# Contents

# 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 a meaning, unless we have a picture associated to each of them in our mind. The next few subsections 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". This is an old known entity originating from sun, moon. Once it was associated with fire, and thought to be the first essential element. In modern language we say that light consists actually of photons, just as matter is made of atoms. Our intuitive picture of atoms is that they can nicely be classified by 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 base, only in a finer delicate version. Photons are as ubiquitous, but quite different from atoms and their constituents. Ubiquitous, because they are associated not only with visible light, but invisible as well (infrared and ultraviolet), x-rays, gamma rays, radio waves, and even the radiation from our electrical network at 50 or 60 Hz. Quite different, because there is no mass associated to 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 start imagining more and more of the examples that the word "wave" is applied to. As a physicist we would like to have a pause and clarify some features of the wave with definitions that can be used to quantify similar observations. If you take a picture from ripples on the pond you realize that there are regular patterns that repeat in water, and you can possibly count the number of peaks in the water level, that are separated by "wavelength". You can also only look at a fixed point, and monitor its motion of water as it goes up and down, or oscillates. It takes a "period" for each point on the lake 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 example of the flag wave, the wave goes through the flag but the fabric itself is not carried away. The wave propagate 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 case, the wave starts from a local oscillation [Fig 1.1 (a)], and propagates radially from there, like rings produced by a duckling paddling on a pond [Fig. 1.1 (b)]. In the case of light, it is the electric field produced by a charge oscillating up and down that starts off the wave.

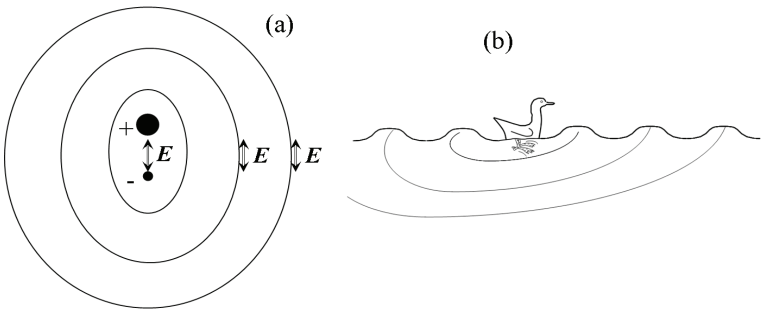


**Figure 1.1** (a) an oscillating electric field is created by a pair of charges with a periodically varying distance. This periodically varying field creates an electromagnetic wave that propagates at the speed of light in vacuum, just as a wave is created in (b) by a duck paddling in a pond.

The velocity of a wave is a property of the medium in which the wave propagates. Sound waves propagate at 343 m/s (1,125 ft/s) in dry air at room temperature, and faster in denser media. It is the opposite for the light waves which 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 movement and collision 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?

Our intuition is based on water waves in a pond, a spring oscillating, 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 given way to simply vacuum, but it does not mean that the understanding of the nature of light has become simpler.

As will be explained in the following 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 takes also discrete values, to which is associated an energy: the photon energy $h\nu$, where $\nu$ the frequency of the oscillation, and $h$ is called the "Planck constant" [see Eq. (1.1) in next section]. It is as if the duckling in Fig 1.1 (a) 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 $(1/2)h\nu$. 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 characteristic, it acts both as a wave (section 1.1.1) and as a particle. In a way photon is a wave that can be counted. This might be a bit uncomfortable for our common sense, but 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.

Lets take a closer look and see how we ignore single photons. A typical red laser pointer has an output power of 3mW (3 mJ/s), which consists of individual photon having an energy in the order of $3 \cdot 10^{-19}$ J. It means that every second there are 10000 million million photons shooting out of a pointer. If we even associate a penny to each photon, in a second we get a sum of money that is more than a wealth of a country.

