CHAPTER 1

Physics of lasers and LEDs: Basic concepts

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Lasers

Laser light has very specific properties, thanks to the way that electromagnetic radiation is generated, and these properties are especially useful in science and technology. A special process produces laser light and this depends on some aspects of the interaction between the atoms that constitute matter and the electromagnetic radiation. To understand why laser light has unique properties, comprehension of the basic concepts of physics is required and these are explained in this chapter.

Key points to be understood include atomic structure, and how light originates and the path it takes through matter. The concept of the atom can be traced back to the ancient philosophers. They defined the "atom," from the Greek for "not divisible," as the smallest possible portion of a rock that could be formed by repeatedly splitting a rock until it could not be split further and without changing the basic properties of the original rock. They believed the atom was indestructible, a belief that has been disproved by scientific advances.

In 1808, the British scientist John Dalton scientifically defined the atom: "The atom is the smallest matter particle. It is indestructible. Its mass and size cannot be changed. Atoms may combine with each other, creating other species of matter." The current definition of the atom diverges from that of Dalton. Unlike in current models, Dalton viewed the atom as a rigid sphere. Nevertheless, Dalton's simplified model may still be used in describing situations such as chemical reactions and the law of definite proportions (Proust's law), in which atoms may be considered as rigid spheres.

Later in the 18th century, Ernest Rutherford, a British scientist, introduced new concepts about atomic structure (the reader is referred to basic chemistry and physics texts for a detailed description of his model). His main concept was that "the atom would be constituted of a central part, called nucleus, and it has positive electric charge. The nucleus's size would be smaller than the atom's size (100 000–10 000 times smaller)." The question then was: if the atom has a nucleus with an expressive positive charge, how is it that matter is usually neutral? Rutherford answered the question by proposing that the positive charge of the nucleus is balanced by particles with a negative charge, called "electrons," which revolve around the nucleus. He proposed a dynamic balance, as illustrated in Figure 1.1, because if electrons were not moving, they would be attracted to the nucleus.

However, there was a problem with Rutherford's model of an electric charge revolving around the nucleus. Electromagnetic theory at that time had already determined that electrically charged particles (such as electrons) emit energy when they accelerate. Therefore, in Rutherford's model, electrons should emit energy constantly (since a curved trajectory implies acceleration according to Newton's laws) and as a result, the radius of their circular trajectory will reduce as kinetic energy, which sustains their movement, is lost. According to this theory, matter would quickly collapse as electrons fall inwards and onto the nucleus.

The Danish physician Niels Bohr (1885–1962) used the basic ideas of Max Planck (1858–1947) to solve the problem of why matter does not collapse. He made certain propositions, known as "Bohr's postulates," to explain the electron–nucleus dynamics:

1. The electrons revolving around the nucleus follow well-defined circular orbits, under the influence of the Coulomb attraction.
2. The radii of the orbits of the electrons around the nucleus can only assume certain values, proportional to $h/2\pi$ (where h is Planck's constant).
3. The energy of the atom has a definite value when the electrons are in a given stationary orbit. When an electron moves to a new orbit, energy is absorbed or emitted. The amount of absorbed/emitted energy can be obtained from the expression $\Delta E = hf$, where ΔE is the energy absorbed or emitted, h is Planck's constant, and f is the frequency of radiation (see later in this chapter). Note that ΔE is the energy difference between the two stationary orbits involved in the process.

The energy emitted or absorbed by an electron when it changes its orbit was named a "photon." A photon can be viewed as a small energy "packet" or "quantum." Therefore, when the

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electron moves to an orbit closer to the nucleus, it emits a photon; when it moves to an orbit that is farther from the nucleus, it absorbs a photon (Fig. 1.2). Bohr assumed that the angular momentum ($\vec{L} = \vec{r}\,\mathrm{x}\,m\vec{v}$, where $\vec{r}$ is the radius vector, m is the scalar mass, and $\vec{v}$ is the velocity vector) of the electron revolving around the nucleus was an integral multiple of Planck's constant h divided by 2π. This is called Bohr's quantization rule.

Bohr's ideas were not pulled out of the hat, but based on experimental studies of the emission spectrum of hydrogen. To understand what is meant by "spectrum," think about white light passing through a prism (Fig. 1.3). It is decomposed into all the colors that constitute the visible light spectrum. This same phenomenon creates rainbows, where water droplets act as spherical prisms and the sun is the light source. Bohr used this technique to decompose the light spectrum emitted by a hydrogen gas lamp.

