yet using laser cooling as a refrigerator, or picking up dust with an optical tweezer, or chopping tomatoes with a laser scalpel. As razor and cream were replaced by electric shavers, should we expect to have laser beard sculpting take over the daily shaving operation? Now that we have cheap laser power at hand, is it going in the direction of having laser drills, laser cookers? A reader with a wild imagination may, at this point, look around and see the possibility of replacements of or benefits from lasers in our daily apparatuses. With more curiosity one may imagine that lasers, as a scientific tool, will enlighten the mysteries of the universe. It is not steam power that replaces a horse, and the laser will not lead to defenestration of mechanics or electromagnetics.

It is a fine tool that steers an electron in an atom and can be so intense as to imitate the sun in a laboratory.

Laser Applications

Laser applications in every area cover a wide umbrella from small to medium and giant sizes as dedicated by its design and required power level. In most cases mid-range lasers are used in our daily applications. In machining we benefit from CO_2 and semiconductor lasers, both in continuous and pulsed operations, to cut steel blocks and drill with miminum damage and highest precision. With the control in the position of the focus, patterns and structures can be formed inside a block, and nanostructures sculpted onto semiconductors with ultraviolet lasers. By the use of laser filaments, we can also transfer energy into further, hitherto unreached distances across the atmosphere. One would expect lasers to harness the energy deposition and material modification in all scales more frequently.

In electronics, lasers will steer currents in atoms and molecules. With the recent realization of molecular transistors [3], the ever shrinking electronic component would ultimately be the size of an atom. Lasers will revolutionize our understanding of chemistry and biology, as chemical bond formation and dissociation are monitored and controlled with laser pulses. Since the laser beam can guide nerve cells to grow and nerve fibers can be stimulated by lasers, it will be possible to change the message of neurons with a laser beam.

A laser cannot read the mind, but new ultrasensitive and miniaturized laser magnetometers will make it possible to provide direct images of the activities in the brain, hence reading the mind. In symbiosis with the development of cameras, lasers will contribute to expand our vision beyond the narrow range of visible light.

Lasers as active elements in quantum optics and quantum information will change our binary logic and transfer our deductions of »yes»and »no« to that of »maybe«. With short laser pulses, communication will not be restricted to electronic barriers. Lasers will not wash the dishes but will be important components of robots (sensors for instance).

The laser was barely born when »Goldfinger« inspired the misconception of the »laser gun«. Chemical explosives will remain the toy of choice to blow up a wall. We can expect to see more lasers for fine surgery down to the cellular level, and for connecting or splicing tiny broken molecular bounds.

References

1 Botez, D. (2005) High-power, high brightness semiconductor lasers, in *Semiconductor and Organic Optoelectronic Materials and Devices*, Vol. 5624 (ed. S.T. Chung-En Zah Yi Luo), SPIE, Bellingham, WA, **5624**, 203–212.

2 Xia, D., Ku, Z., Lee, S.C., and Brueck, S.R.J. (2011) Nanostructures and functional materials fabricated by interferometric lithography. *Advanced Materials*, **23**.

3 Song, H., Kim, Y., Y.H.Jang, Jeong, H., M.A.Reed, and Lee, T. (2009) Observation of molecular orbital gating. *Nature*, **462**, 1039–1043.

Index

a
Above barrier ionization 164
Absorption 11, 76
Accelerator 172
Acne laser treatment 108
Acoustic analogy 17
Actinic keratoses (AK) treatment 107
Active sensors 217
Acupuncture 113
Aerodynamic window 185
Air turbine 37
Albert Einstein 10
Amplified spontaneous emission (ASE) 176
Amplifier with feedback 17
Angular momentum 209
Atomic force microscope (AFM) 138, 139
Attosecond 160
– recollision 166
– short and long trajectory 166
Audience scanning 98
Aurora Boreal 187
Avalanche 194
– ionization 185
Axons 102

b
Band gap 26
Barcode reader 86
– camera barcode reader 86
– CCD barcode scanner 86
– laser barcode scanner 86
– pen type 86
Basal cell carcinoma (BCC) treatment 107
Beam divergence 13
Beam waist 42
Beer–Lambert law 105
Biostimulation lasers 113
Birefringent medium 38, 211
Blink reflex 100
Braking radiation 173
Bremsstrahlung 173, 197
– inverse Bremsstrahlung 185
Brewster angle 23
Brownian motion 9

c
Carbon dioxide laser 22
Carrier to envelope offset (CEO) 69
Carrier to envelope phase (CEP) 69
Cascade ionization 77
Cavity 203
– lifetime 19
– modes 48
CD 87
– pit 88
Cesium clock 150
Charge coupled devices (CCD) 83
Chirp 50
Chirped pulse amplification 65
Circular polarization 12
– helicity 12
CO_2 laser 194
Coherence 8
– spatial 44
– temporal 44
Colliding pulse mode-locking 53
COLTRIMS 169
Compact disc (CD) 87
Compton wavelength 63, 174
Conduction band 26
Conical emission 187
Corona 192
Coulomb explosion 190
Coulomb force 172
Crookes radiometer 62

Crowd scanning 98
Cutting 134

d
Data storage 87
Dendrites 102
Dermis 104
Diagnodent 114
Dielectric mirror 33
Difference frequency generation 73
Diffraction 13, 41
Diode laser 26
Dipole oscillation 167
Directionality 59
Dispersion 48, 49
– negative dispersion 50
Divergence 13
Doppler anemometry 122
Doppler blood anemometry 123
Doppler effect 121
Doppler shift 177, 218
Doppler velocimetry 122
Drilling 134
Droplet 206
DVD 87
– groove 88
– multilayer 89
– multiplexing 89
– pit 88
– reader and writer 87
– three dimensional recording 89
Dye laser 51

e
Electro-optic effect 39, 145
Electron attachment 195
Electron levels 6
Electron–positron pair 171
Electronic Q-switching 38
ELI 64
Emission 10
– stimulated 10
Energy levels 9
Engraving 133
Epidermis 104
Ether 3, 215
Evanescent wave 211
– coupling 211
Extreme light infrastructure 175
Eye refractive surgery 97

f
Fabry–Pérot 203
Feedback 18
Fiber gyroscope 215
Fiber ring 204
Filament 60, 181
– conical emission 187
– continuous 182
– explosive detection 188
– Kerr effect 184
– remote sensing 187
– THz spectroscopy 188
– UV 185
Fine structure constant 152
Fission 172
FOG 215
Frequency combs 68, 149
Frequency generation
– difference frequency generation 73
– sum frequency generation 73
Frustrated total internal reflection 211
Fused silica 138

g
Gain 11
– lifetime 16
– saturation 35
Gamma radiation 172
Gaussian probability 59
Glaucoma treatment 97
Glial cells 102
Glory 207
Group velocity 48
Gyroscopic response 218

h
He-Ne lasers 20
Helicity 12
HHG 166
High harmonic generation 166, 169
High *Q* 19
– optical resonators 121

i
Impulsive stimulated Raman 115
Incoherence 8
Index of refraction 49
Injection locking 20
Inkjet printer 83
Interference 8, 13, 204
Interferometric autocorrelation 214

Intracavity phase interferometry (IPI) 220
inverse Bremsstrahlung 185
Ionization
– above barrier 164
– avalanche 185
– multiphoton 164
– potential 162
– tunneling 164

k
Keldysh parameter 164
Kerr effect 38, 49, 184
Kinesin 118
Kramers–Krönig 11
Krypton emission 150

l
LADAR 85
Laguerre modes 210
Laser
– cavity 15
– high *Q* 19
– cavity lifetime 19
– cavity round trip 19
– cooling 117, 177
– damage
– photochemical damage 99
– thermal 99
– directionality 41
– gain 15, 16, 161
– gyroscope 217
– in construction 90
– level 90
– lithotripsy 111
– mode-locking 47
– output coupler 19
– pointer 90
– printer 81
– pump 15
– Q-switching 36
– resonator 15
– scanner 83
– seed 20
– slave 20
– threshold 18, 20
– Ti:sapphire 170
– type
– carbon dioxide 22
– dye 51
– fiber 29
– He-Ne 20
– nitrogen 24
– semiconductor 26
– TEA 24
– Ti:sapphire 56
– welding 135
Laser-induced breakdown spectroscopy 189
Laser-induced fission 171
Laser-induced lightning 191
Levitation trap 121
LIBS 189
LIDAR 84
Light emitting diode (LED) 82
Light mill 62
Lightning 191
Linear polarization 13
Lithotripsy 111
Low level laser therapy (LLLT) 113

m
Magneto-optical trap (MOT) 178
Marking 133
Mars orbital laser altimeter 85
Mendeleev table 1
Meter standard 150
Methane stabilized He-Ne 150
Michelson 213
Microscopy
– fluorescence 142
– multiphoton 142
– nonlinear 143
– two-photon 142
Microsphere 206
Microstructure fibers 152
Mitosis 118
Modal dispersion 29
Mode competition 219
Mode-locked laser 47, 48
Mode-locking
– colliding pulse 53
Molecular alignment
– revival 168
Momentum 62, 208
Moving focus 182, 183
Multimode fiber 29
Multiphoton 140
– absorption 76