Just as not all currencies have the same value, the photons have different energies.. Here we need to use the wave aspect of the photon. The faster a wave oscillate, 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. Because of that network, the earth radiates, making one oscillation over a distance of 6000 km Radio waves are long too : it takes 3 meter (3.3 yard) for a short wave (FM radio) to make an oscillation. for a long wave (AM) it takes about 300 meter (330 yard) 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 nanometer 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 wavelength of about one nanometer, oscillates 100000 times over the same paper thickness. It appears thus 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 Plank's constant, "$c$" is the speed of light , "$\nu''$ is the number of oscillation of a photon in a second, and "$\lambda''$ is the wavelength, or the length in which one oscillation takes place. For the photon associated with visible radiation, the elementary photon energy is too small to be using the traditional energy unit of Joule. Instead, the unit energy used by physicists is the electron-volt (eV). One eV ($1.602 \cdot 10^{-19}$ J) is the energy acquired by an electron that is accelerated under of potential difference of one volt. Infrared radiation at a wavelength of 1.24 $\mu$m has exactly the energy of 1 eV. As shown in table 1.2, our earth, because of the electric power network, radiates photons of an energy of... $2.067 \cdot 10^{-13}$ eV.

### 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 won't scale linearly. Body mass increases linearly with volume in three dimensions while muscle strength in arms and legs are proportional to cross sections, and therefore they increase only in two dimensions. If a human is million times more massive than an ant, he is only 10000 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 physicist like to draw a box around the object that they study, and they know as the box gets smaller they are dealing with higher 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 **??** we can look more closely at the size-energy relation. Consider fitting one full wave in two boxes with different sizes. The wave that fits in a small box has a smaller wavelength than the one in a big box. Using the photon energy equation [Eq. (1.1)], the wave with a smaller wavelength has higher energy. It seems 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 like Russian nesting dolls. The electrons in bigger shells have less energy and are loosely bound, which is why in most ionization processes the chance of knocking off from outer shell is 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 internal shells, leaving the external ones in place (not something you could to with the Russian dolls).

Looking at the waves in boxes, we were only concentrated on the concepts of size, energy and wavelength. There are other parallel manifestations of waves, such as time and frequency. If the boxes are filled with the same material, the speed of light is the same for both long and short wave. Then it is obvious that it takes less time for a short wave to make one full oscillation. The frequency of oscillation of the short wave is higher. This means that in smaller boxes we are dealing with shorter time scales and faster frequencies. This is 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 Fig. 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 one word in a femtosecond, the first Harry Potter book with 2.7 million words, the whole book was finished in a few nanosecond. Or in other words you could read Harry Potter a thousand million times in just one second. A femtosecond is to the second, as a second is to the age of the Universe.

Figure 1.2 illustrates the various sources of radiation that affect our lives, and how they are associated with energy, size and time.

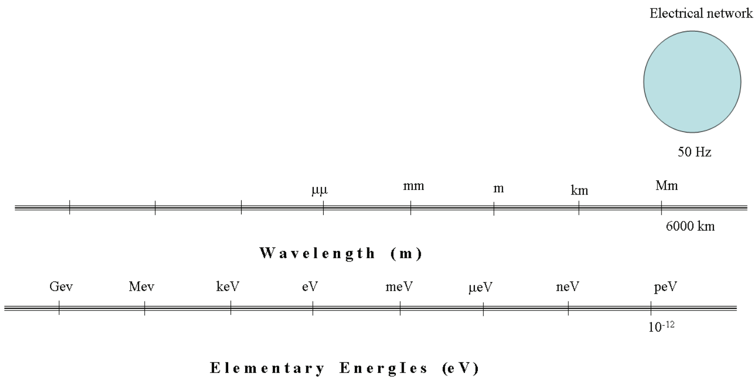


**Figure 1.2** (a) The different objects that radiate electromagnetic waves; wavelength and elementary energy associated with them.

#### 1.1.3.1 **Light energy**

In previous sections we talked about 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 a 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 in total sum is always lost, just like a photon in a light source.