The frequency of each light wave (which our eyes interpret as different colors) is associated with its length (the so-called "wavelength"). A light wave oscillates in time and space. If we stop it in time, its wavelength is the distance at which the wave shape repeats itself. If we stop it in one specific position, its frequency is the number of times the wave repeats itself (cycles) per second. Several, hardly distinguishable wavelengths constitute what we call the "white" color, and the observed effect is called a "continuum spectrum."

Bohr observed discrete lines of emission in the spectrum of the hydrogen lamp. The word "discrete" here means that there are separated, very specific lines, which are observed instead of a continuum spectrum composed of photons carrying a specific amount or quantum of energy (Fig. 1.4). These discrete lines in the spectrum from the hydrogen lamp are composed of a few specific wavelengths only; this is referred to as a "discrete spectrum." However, how is the emission generated?

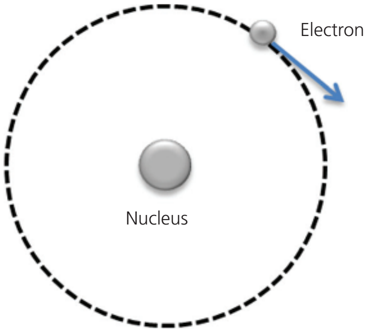

Figure 1.1 Schematic of the atom according to Bohr.

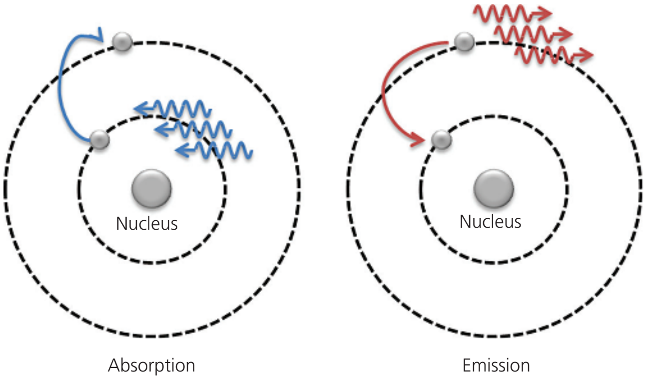

Figure 1.2 Representation of absorption and emission of photons by an electron, with transition to an energy level farther from (absorption) or closer to the nucleus (emission).

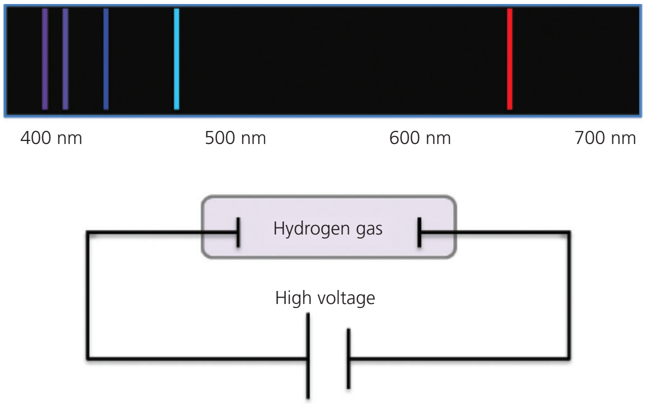

Figure 1.4 Schematic of the hydrogen gas lamp (bottom) and the specific lines (wavelengths) obtained form the emission of that gas (top).

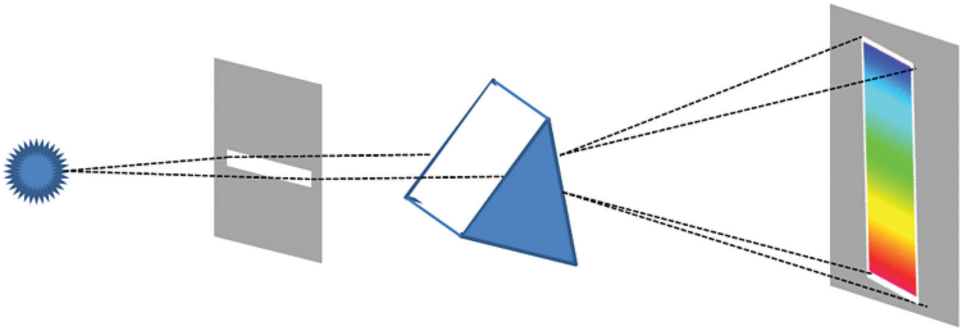

Figure 1.3 A beam of white light may be diffracted into different colors when passed through a prism. Each wavelength has a specific angle of diffraction, which "bends" light more or less, separating the colors (the colors of the rainbow are seen because of this phenomenon when water droplets diffract light).