– fluorescence 77
– ionization 77, 164
Multiplexing 90, 146
– time multiplexing 147
– wavelength multiplexing 146

n
Negative dispersion 50
Neural network 102
Neurones 102
Niels Ryberg Finsen 93
Nitrogen laser 24
Nonlinear
– index 182
– lensing 182
– Schrödinger equation 57
Nonsequential double ionization 166
Nuclear fission 171
Nucleon 172
Numerical aperture 15

o
Offset frequency 69
Optical coherence tomography (OCT) 126
Optical lattice 119
Optical parametric generator 75
Optical rectification 73
Optical stretching (OS) 119
Optical tweezers trap 121
Optomechanics 209
Orbital 161
Orbital angular momentum 211

p
Pair production 171
Parametric gain 73
Passive Q-switching 39
Passive resonators 203
Periodically poled crystal 72
Permittivity 11
Phase matching 71
Photochemical damage 99
Photodetachment 195
Photodynamic therapy (PDT) 107
Photoelectric 173
– effect 159
Photon 2, 209
– energy 4
Photon lifetime 204
Photosynthesis 159
Pion 171
Planck's constant 3, 4
Plane wave 14
Plasma heating 185
Plasma shutter 77
Pockel's cell 38
Point source 44
Polarizability 120
Polarization 12
– circular 12
– linear 13
Polarizers 38
Polarizing beam splitter 38
Pondermotive potential 166
Population inversion 16
PPLN 72
Preform 31
Printer
– inkjet 83
– laser printer 82
Probability
– Gaussian 59
Probability distribution 59
Psoriasis treatment 108
Pulse shaper 154

q
Q factor 204
Q-switching 36
QED 174
Quasi phase matching 72

r
Radar 84
Radiation 10, 20
– spontaneous 10
– stimulated 10
Radiation pressure 62, 117, 177, 208, 209
– gradient force 118
– scattering force 118
Raindrop 206
Raman spectroscopy 114
Rayleigh
– criterion 14, 88
– length 43, 181
Recollision 166
Resonance Raman spectroscopy 115
Resonator 18

Restoration
– monuments 135
Retinal photo-coagulation 97
Revival 168
Rotating mirror 37
Round trip 19

s
Sagnac interferometer 215
Saturable absorber 39
Saturable absorption 52
Saturation 35, 97
– gain saturation 35
– mutual 219
– rate 35
Scale factor 218
Scanning
– audience 98
Scanning electron microscope 138
Second harmonic 70, 185
Seed laser 20
Self-focusing 185
Self-induced waveguide 183
Self-phase modulation 55
Semiconductor lasers 26
Shack–Hartman 130
Short range nuclear force 171
Single mode fiber 29
SLAC 175
Slave laser 20
Soliton
– communication 145
– compression 55
Spatial coherence 44
Speed of light 45, 49, 67, 172
Spontaneous radiation 10, 176
Spontaneous Raman scattering 115
Squamous cell carcinoma (SCC) treatment 108
Standing waves 18
Stimulated radiation 10, 176
Sum frequency generation 73
Surface enhanced Raman scattering 116
Susceptibility 11

t
TEA laser 24
Temporal coherence 44
Thermal damage 99
Thin disk laser 135
Three step model 162
Threshold 20
Ti:sapphire 56
Time of flight 84
Time-space duality 147
Time standard 150
Total internal reflection 29
Triangulation 84
Tunnel effect 211
Tunnel ionization 164
Tunneling 211
Two-photon absorption 76, 89

u
Ultrashort pulses 45
Upchirp 49
Uranium 171

v
Vacuum fluctuation 3, 75
Valence band 26
Velocity map imaging 165
Vibrational modes 23
VIPA 155
Vitiligo treatment 108

w
Water droplet 206
Wave 2
– amplitude 2
– packet 49
– period 2
– plate 211
– speed 2
– velocity 2, 49
Waveguide 138
Wavelength 2
Waveplate 38
Whispering gallery mode 206
Wire trailing rocket 194
Wood cutting 136
Work function 159

x
x-ray free-electron laser 175
Xerography 81

z
Zero point energy 3

Color Plates

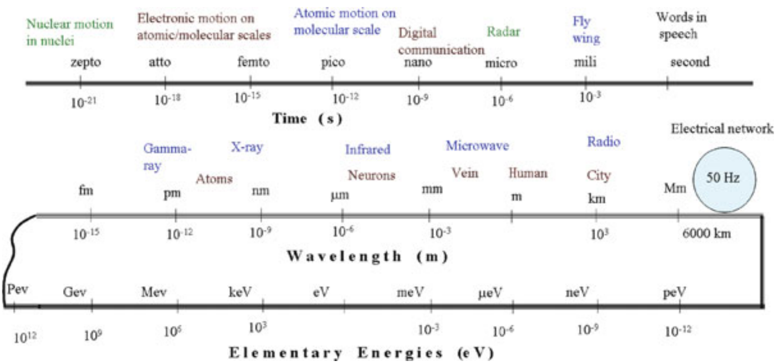


Figure 1.2 Different objects that radiate electromagnetic waves and the wavelength and elementary energy associated with them.

Lasers, The Power and Precision of Light, First Edition. Ladan Arissian and Jean-Claude Diels

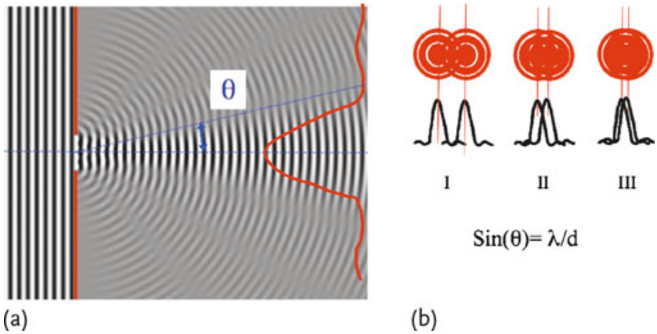


Figure 1.6 (a) Diffraction of a beam through an aperture. The path difference varies across the screen, showing more intensities where peaks from waves of different parts of the opening coincide and darker regions where peaks and valley coincide on the screen This results in an image (red pattern) of the aperture that is not so clear. (b) It is shown how far two points can be from each other in order to be distinguished. In order to resolve two images, the »Rayleigh criterion« defines the distance between the two points to be such that the first minimum ring overlaps the central maximum of the other image (case II). If the distance between the two points is larger (case I) the images are better resolved, while if the distance is smaller (case III) the resolution is lost.

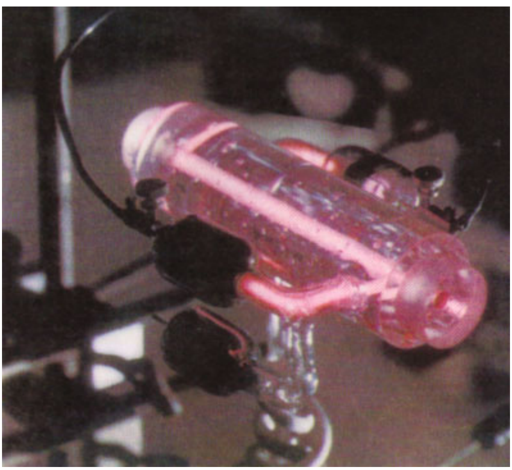


Figure 1.8 Short (12 cm) stable He-Ne laser with flat optical elements, directly bounded to the fused silica body (courtesy of Dr. Haisma, with permission from Koninklijke Philips Electronics N.V., Eindhoven from [1]).

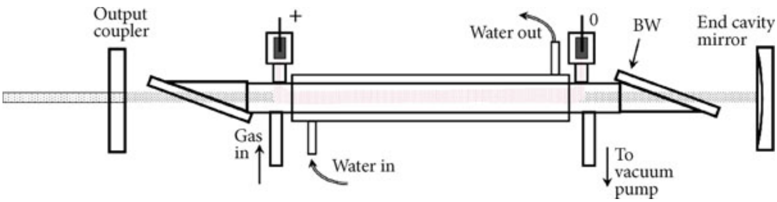


Figure 1.9 Typical low pressure CO_2 laser. The two windows (BW) can be made of germanium or salt (transparent to the wavelength of 10 μm emitted by the laser). They are at an angle such that there are no reflection losses for a beam polarized in the plane of the figure (called the Brewster angle). The electrodes can be small cylinders of nickel. The reflectivity of a flat plate of germanium (80%) is sufficient to achieve lasing action. The other reflector can be a flat metallic mirror (a concave mirror – typically 20 m radius of curvature – is generally used).