However, the analogy between the currency and light stumbles at laser light. In our daily life and economics there is only one way to add numbers, luckily in science there are more. Let us assume not one ducking as in Fig. 1.1 (b), but two paddling in synchronism as if they were competing for synchronized swimming. Along certain directions the wave will add "in phase", along other direction 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. In the case of laser light, of *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 add up coherently. The total electric field is the sum of the electric field of each source element. The total *intensity* in the beam is proportional to the *square* of the total field, thus proportional of the square of the number of emitters. 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 the coherence can be found in a stock market. If we knew how to add coherently to the phase fluctuations of the market, there should 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 physicist 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 than that incoherent "white light" adds proportionally to the number of emitters $N$, rather than $N^2$? A similar addition takes place in our daily life, or 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 for the last time his favorite lamp-post. The analog 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, of $\sqrt{N}$ 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 $E_e$ of random direction adds to a total field of magnitude $\sqrt{N}E_e$. To each field $E_e$ is associated an intensity $I_e$ proportional to the square of the field. The total intensity, in the incoherent sum, is $(\sqrt{N})^2 I_e = NI_e$. In the case of laser light or coherent light, the elementary fields line up, resulting in a total field $NE_e$, and a total intensity $I = N^2 I_e$.

## 1.2
## Radiation from an atom

So far we have talked about photons as units of light energy that can be counted but are not rigid, they do act and move like waves. Now we want to know where they are coming from and how we can make them. In following sections we learn how to add them properly ( coherently ) to get a laser source. Photons are electromagnetic waves and they generate 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 do act like waves, which means that it is hard to point at them, they are moving around. Electrons are moving around nucleus of the atoms in well defined shells. There are steps of energy and an electron can absorb a photon to change its energy a ph

**Figure 1.3** (a) The different objects that radiated electromagnetic waves; wavelength and elementary energy associated with them.

how to get photons stimulated and spontaneous emission shopping

### 1.2.1
### About the nature of the wave

POLARIZATION

## 1.3
## The black box that emits light

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. It has in general two main components: a medium with optical gain discussed in the previous section, and a "resonator", responsible for selecting the laser wavelength. The gain medium is the source of energy, a converter of electrical or chemical energy into optical energy.

The resonator or optical cavity is not mentioned in the acronym, despite its essential role in the generation of laser light.

The analogy 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 all have heard the high pitch noise that drowns any other sound when the gain of the amplifier is turned up. Some noise from the speaker enters the microphone, gets amplified, blasted from the speaker into the microphone again, etc... It is a case of dog chasing his tail. There exists the same synergy 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 int the "input". In the "acoustic laser", 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 ...

The closest analogy to the laser is that sketched in Fig. 1.4 (a), 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, resulting 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 Fig. 1.4 (b). 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 wavelength has to fit in the "box" defined by the two mirrors of the laser resonator, or the crest and the through of successive waves will cancel each other. A similar situation occurs when a birdie takes a bath in a perfect rectangular container. No matter how wild he splashes in the water, he will produce standing waves that fit exactly the length of the box. This is a one dimensional analogy – we should here assume 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 non-perfectly axial beam will still reflect back within a narrow cone. But... it is no longer the "ideal resonator".

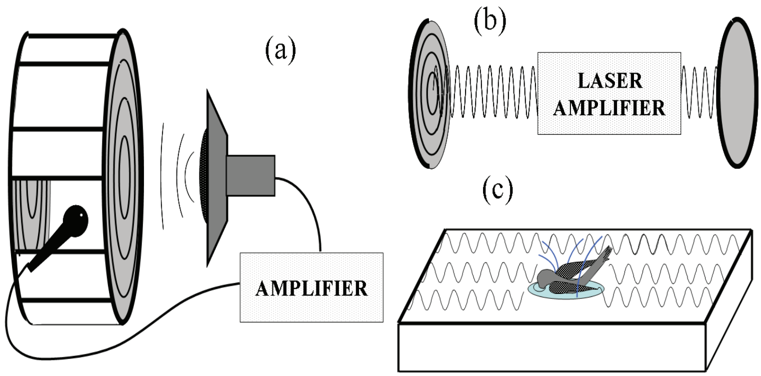


**Figure 1.4** (a) An acoustic analogy of the laser: an amplifier with feedback. The pitch or wavelength of the sound produced is determined by the acoustic (mechanical) resonance of the drum. The laser is also an amplifier with feedback. A light beam that happens to be perpendicular to the two mirrors 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 birdie that takes a bath: out of all the "noise waves" that he 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.