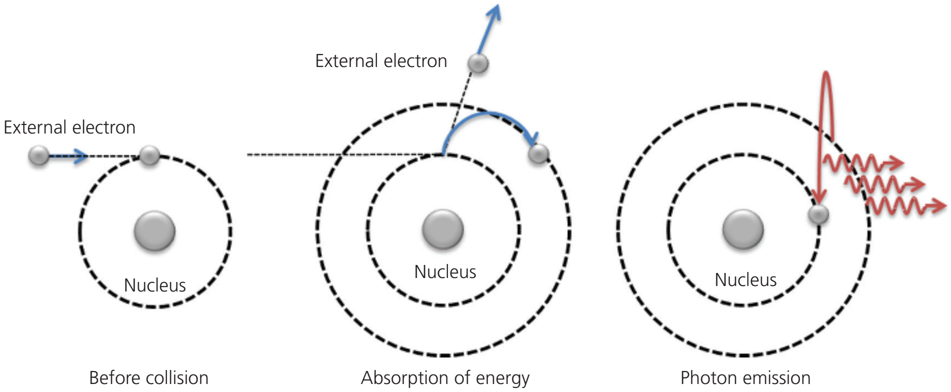

Figure 1.5 Example of an external electron interacting with an electron in an atom: the incoming electron collides with the internal electron, transfering energy to it; the incoming electron can then move to an orbit farther from the nucleus; this new orbit can accommodate an electron with this new amount of energy. Later, this excited electron emits energy (e.g. as photons) and "relaxes" back to a lower energy level.

When a gas, such as hydrogen, at low pressure is subjected to a high voltage between two electrodes, an electrical field is generated in the tube and the free electrons in the ionized gas are accelerated from the cathode to the anode. On their path, the free electrons may collide with hydrogen atoms and transfer energy to the latter. The "ground" state electron (i.e. the one having the minimum possible energy) in the hydrogen atom absorbs the energy and moves to an orbit farther from the nucleus. This process is called "excitation"; it is said that the electron moves to an "excited" state.

An excited state is unstable as the most stable atomic configuration is the one with the lowest possible energy. Therefore, shortly after absorbing this energy, the atom "expels" it (which may happen in many different forms) and the electron returns to its most stable orbit. Therefore, as illustrated in Figure 1.5, a photon can emit energy equivalent to the energy difference between the two orbits. Different photons, with different energies, may be emitted by the atom because following the collision between an electron and an atom, the atom's electron might be excited to different orbits depending on the amount of energy absorbed. However, only certain photon energies can be observed and these make up the discrete spectrum observed by Bohr. The spectrum provides a "fingerprint" of the atom, where each photon represents emission from a different orbit.

Electrons within a given orbit have a specific energy. The orbits are called "energy levels." Each energy level is assigned an integer number ($n = 1, 2, 3\ldots$), which is called the "principal quantum number" and corresponds to the number obtained from Bohr's quantization rule. This number characterizes the energy for an electron in a specific orbit and the "leaps" between two energy levels are called "electronic transitions". The wavelength for a photon emitted when an electron moves to an orbit closer to the nucleus will not be observed if it falls outside the visible spectrum.

The above may appear to be a long explanation, but understanding how electrons allow atoms and molecules to absorb and emit light is critical to understanding how the laser works.

Laser light generation

So far, we have discussed two main processes: absorption and emission. When an atom (or molecule) absorbs a photon, this energy promotes an electron to a more energetic state. When emitting a photon, an atom (or molecule) expels energy corresponding to the difference between the excited and the more stable state involved.

A third and equally important process for atomic systems needs to be considered: the *stimulated emission*. Suppose that an atom is in an excited state. As has already been discussed, this is not a stable condition and the atom will eventually return to its fundamental state. In fact, any disturbance in its equilibrium may result in decay from the excited state, with consequent emission. Therefore, the amount of time that the system stays in the excited state, called the "lifetime" of the excited state, is an essential characteristic of the atomic system for the generation of laser light. In stimulated emission, if a photon "passes nearby" an excited atom, it can induce an electrical perturbation (which works as a "seed") that stimulates the system to emit an identical photon, but only if the lifetime of the excited state is long enough to allow the photon to pass by the atom, therefore increasing the "probability" of the event occurring. Also, the photon energy has to correspond to a permitted (i.e. highly probable) electronic transition of the atomic system. The stimulated photon may be seen as the "twin" of the seed photon. They both have the same energy; therefore, their frequencies and wavelengths are identical and they leave the atomic system with the same direction and "phase" (i.e. they propagate in unison in space).