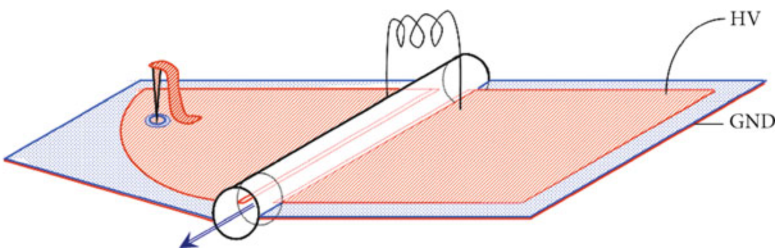
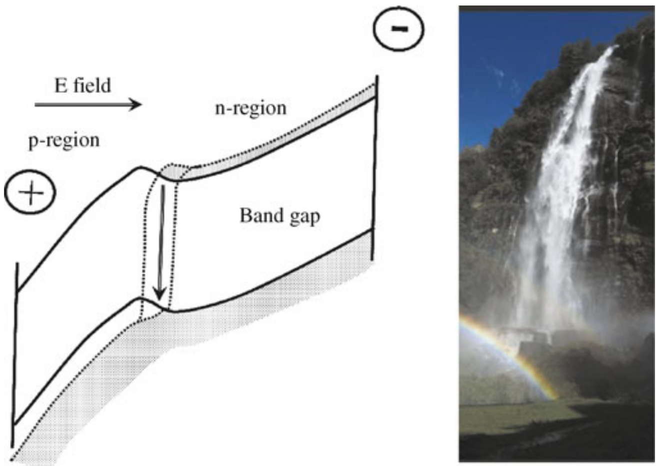


Figure 1.10 Sketch of a typical nitrogen laser. Copper foil is taped on both faces of a thin dielectric (circuit board, Kapton, or Mylar), creating a capacitive transmission line, which is charged via a resistance by a high voltage power supply (right side). The upper copper plates terminate as line electrodes in a discharge tube. The left capacitor/transmission line is connected to the right one via inductance of a resistance. On the far left: the spark gap that acts as a switch short-circuiting the capacitor (it can be a needle connected to the upper plate, pointing towards the ground plate, or a car spark plug). The short circuit propagates towards the right, brings the left electrode to ground potential, inducing a discharge across the tube, lasting until the complete capacitance is discharged (about 1 ns). The tube is closed by two windows, or one window and a mirror. Pure nitrogen at 25—50 torr pressure is pumped through the tube (air can also be used, but the performances are reduced).



(a) (b)

Figure 1.11 Energy band structure of a semiconductor laser. The occupation of electrons shown by the gray area extends in the conduction band in the n region and does not reach the top of the valence band in the p region. As a field is applied to the semiconductor, the electric potential adds to the electron energies, resulting in slanted bands (a). The current of electrons flows down the »river« of the conduction band to cascade down to the valence band at the junction just as a waterfall (b).

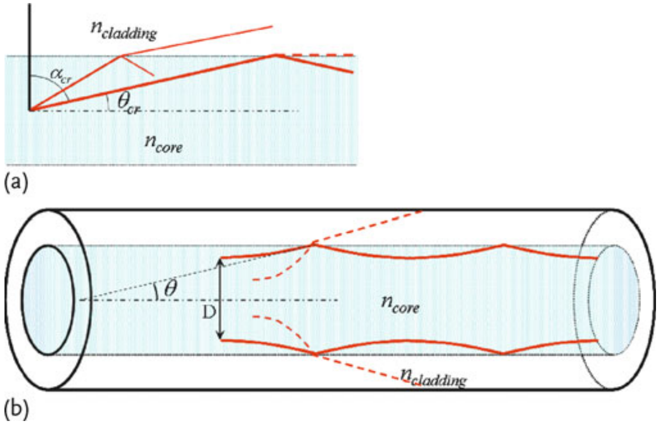


Figure 1.12 (a) Beam incident from the bottom on the interface between two glasses of different index of refraction $n_{\text{core}} > n_{\text{cladding}}$. Rays incident at an angle larger than or equal to α_{cr} are totally reflected, without any loss in the medium of index n_{cladding}. (b) Total internal reflection takes place between the core of an optical fiber and the cladding, provided that the rays make an angle with the axis of the fiber smaller than the critical value $\theta = 90° - \alpha_{\text{cr}}$. The smallest beam diameter D that can be trapped is the one for which the diffraction angle λ/D (see Section 1.2.3) corresponds to the critical θ. If the core diameter is equal to D, the fiber is said to be single mode.

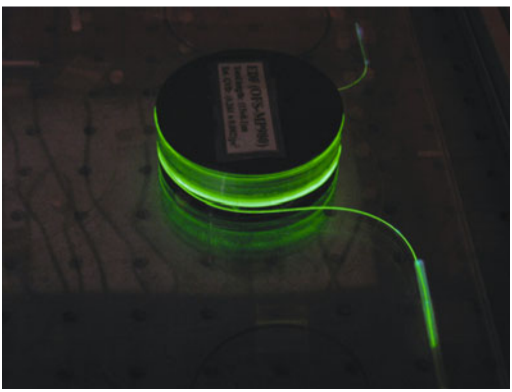


Figure 1.13 Erbium doped fiber glowing in the dark, upon excitation by the pump radiation at 980 nm.

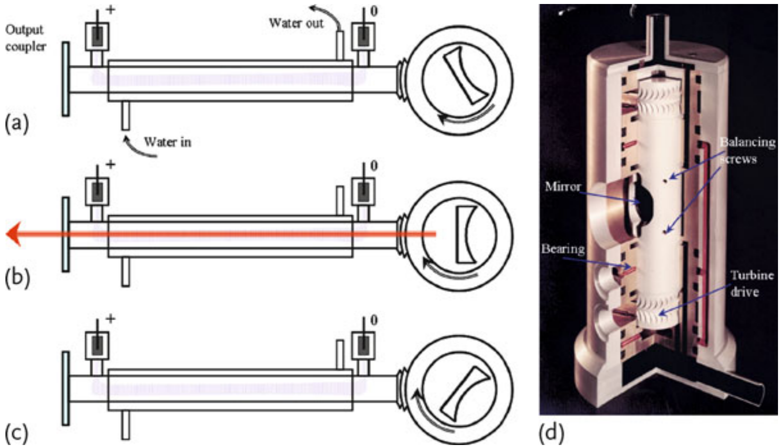


Figure 1.15 (a) A CO_2 laser tube is closed at one end by a partially reflecting mirror, an uncoated germanium plate, or a coated ZnSe plate. The other end is sealed with an enclosure containing the rotating mirror. In position (a), with the rotating mirror at a nonzero incidence with respect to the tube axis, the gain develops inside the discharge tube. As the rotating mirror arrives in position (b), the output mirror and the rotating mirror are parallel, forming a resonator in which a laser pulse forms, and depletes the gain. As the mirror pursues its rotation (c), there is no longer a resonator, and the gain can recover until the next position (b). (d) Exploded view of an air turbine used for Q-switching. The rotation speed could reach 60 000 revolutions/min, limited by the centrifugal expansion of the shaft (courtesy of Koninklijke Philips Electronics N.V., Eindhoven, 1970).

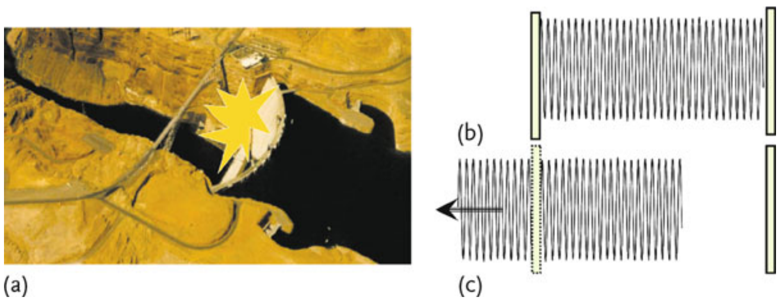


Figure 1.17 (a) A dam is filled slowly to capacity, ideally by closing all water release. The energy stored by the dam can be released in a minimum amount of time by blowing up the dam. (b) Similarly, in a laser cavity with totally reflecting mirrors, the optical power increases swiftly with time. (c) To release the energy stored in that cavity in the shortest amount of time, one of the cavity mirrors is »removed« in a time short compared with the time it takes light to make a complete round trip in the cavity.

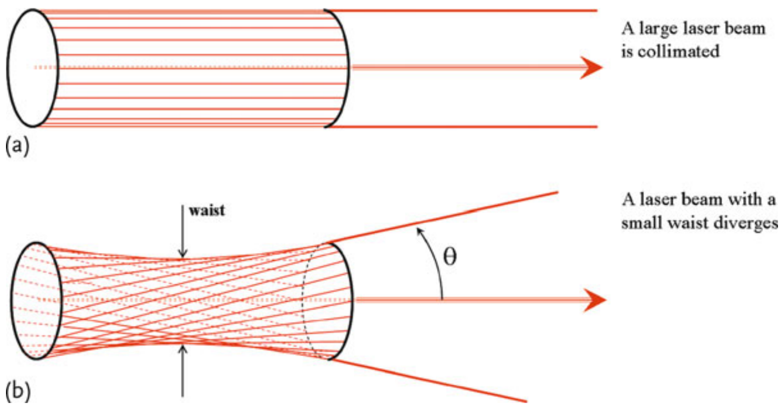


Figure 1.18 (a) A well collimated output of a laser. Rigorously speaking, such a perfect collimation can only take place for beams of infinitely large diameter. In general, the diameter of a laser beam will increase from the smallest value (the waist) as in (b). The diameter of the waist defines the angle θ of the divergence. The situation of (a) applies to a laser with flat mirrors, where the light rays are the strings spanned between the two mirrors. Curved mirrors lead to the situation of (b): the »rings« are twisted with respect to each other. The envelope of the rays (that are perpendicular to the surface of the mirror) draw an hyperboloid which can often be seen with a laser beam in a dusty environment. If the curvature of the mirrors is equal, the minimum diameter »*D*« – the waist – is at the midpoint of the cavity.