The light amplifier and the resonator are not in perfect symbiosis, but thrive for different properties. As in acoustic, 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 $n_\lambda = 1000000$ wavelengths of one micron in a round-trip (1 m). At a wavelength of 0.9999995 micron, the round-trip corresponds to 1000000.5 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. Let us take as an example a mirror of reflectivity of 100%, and the "output coupler" or reflectivity 99.9%. To understand why the selectivity is high, let us turn off the gain, and visualize a beam of intensity $I_i$ rattling back and forth between the mirrors. The intensity will have dropped to $I_i/2$ after $n$ round-trips such that $(0.999^n)I_i == I_i/2$. Playing a bit with a calculator, and one finds that the intensity has dropped to 1/2 of its initial value after 693 round-trips. The effective length of the cavity has now been multiplied by 693. In the example of the 0.5 m cavity, even a wavelength off by $\lambda/(n_lambda \times n)$ will be selected out, because it will interfere destructively with itself after $n$ round-trips.

While a laser with a good resonator – called a "high $Q$" cavity,[1] provides a stringent wavelength selection, it does not produce large output power. Only a trickle (0.02%) of the power generated inside the resonator leaks out as useful output. In

1) The letter $Q$ is used to designate a "Quality factor" of a resonator – it is proportional to the number $n$ of round-trips that survive in the cavity.

order to get a large power out of a laser, one would like an end cavity mirror of large transmission, for instance 50%, requiring a gain of at least a factor 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 on round-trip, any oblique ray that experiences two traversal of the gain volume will be part of the output beam.

### 1.3.1 Which came first, the technology or the idea?

#### 1.3.1.1 He-Ne lasers

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 "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, 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 60's, just after the first Helium-Neon laser was demonstrated, Dr. Haisma at Philips Research Laboratories in Eindhoven took on the challenge to make the perfect laser with perfect flat resonator. The result was a thick wall cylinder of quartz, polished at both end to better than 0.05 micron flatness, and a parallelism of better than 1 second of arc. Picture to find? Mirrors and the polished quartz were of such perfect flatness and polished that they formed a vacuum tight seal when put in contact — a technique not very often used because of the stringent finish requirements. There was no alignment possible, no room for error. But it worked, and was probably the first and last of its kind. The perfectly cylindrically symmetric laser allowed to put some fundamental questions to test, what is the electric field produced by a laser? Is it always a linearly polarized beam, and 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.

#### 1.3.1.2 Lasers for the cavemen

Other gas lasers, such as 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 built and more efficient than, for instance, ultraviolet lasers.

The reason is that spontaneous emission rates are higher for more energetic transitions. The kids suicide rate increases with the height – they all have acrophobia?

## 1.4
## Energy storage and brutal release

### 1.4.1
### The laser as energy storage

A low gain laser required 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 the level of water, and the pressure increases when a river is dammed (Fig. 1.5). The power input to the laser comes eventually 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 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.

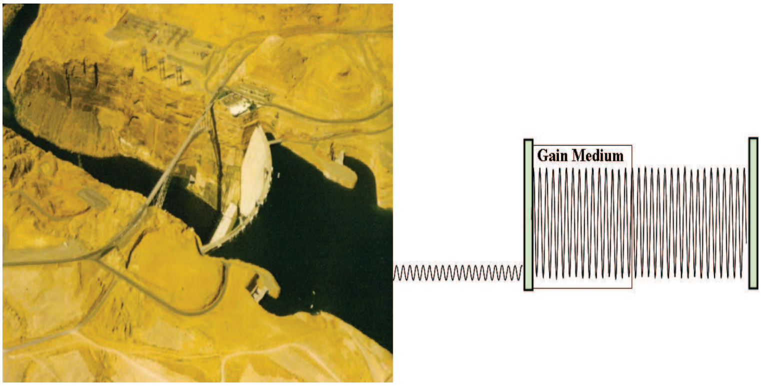


**Figure 1.5** Optical power is stored between the two mirrors of a laser cavity. The laser beam issued from this device is actually the trickle transmitted by the output mirror. This is the analogous situation as in a dam: most of the energy is stored in the lake before the dam. Only a small fraction of the stored water flows through the release of the dam.

