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Lasers

The Power and Precision of Light

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WILEY-VCH Verlag GmbH & Co. KGaA

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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

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

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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?

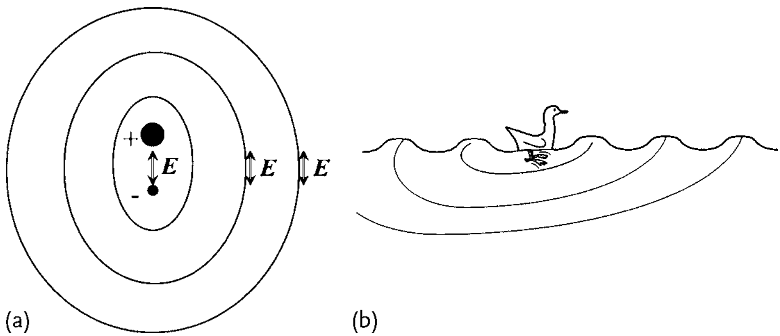

Figure 1.1 (a) An oscillating electric field is created by a pair of charges with a periodically varying distance (oscillating dipole). This periodically varying field creates an electromagnetic wave that propagates at the speed of light in vacuum, just as a wave is created in (b) by a duck paddling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

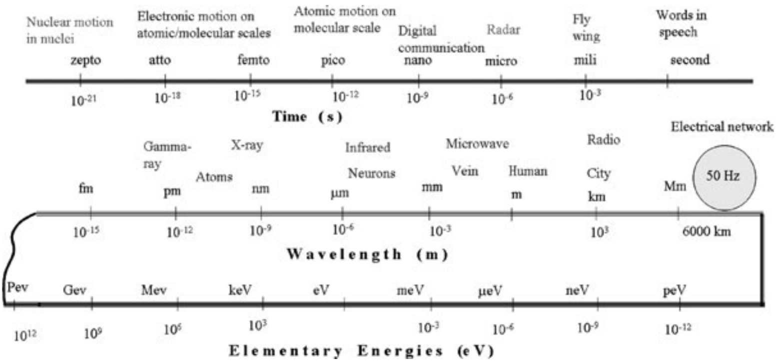

Figure 1.2 Different objects that radiate electromagnetic waves and the wavelength and elementary energy associated with them. Please find a color version of this figure on the color plates.

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

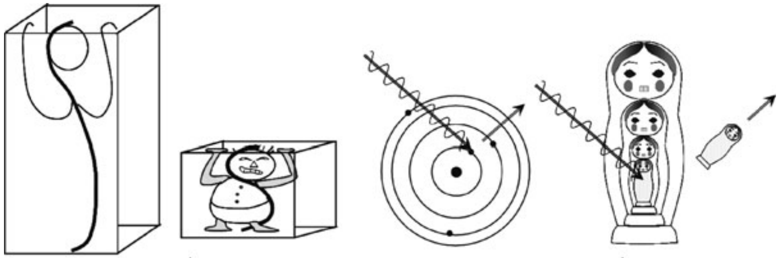

Figure 1.3 Particle and wave in a box: the longer wavelength fits in the larger box (a). A shorter wavelength fits in the smaller box (b), corresponding also to a larger particle energy. Electrons (c) orbiting around the nucleus are analogous to nested Russian dolls (d). A photon of sufficient energy 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 $(\sqrt{N})^2 I = N I$. In the case of laser light or coherent light, the elementary fields line up, resulting in a total field $N E$ 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.

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-

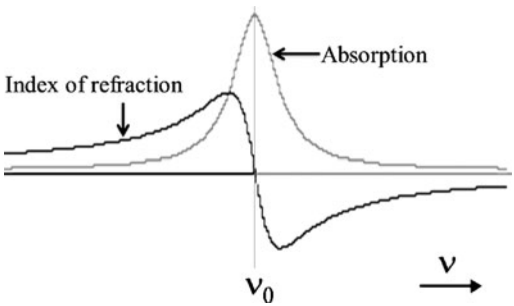

Figure 1.5 Absorption and index of refraction as a function of frequency ν. The absorption is maximized for the characteristic frequency ν_0. Any gain or absorption structure in the medium will effect the speed of light; as seen in the figure the light slows down for the frequencies less than the resonance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