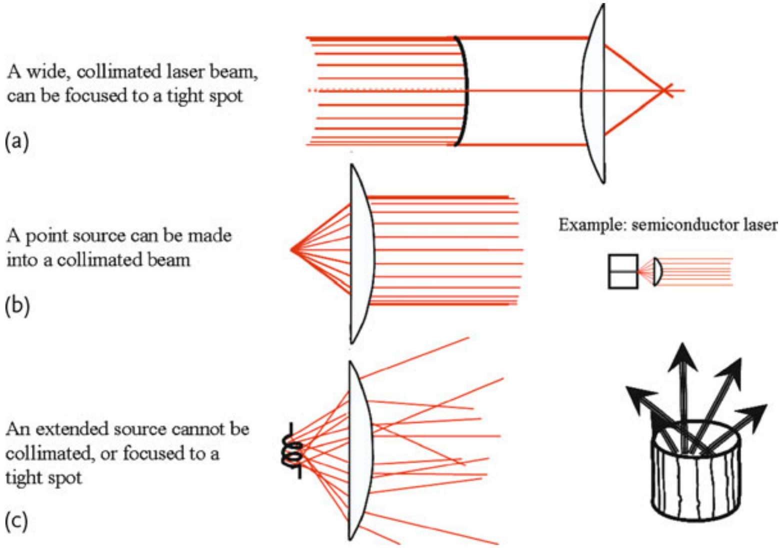


Figure 1.19 (a) The illustration of coherence at source is given by comparing a point source with an extended one like a flash lamp filament. If all rays come from a tiny (compared to the light wavelength) source, they all generate waves (photons) with the same oscillation phase. With ideal lenses and mirrors one can generate a parallel beam to infinity. (b) The same applies in reverse, if a beam is parallel it can be focused to one spot. (c) Since we do not live in an ideal word all these terms are relative, such that as the source get more extended the collimation is less. If the source emission is not spatially coherent, the radiation is like having spears out of a trash can that are all in different directions. An extended filament, even if emits light at the same time, will not generate a well collimated beam and will not be able to merge to a focal point. The smallest beam at the focus corresponds to imaging the filament.

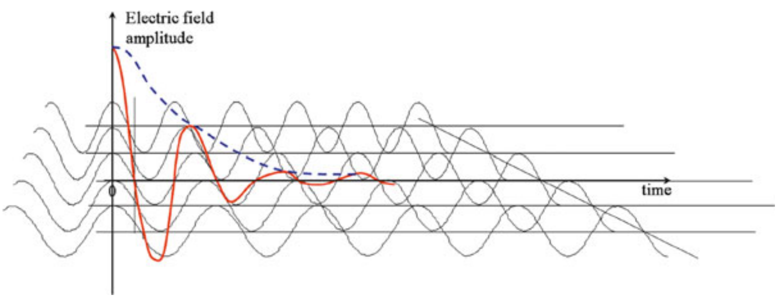


Figure 1.20 Five waves are added on top of each other such that at a given time all the crests coincide.

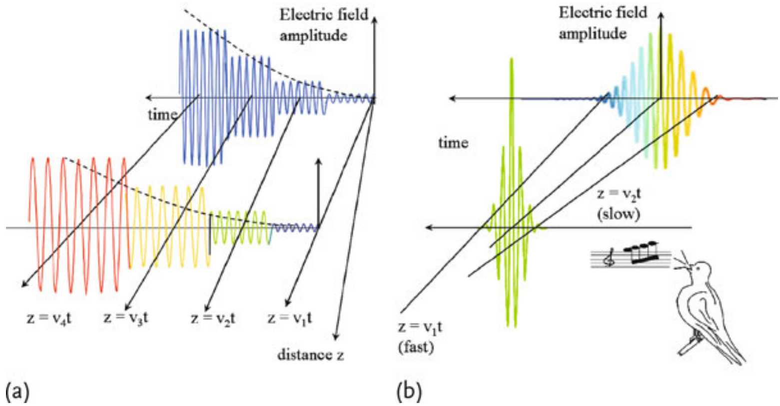


Figure 1.21 (a) Generation of new optical frequencies by propagation of a pulse in a medium where the wave velocity increases with intensity. The optical signal of increasing intensity is shown as having a stepwise increase on its leading edge (the time axis points to the left, for a better visualization of a pulse propagating to the right). The different intensities propagate at velocities v_1, v_2, v_3, and v_4 with $v_4 < v_3 < v_2 < v_1$. As a result, the pulse optical frequencies decrease with time along the pulse (or the wavelengths increase along the pulse) after some propagation distance. (b) Through the process shown in (a), one has generated an »upchirped« pulse, that is, a pulse of which the optical frequency increases with time. This is exactly what the little bird at the bottom of the picture is singing. This pulse is now sent through a medium with negative dispersion (i.e., a medium in which the higher frequencies (blue) propagate faster than the lower frequencies (red)). As a result, the tail of the pulse catches up with the pulse leading edge, resulting in pulse compression.

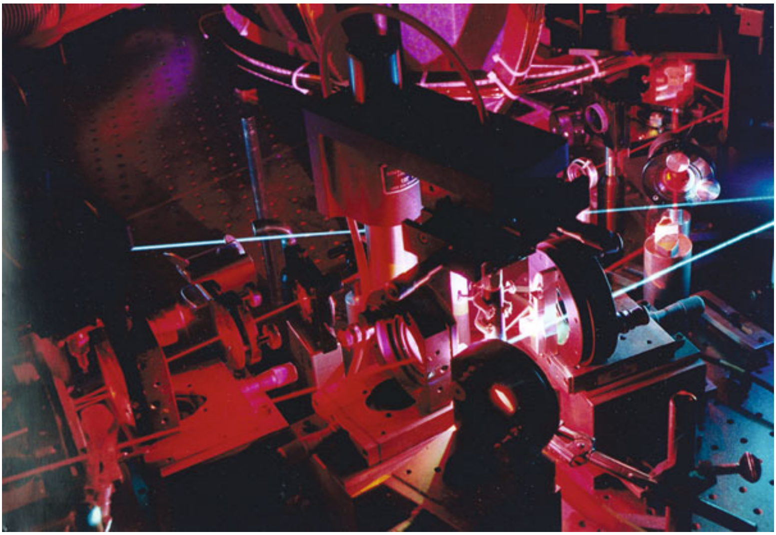


Figure 1.22 A ring dye laser. The dye jet is seen in the middle of the picture, pumped by the bright blue beam of an argon ion laser. The mirror in the foreground focuses the argon leaser beam at a tiny spot in the dye jet. This gain spot is at the focus of two curved mirrors, which direct a collimated beam in the other part of the cavity. The red intracavity beam of the dye laser can be seen on the picture.

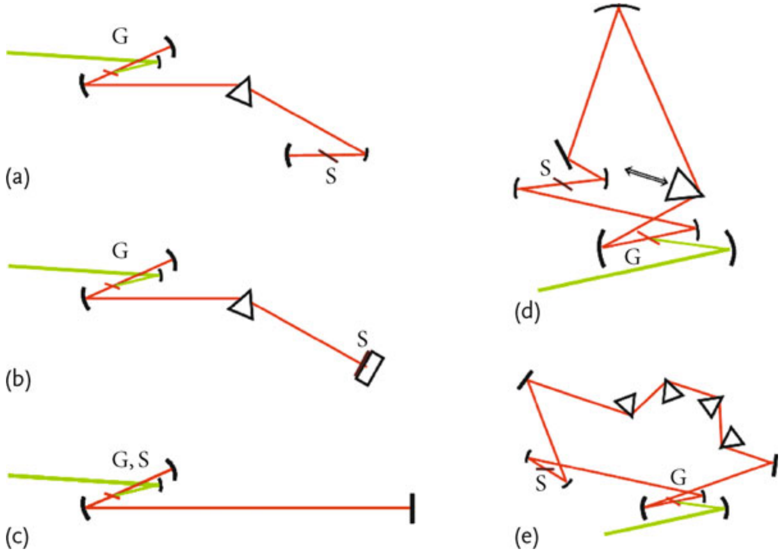


Figure 1.23 Successive configurations of mode-locked dye lasers. G is the gain jet – most commonly Rhodamine 6G – and S is the saturable absorber – most commonly diethyloxadicarbocyanine iodide. The configuration (a) of the early 1970s [13] gave way to (b) a »colliding pulse mode locked cavity« [14]. A simpler cavity in (c) used all dyes mixed in one jet, and mirrors with square spectral bandwidth [15, 16]. In (d), with the »colliding pulse« mode-locking implemented in a ring cavity, the prism is reinstated but at the center of curvature of a mirror [17]. In (e), a four prism sequence is introduced in the ring to produce negative dispersion [18].