### 1.4.2
### saturation

Saturation is an 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. The more power in a laser beam, i.e. 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 be seen also as a gate that gives way under the pressure of a crowd (in this case of photons). This properties is used quite often in laser technology as a fast gate that gives way to an excess of optical energy.

### 1.4.3 Storing and releasing the energy

#### 1.4.3.1 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. 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 laser, a cavity mirror should be removed, so that the gain can accumulate 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. Then the mirror is suddenly put in place, allowing the laser oscillation to start at a very fast pace, because the gain has reached a high value.

#### 1.4.3.2 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 [**?** ], that was used for Q-switching a $CO_2$ laser at Philips Research Laboratories in Eindhoven, the Netherlands, is shown in Fig. 1.6. The alignment of the rotating mirror is rather easy: there is only one degree of freedom (around an horizontal axis), since the mirror is scanning 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 1.3.1.2. During most of the revolution of the shaft, the laser cavity is not aligned, and the gain accumulate. 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 strigent 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 60's, it was abandoned in favor of either electronic Q-switching or passive Q-switching.

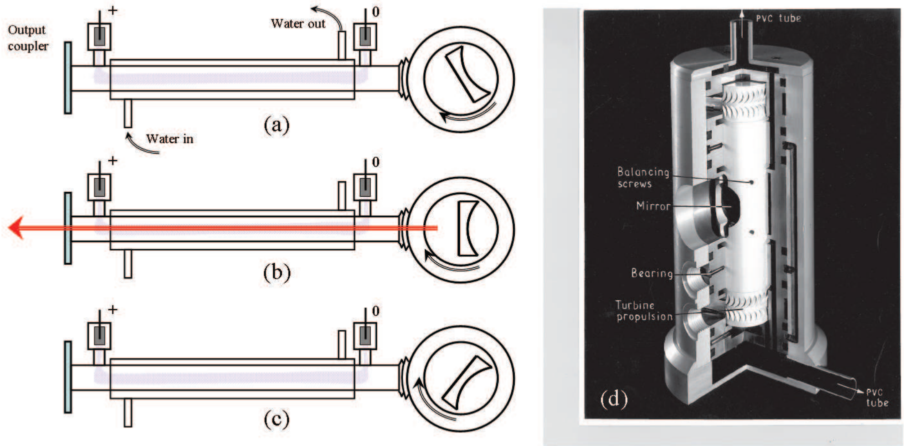


**Figure 1.6** (a) A $CO_2$ laser tube is closed at one end by a partial reflectivity mirror uncoated germanium plate, or coated ZnSe plate). The other end is sealed with an enclosure containing the rotating mirror. In position (a), with the rotating mirror at a non-zero incidence with respect to the 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). In (c), an exploded view of an air turbine used for Q-switching. The rotation speed could reach 60,000 revolutions/minute, limited by the centrifugal expansion of the shaft.

### 1.4.3.3 **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 it peak value. This technique was conceived and demonstrated by Hellwarth and co-workers at the early days of the ruby laser [**?** ]. The key to optical switching is the Kerr effect, which is a change of the index of refraction of a material under application of an electric field. The original implementation involved a liquid. Today's Q-switch elements are nonlinear crystals called Pockel's cells. The principle involves the manipulation of the laser polarization discussed in Section 1.2.1.

### 1.4.3.4 **Passive Q-switching**

The solution is to minimize or even stop the release, let the water level raise to its highest level, and blow up the dam, as in Fig. 1.7.