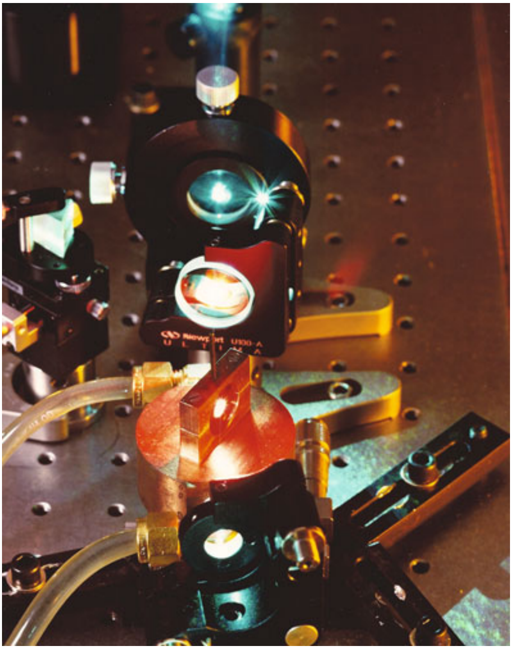
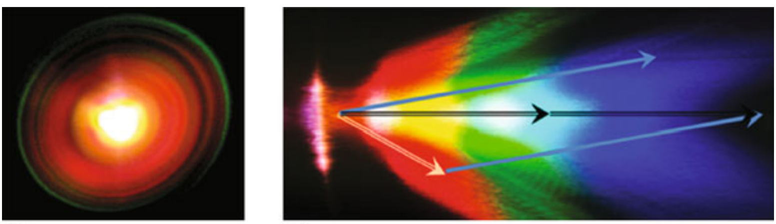


Figure 1.24 A Ti:sapphire laser. The Ti:sapphire crystal is pumped through one of the two curved mirrors projecting the gain spot into the cavity by a frequency doubled vanadate mirror.



(a) (b)

Figure 1.27 (a) The annular display seen on a door, 25 m away from the intense short pulse laser source. The beam has collapsed into a single filament, which has produced these concentric colorful cones. (b) A filament produced in glass. The color spectrum is displayed horizontally (from long wavelength to the left, to short wavelengths to the right), and the angle the individual rays make with the horizontal is the vertical axis. The intense beam propagates along an horizontal axis (shown in black). The directions of the rays is indicated for different colors.

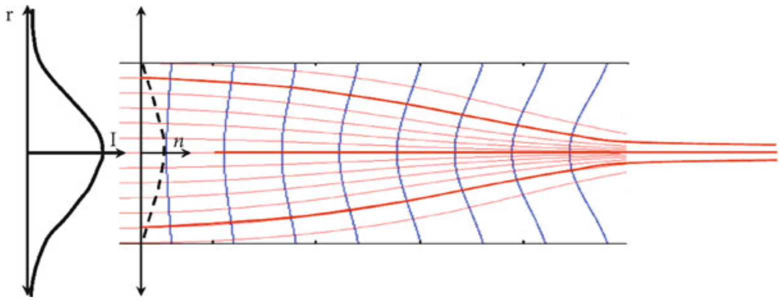


Figure 1.28 Formation of a »filament« or a self-guided intense beam in air. A laser beam is propagating from left to right, with an intensity versus radius sketched at the extreme left. Given a sufficiently high intensity, the index of refraction will increase proportionally to the intensity, as indicated by the dashed curve. This spatial dependence of the index of refraction results in a lensing effect. The wavefronts will curve, and the rays, perpendicular to the wavefronts, will bend towards the axis. A waveguide is formed by the beam itself, similar to the fiber sketched in Figure 1.12.

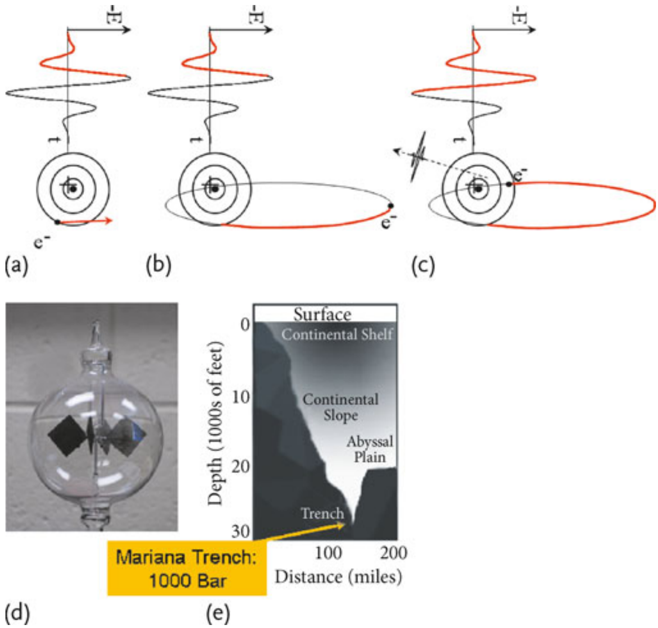


Figure 1.29 The electric field of a pulse, near the peak of a cycle, is sufficiently high to eject an electron from its orbit (a). The electron is accelerated away from the atom, then decelerated to a halt the next half cycle, as the light electric field reverses sign (b). During the next quarter cycle of the light pulse, the electron is accelerated back towards the atom. Numerous complex physical phenomena can occur during that recollision, one of them being the emission of an extremely short (typically 100 as) burst of x-ray radiation. (d) The pressure of sunlight or a He-Ne laser is not sufficient to make the »light mill« (or »Crookes radiometer«) spin. However, the radiation pressure at intensities used to create attosecond pulses is 10 000 times larger than that at the bottom of the ocean (e).

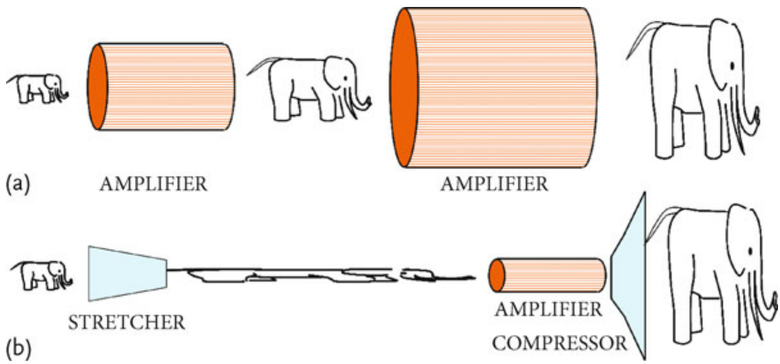


Figure 1.30 (a) Any amplifier stage has to be matched to the size of the amplified pulse. For a given amplifier diameter, the saturation limits the maximum pulse energy that can be extracted, as the diameter of the tube limits the size of the elephant that can pass through it. (b) Instead of increasing the diameter of the tube, why not stretch the elephant to make him pass through a narrower tube and give him the original proportion after amplification?

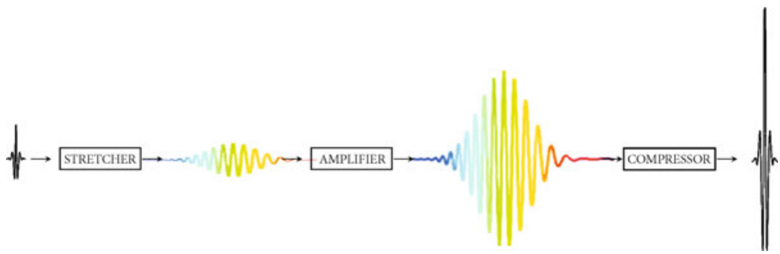


Figure 1.31 Chirped pulse amplification. An ultrashort pulse is sent through a stretcher, which can be constructed with discrete elements (gratings, prism) or be a piece of glass or a fiber. The different frequency components of the pulse are delayed with respect to each other, resulting in chirp and pulse stretching. The 10 000 to 100 000 times pulse stretching ratio allows considerable amplification before the damage limit to the components of the amplifier is reached. The action of the stretcher is reversed in the amplifier, resulting in the creation of an extremely intense ultrashort pulse.

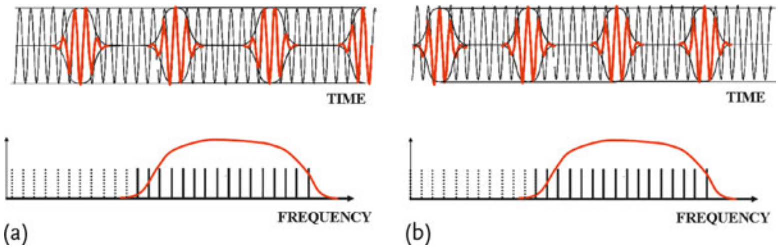


Figure 1.33 The mode-locked pulse train, in the time domain (top) is shown as a wave at a single carrier frequency, modulated by and envelope. The corresponding comb of optical frequencies is represented on the bottom. (a) A general case where the envelope spacing is not an integer number of optical cycles. (b) The envelope spacing is an integer number of light periods, and, in addition, the carrier to envelope phase is zero.

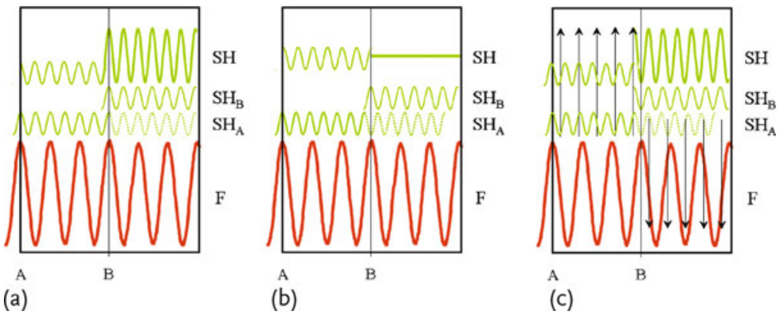


Figure 1.34 Simplified sketch to illustrate the second harmonic generation in a nonlinear crystal. F is the fundamental wave sent through the crystal. In (a) the crystal is phase matched: the second harmonic generated at the entrance plane *A* propagates to the plane *B* (SH_A), and adds constructively with the second harmonic produced by the fundamental at plane *B* (SH_B, to form a large second harmonic field SH). In (b), case of a nonphase matched crystal, the second harmonic SH_A is out of phase with the second harmonic produced by the fundamental at plane *B* (SH_B: the two fields cancel out to form a zero second harmonic SH). (c) is the case of a periodically poled crystal. With the optic axis oriented as shown by the arrows, the propagation and second harmonic generation from plane *A* to *B* are the same as in case (b). In case (c), the optic axis is reversed after plane *B*, and the second harmonic generated in *B* is reversed as compared to cases (a) and (b). Consequently, the two fields SH_A and SH_B add in phase to create a large second harmonic SH.

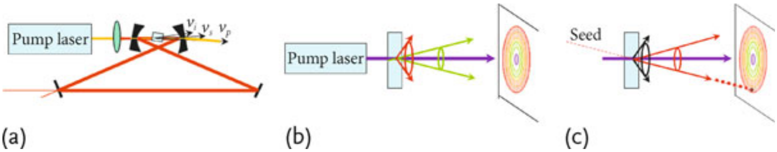


Figure 1.36 (a) An optical parametric oscillator in a ring cavity. (b) An optical parametric generator. (c) A seeded optical parametric generator.

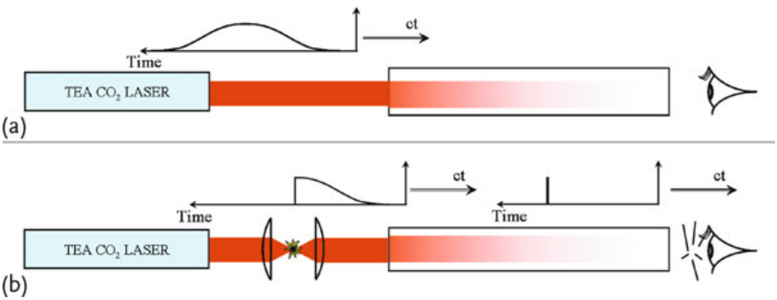


Figure 1.37 Absorption can be interpreted as being due to the incoming light exciting dipoles that radiate with opposite phase. In (a) A CO_2 laser pulse is sent through a resonant absorber (typically heated CO_2). The excited molecules emit a wave that destructively interferes with the incoming wave, resulting in a null signal on the detector. In (b), a plasma is created in air, which abruptly cuts the tail of the ns pulse. There is no more incoming wave to destructively interfere with the radiation from the excited molecules. An intense pulse is observed on the detector, which has a duration determined by the time that the excited molecules remain in phase. That time is related to the collision time between an excited molecule and any other atom or molecule in the cell.

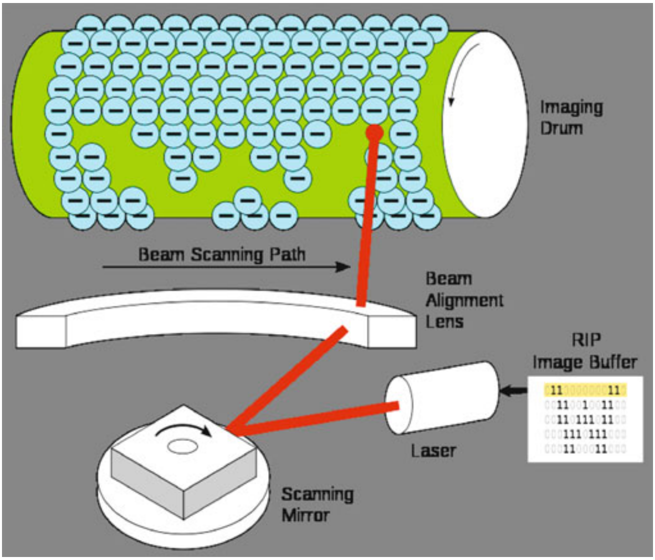


Figure 2.1 Schematic of a laser printer. The computer digital data of the image is transferred to brightness and darkness of the laser. Then the laser is steered with a mirror and a lens to discharge the negative charge of the drum where there is brightness (ones). Based on the electrostatic charge attraction, negative toners will ride on the discharged points of the drum. The toner is picked up by paper and the image is transferred for a particular toner color (picture from Wikipedia).

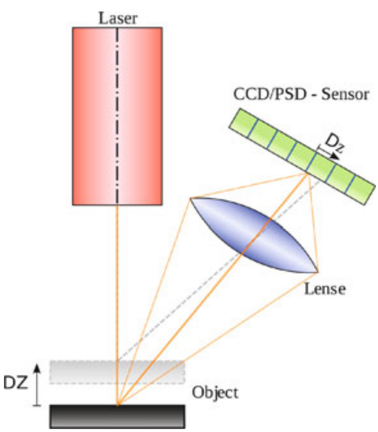


Figure 2.2 Principle of laser scanning based on triangulation. The object and image are fixed in space and only the laser light is steered across the sample. Reflection from front and back faces and corners of the object end up on different spots on a CCD.

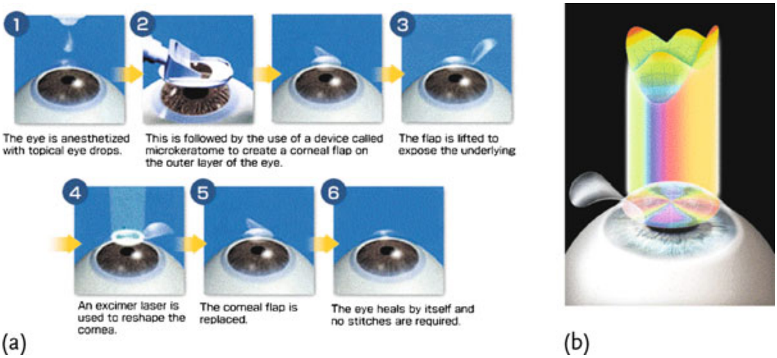


Figure 3.1 (a) The LASIK operation procedure. (b) Wavefront LASIK which not only looks at correcting the focal point on the retina but also follows the whole wavefront of the eye as seen and collected on the retina.

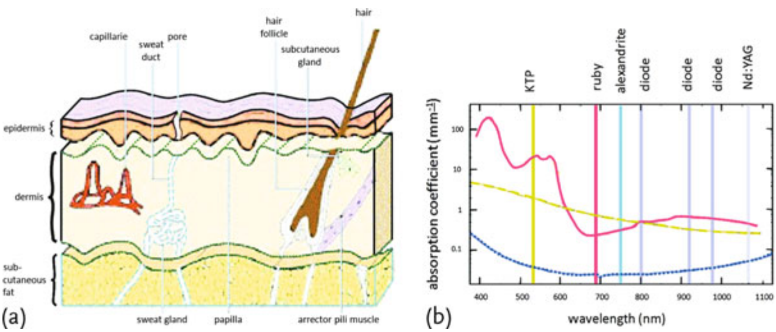


Figure 3.3 (a) The skin has a layered structure of epidermis and dermis with many small structures embedded. (b) Absorption spectra of the skin main absorbers: water (blue), melanin (brown), and hemoglobin (red). Also shown are wavelengths of some important dermatological lasers.

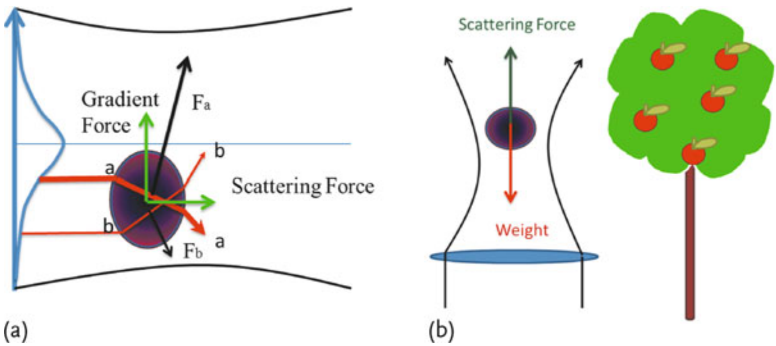


Figure 3.4 (a) The effect of the light pressure on small objects. A incident beam with a spatial intensity gradient creates a nonuniform push to a particle and steers it towards the center (high intensity) part of the beam, in the transverse direction (gradient force). In the longitudinal direction the beam pushes the particle along the propagation axis. This is a scattering force from reflected photons that bounce back from the surface. Transmitted light also transfers some momentum; for a gradient intensity profile, we can follow this force as normal to the beam ray bending in the sphere. The thickness of the line representing each ray is an indication of the intensity of that portion of light. (b) With proper adjustment of the light intensity, radiation pressure can be used to make a levitation trap. If the force due to radiation pressure cancels the weight of the particle, a stable suspension is achieved.