### 1.4.3.5 **Cavity Dumping**

"Blowing up the dam" is a brute force method that has some equivalents in the laser field. A common device is

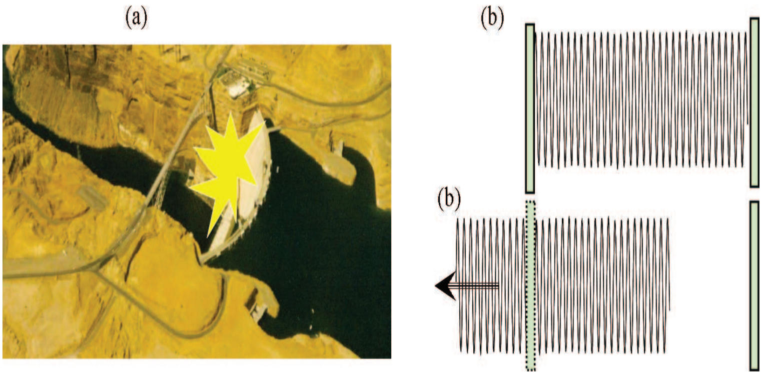


**Figure 1.7** (a) A dam is filled slowly to capacity, ideally by closing all water release. The energy stored by the dam can be released in a minimum amount of time by blowing up the dam. Similarly, in a laser cavity with totally reflecting mirrors, the optical power increases slowly with time. The method 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.

## 1.5 The generation of ultrashort pulses

The methods of "Q-switching" and "cavity dumping" produce energetic laser pulses, but not the shortest possible. As shown in the previous sections, the shortest pulse that can be generated correspond to the length of the laser. Since this packet of energy propagating at the speed of light of $3 \cdot 10^8$ m/s, the pulse dumped from a 1 meter long cavity will pass through an object in a time of $1/(3 \cdot 10^8) = 3 \cdot 10^{-9}$ s = 3 ns. This is not a short time by the standard of "ultrashort pulses". The conformation of the laser producing extremely short pulses is as simple as the elementary device sketched in Fig. **??**. Yet, each of the element of the cavity has to have its property accurately selected, in order to develop the shortest pulse possible.

### 1.5.1 Mechanism of pulse compression by propagation

To understand how short pulses can be generated, we refer to Section **??** 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 mechanism in the production of ultrashort pulses in a laser: A mechanism —dubbed "nonlinear" because it is dependent 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, we have seen that all waves have to "fit in the box", i.e.

they 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 packet (long wavelength) that constitute the "wave packet". This wavelength dependence of the velocity is called dispersion, and applies to water waves as well. How could then ultrashort pulses be generated, in presence of this ubiquitous dispersion? The answer is in a nonlinear phenomenon, by which the wave velocity is linked to the intensity of the wave. The speed of light is highest in vacuum: $c = 299792458$ m / s As it propagates through matter, it is slowed down by the interaction with atoms and molecules, resulting in a wave velocity $v_w = c/n$ where $n$ is called 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, 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" [Fig. 1.8 (a)]. This is the important first step in pulse compression: the sweep in frequency, such that the lower frequencies are pushed ahead of the pulse, and the higher frequencies towards the trailing edge. The trick to continuously compress the pulse is now to select the cavity of the laser such that the lower frequencies propagate slower than the higher frequencies[2)], which implies that the leading edge moves towards the peak, and the trailing edge recedes ...also towards the peak. Hence, the pulse is compressed, as sketched in Fig. 1.8 (b).

## 1.5.2
## From water to laser, back to water, then back to laser

### 1.5.2.1 From water to laser: the soliton

The equation that describe this evolution 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, 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) [**?** ] who named it "the wave of translation". In 1834 he was riding by the Grand Union Canal at Hermis-

2) This is called a cavity with negative dispersion.