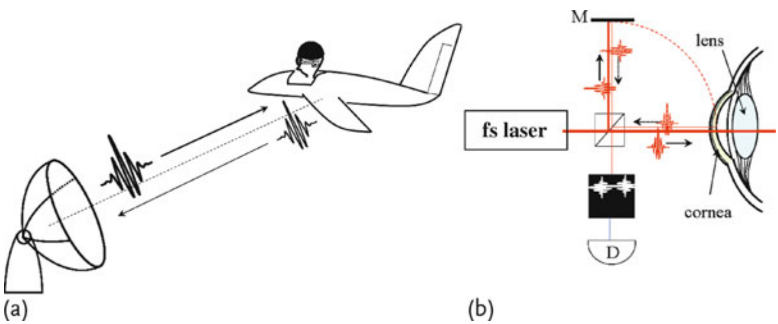
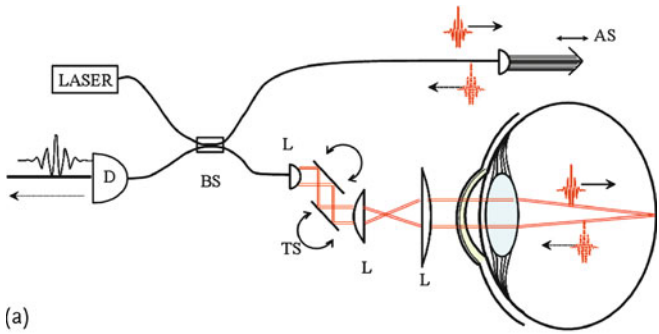


Figure 3.7 (a) The radar emitter sends a few cycles of electromagnetic waves in a nanosecond pulse towards a target in the sky. The distance to the target is determined from the measurement of the time it took the pulse to make the »round trip«. (b) The same technique applied to the measurement of the eye. It is now a fs pulse from a mode-locked laser that is sent to reflect off the various interfaces within the eye. The pulse length (pulse duration $\times c$) is shorter than even the thickness of the epithelium (membrane in front of the cornea). The time of flight measurement is performed as a pure optical coincidence method: the »black box« only detects a signal if the »reference« and »signal« (from the eye) pulses arrive at the same time.



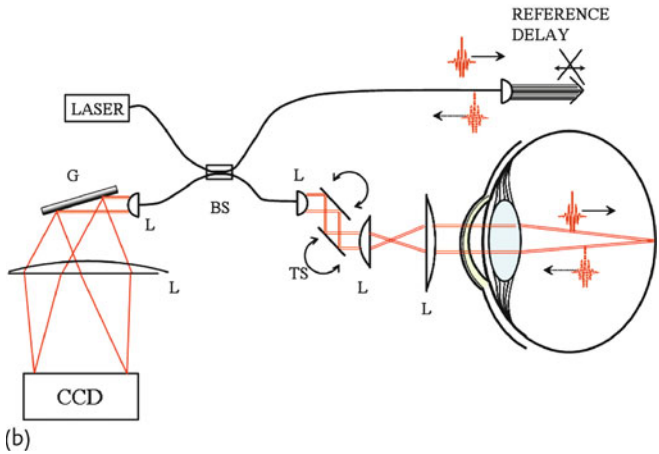


Figure 3.8 (a) Typical set-up for optical coherent tomography. The source is either an ultrashort (femtosecond) pulse source or a low coherence semiconductor source, coupled to a fiber which is divided into two arms at the beam splitter BS. A scanning retroreflector AC at the end of the reference arm returns a signal back towards the beam splitter BS. The other fiber arm is collimated by the lens L, given a transverse scanning (in *x* and *y*) by the scanner TS, before being sent to the eye by a set of lenses *L*. The backscattered radiation from the eye is mixed with the reference signal in the detector *D*.

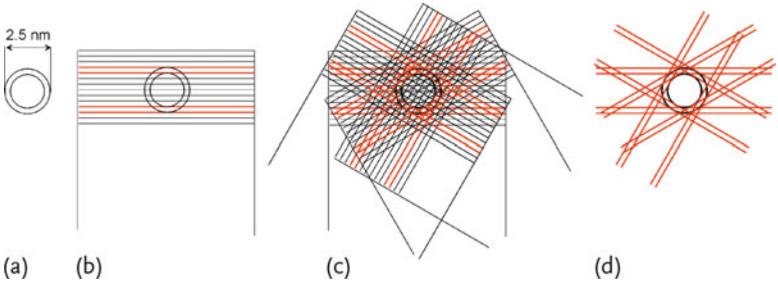


Figure 3.9 Successive steps of tomographic reconstruction. (a) The object under investigation. (b) One-dimensional scanning. (c) Scanning from four different directions. (d) The planes that define the object.

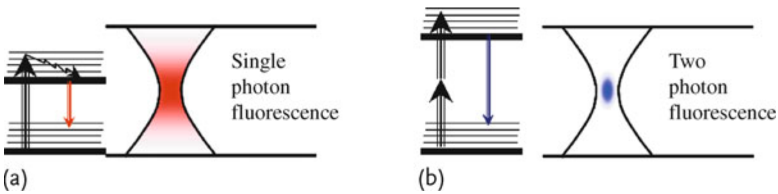


Figure 5.1 (a) Conventional fluorescence (single photon) microscopy. If the fluorescing material is uniformly distributed in the sample, the entire spectral volume will emit fluorescence radiation. (b) In the case of two-photon fluorescence, the fluorescence is confined to the center of the focal volume.

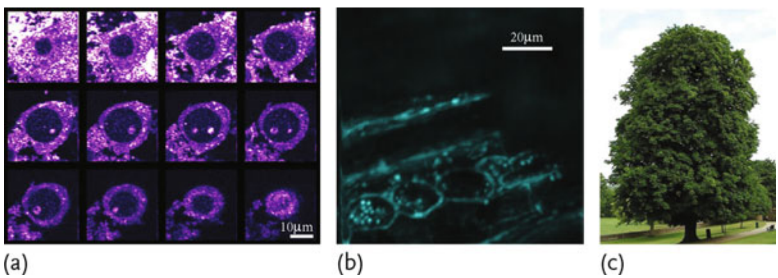


Figure 5.2 (a) Third harmonic generated picture of sections of a live neuron (courtesy of http://www.weizmann.ac.il/home/feyaron/index.htm.). (b) Two-photon fluorescence of horse chestnut bark. From http://www.uni-muenster.de/Physik.AP/Fallnich/Forschen/NichtlineareMikroskopie.html. (c) A picture of the horse chestnut.

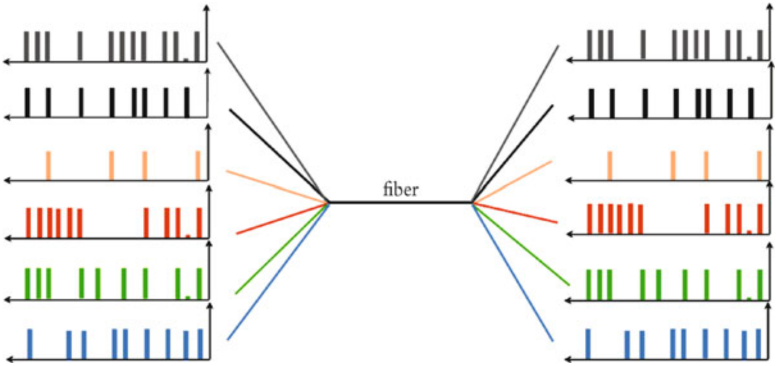
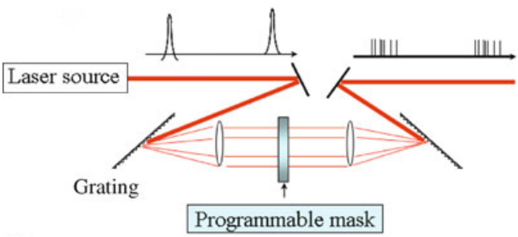
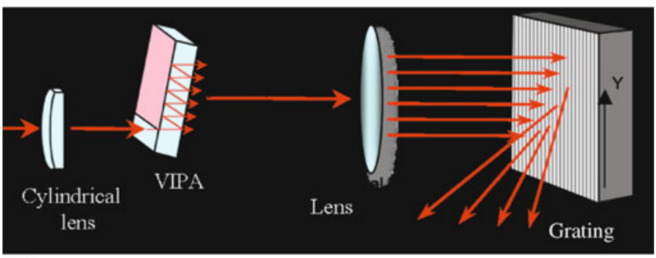


Figure 5.4 The principle of wavelength multiplexing. Several words (pulse strings) from various sources modulate a difference color channel in a fiber. Filters (resonators) are used at the detection to separate the different wavelength, hence restituting the individuality of each channel.



(a)



(b)

Figure 5.7 (a) A standard pulse shaper. A first grating displays the spectrum of each pulse of a pulse train onto a programmable mask. The mask manipulates the spectral components in amplitude and phase. The transformed spectral components are brought back together by a second grating. Each pulse of the original train has given birth to a sequence of pulses, controlled by the mask. (b) Combination of a VIPA and a grating to isolate every single tooth of a frequency comb (courtesy of Scott Diddams [12]).