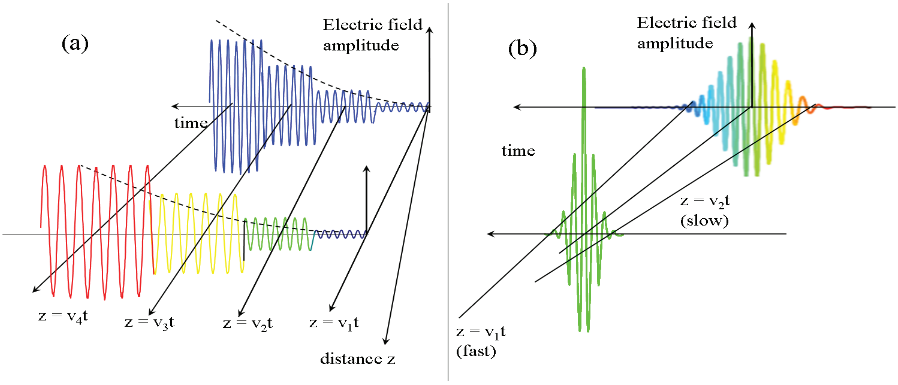


**Figure 1.8** (a) Generation of new optical frequencies by propagation of a pulse in a medium where the wave velocity increases with intensity. The optical signal of increasing intensity is shown as having a stepwise increase on its leading edge (the time axis is pointing left, for a better visualization of a pulse propagating to the right). The difference 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, i.e. a pulse of which the optical frequency increases with time. 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.

ton, 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 60's 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 [**?** ]. 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. Fig 1.9 shows a picture of a re-creation of that event.

#### 1.5.2.2 **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 thee propagation of ultrashort optical pulses, came under renewed interest to solve a puzzling problem of oceanographers. It was the biggest mystery of the seas. Large ships disappeared over centuries, without leaving any tracks. It lead to the creation of myths of Sea Monsters, then that of "Giant waves". These stories were dismissed as seaman's tales, until two well documented events in 1995. The first was an automated recording at the Norwegian Oilplatform Draupner-E, which indicated in the New Yeare night a single wave of 26 meter height. The second was on September 11 of the

**Figure 1.9** Recreation of the soliton in 1984– soliton home page, Heriot Watt University http://www.ma.hw.ac.uk/solitons/index.html

same year, when the luxury liner Queen Elezabeth 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 2 November 14, 2002]. All oceanographic models so far predicted a statistical distribution of waves not exceeding 7 meter, 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 have only a very small, but finite probability to be in the condition of "pulse compression" defined in Section 1.5.1, hence the freak occurrence of the "giant wave".

#### 1.5.2.3 **Back from water to laser: freak colors**

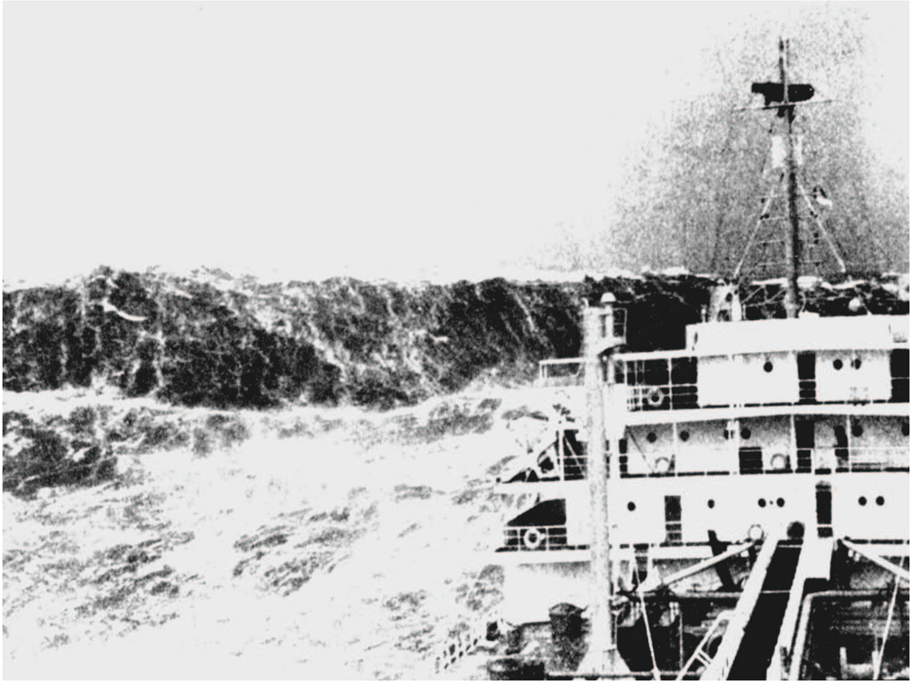

**Figure 1.10** Merchant=20 ship laboring in heavy seas as huge wave looms astern. Huge = waves=20 are common near the 100-fathom curve on the Bay of Biscay. = Published=20 in Fall 1993 issue of Mariner's Weather Log=20 Image = ID:=20 wea00800, NOAA's National Weather Service (NWS) Collection = Location: Atlantic Ocean, Bay of = Biscay Photo=20 Date: 1940 ca.