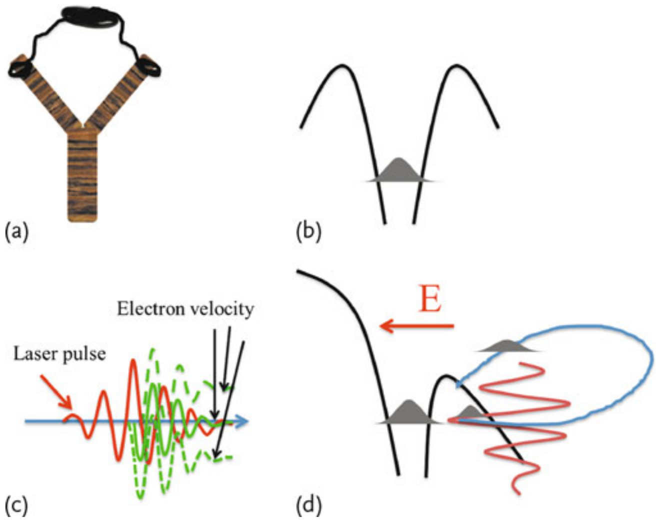


Figure 6.1 (a) A laser pulse takes the electron and accelerates it just like a slingshot taking a stone. For the light photon of 800 nm, the electron wavelength after this acceleration is only between 10 to 0.3 Å. (b) The electron in an atom or molecule is held in a potential well by Coulomb attraction to the positive nucleus. Although in quantum mechanics, contrary to classical physics, a particle has a chance to pass a barrier beyond its energy, the probability of this event is negligible when the particle is at rest. (c) With the high electric field of the laser the atom is ionized and the electron oscillates with the laser field. The three curves on the right side represent three different moments of ionization, which will lead to different acceleration and ultimate speed of electron. The trajectory of the electrons with applied laser field is calculated by classical physics. (d) The ejected electron travels with the laser field and may return and recombine with its parent ion.

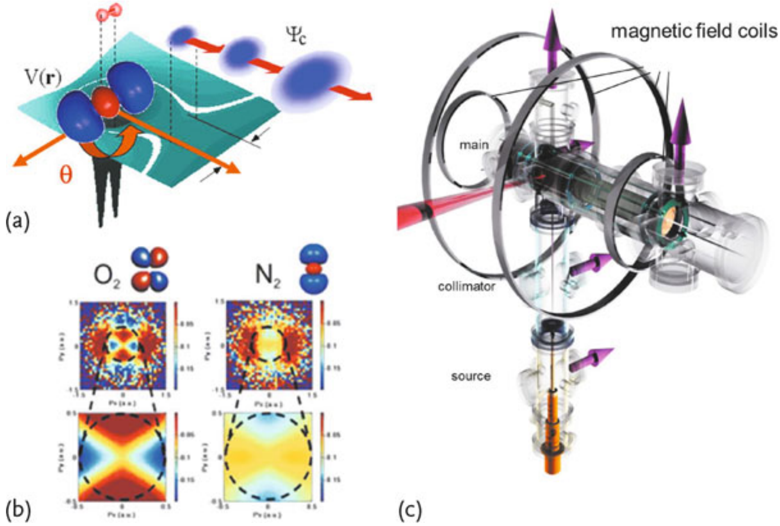


Figure 6.3 (a) Tunneling with high laser field. The ejected electron from the tunnel carries the information about the orbital that it left. (b) Recording of the momentum distribution of aligned and anti-aligned molecules is used to produce a normalized image of the electron orbital. The image recorded of low energy tunneled electrons with the highest electronic orbital calculated for nitrogen and oxygen is in agreement with the image of direct electrons [9]. (c) A schematic of a COLTRIM to synchronously record the momentum of the ejected electrons and ions. The source is the gas jet that moves up in the picture to meet with the laser (the red light from the left) at its focal spot. After the reaction the charged products are guided to their proper recording device. The high voltage bias separates the ions from electrons. The magnetic coil on the COLTRIMS overpowers the earth magnetic field and extends the travel time of electrons. COLTRIMS are made of various chambers to separate the interaction and detection procedures (courtesy of Andre Staudte and Mortiz Meckel).

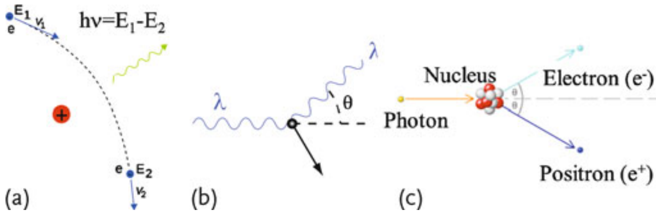


Figure 6.5 (a) Bremsstrahlung radiation or braking radiation of an electron. The electron trajectory is affected by the positive charge of the nucleus. This energy loss due to the deceleration of the electron is transferred to a photon in the x-ray and gamma ray range. (b) Compton scattering, the high energy photon is deflected by collision with electrons in matter. The photon energy is reduced (its wavelength is increased) and the energy difference is given to the electron. (c) Pair production, when a light photon has high enough energy that can produce an electron and a positron pair (= 2×511 keV), a photon can be annihilated and be replaced by matter. The excess energy is given as kinetic energy to the electron and positron going in opposite direction to conserve the momentum.

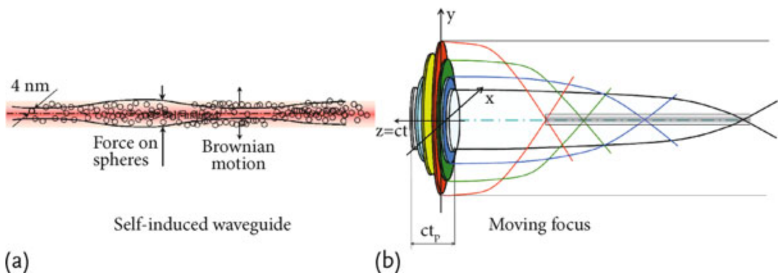


Figure 7.1 Comparison of the moving focus model and true self-induced waveguide. For the moving focus, successive slices in intensity reach a focus at a different point along the beam axis, giving the illusion of a filament. True self-waveguiding is observed in suspensions of nanospheres, which tend to aggregate in the most intense part of the beam (on the axis in the case of the figure). As the particles accumulate on the axis, they increase the average index of refraction of the suspension and create a lens. The Brownian motion counteracts this effect by dispersing the nanoparticles.

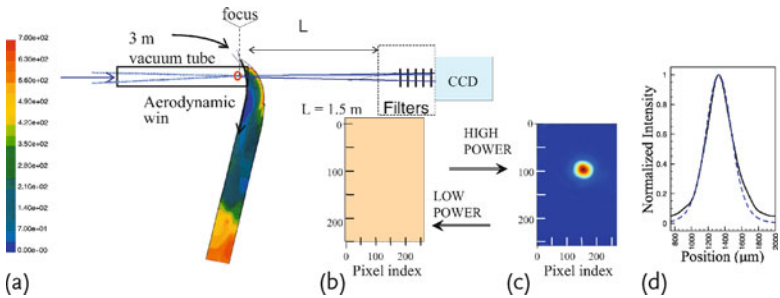


Figure 7.2 UV Filament. A 2 cm diameter high power laser beam at 266 nm is focused through a 3 m long vacuum tube. The focal spot is located 1 to 2 cm in front of the aperture of an aerodynamic window, where a supersonic flow of air serves as seal between vacuum and atmosphere. The various colors inside the expansion chamber of the aerodynamic window indicate the local pressure (from dark blue, 0 torr to red, 700–760 torr). At low intensity, the beam diverges after the focus, covering the entire aperture of the CCD at 1 m distance. At high intensity, the beam diameter remains constant at 300 μm of the 4 m propagation distance available in the laboratory. To attenuate the beam without any distortion, a 15 cm diameter mirror at grazing (89°) incidence first reduced the filament intensity by a factor of 10 million. Further attenuation can thereafter be made by simple absorbing gray filters (»neutral density filters«).

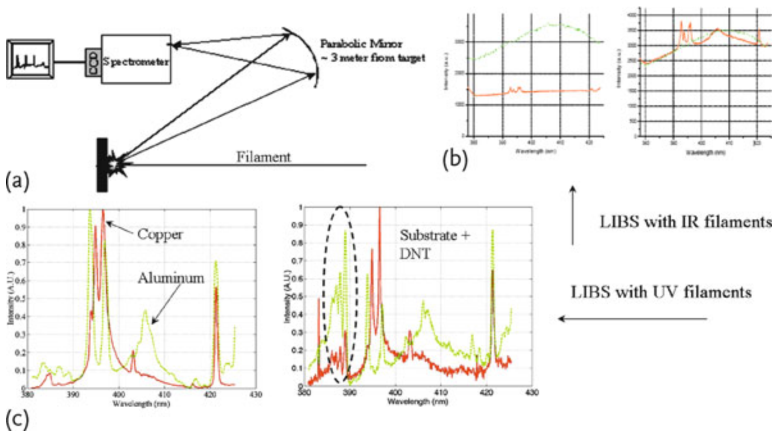


Figure 7.4 Comparison of laser-induced breakdown spectroscopy with UV and IR filaments. (a) Experimental setup. (b) Comparison of the spectrum of Al and Cu, with and without a film of DNT, through irradiation by a IR filament. No new spectral feature appears. (c) Comparison of the spectrum of Al and Cu, without (left) and with a film of DNT. Spectral lines characteristic of CNT are clearly identified.