### 1.5.3 The nature of a pulse

labelnatureofpulse 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 on one point, 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 Fig. 1.13, were 5 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 add up to 5 $\times$ the field of a single wave, which implies that the intensity is 25 $\times$ 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.

Figure 1.11

### 1.5.4 **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 Fig. 1.1. He produces a series of waves that have different wavelengths, with the condition that all these wavelengths are a submultiple of the box length.

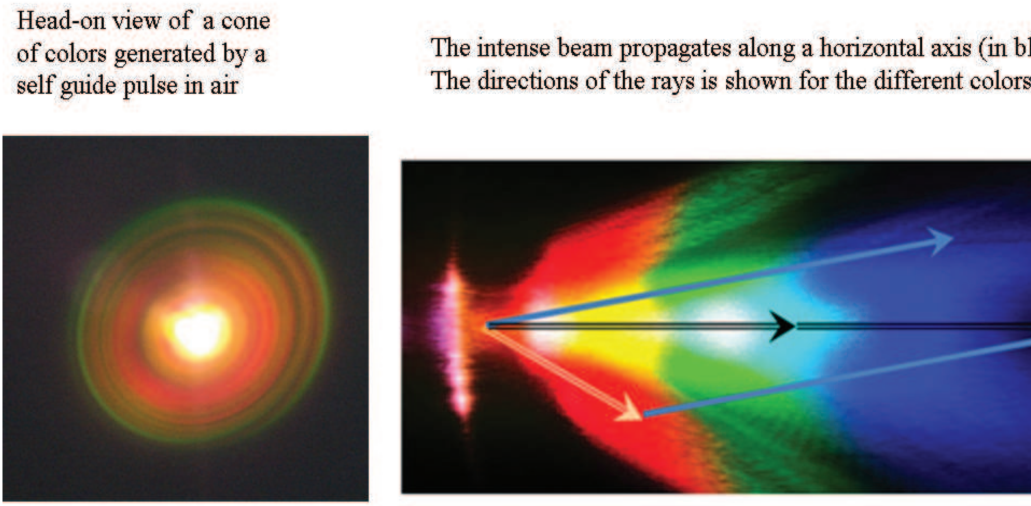


**Figure 1.12**

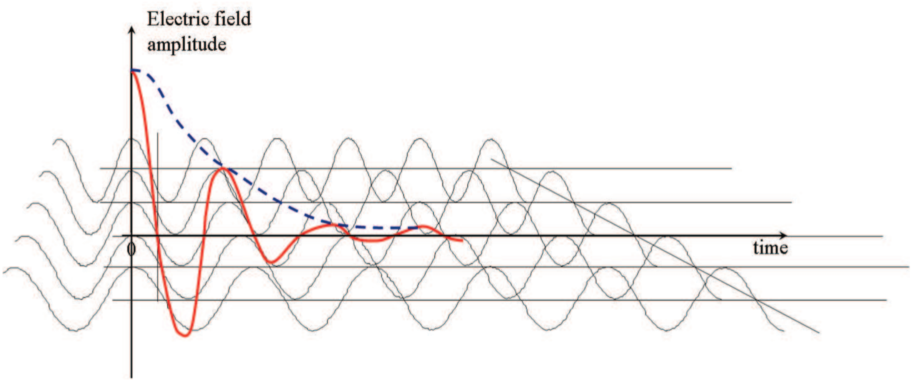


**Figure 1.13** Five waves are added in top of each other, such that at a given time all the crests coincide.

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