Figure 1.6 shows the three processes that have been described. The schematic on the left represents the absorption process, where a photon interacts with the atomic system and is absorbed. In the middle schematic, emission is represented, where the atomic system, which is in the excited state, emits a photon and an electron is demoted to a lower energy level. On the right, stimulated emission is represented, where a photon stimulates the emission of a second, identical photon.

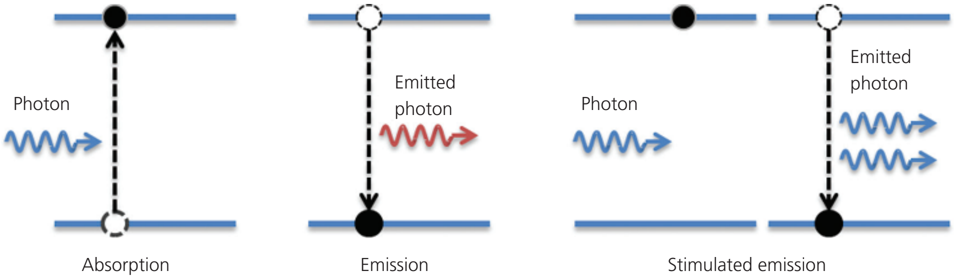

Figure 1.6 Schematic comparing absorption, simple emission, and stimulated emission of radiation. The latter processes both start with the first one (absorption), but the last one needs an excited electron to be disturbed by its interaction with a photon with the same energy as the one to be emitted. When this happens, a photon is emitted in phase with the incoming photon, and with the same energy (i.e. wavelength).

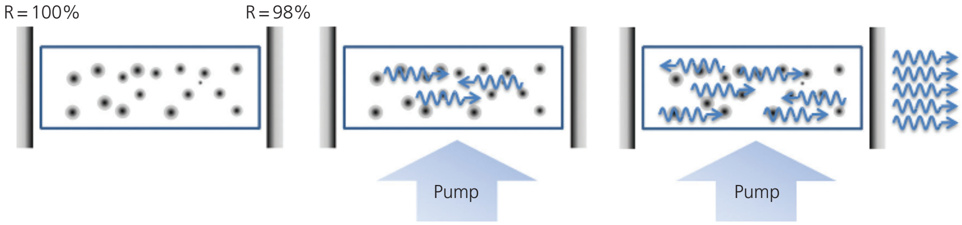

Figure 1.7 Schematic showing the generation of laser light. The active medium (rectangle) has a mirror at each end: one is a 100% reflector and the other is a partial reflector (e.g. 98%; the remaining light leaves the medium). An energy source (electricity, another laser, etc.) is used to "pump" electrons to the excited states so that photons can be stimulated. Those photons are reflected backwards and forwards inside the cavity and stimulate new photons. Part of the energy is emitted as the laser beam.

If the conditions are correct, each of the two resulting photons from the stimulated emission will disturb other excited atoms, promoting more stimulated emissions. Therefore, there is a cascade of stimulated emissions. These stimulated emissions are later amplified by the laser device design, and it is this amplification of the stimulated emission that results in laser light generation.

Consider a material medium (active medium) where most of the atoms are in excited states (this is known as "inversion of population," because under normal conditions, the majority of the atoms will not be excited). Suppose a photon stimulates the emission of a second photon in this medium. Each of those photons may stimulate new emissions if they interact with other already excited atoms. This generates four photons, then eight, and so on. Very quickly there will be a great number of photons emitted in the same direction, since each stimulated photon is released in the direction of its seed. Then, if all those photons are redirected back to the active medium (using mirrors, for example) and the medium is maintained in the inversion of population condition (i.e. if electrons are constantly excited), in a very short time a huge number of photons with the same characteristics will be generated. This is the basis of the technique known as "**L**ight **A**mplification by **S**timulated **E**mission of **R**adiation" – or just LASER.

Laser devices must include an optical cavity to produce the laser beam (or "ray"). It is usually composed of the active medium (composed of atoms and molecules whose electrons will be excited to obtain the stimulated photons) plus two mirrored surfaces at the extremities: one must be a complete reflector, and the other a semi-reflector. These are necessary to keep a positive gain of photons inside the optical cavity (i.e. more photons are emitted than absorbed by the active medium) and also to emit part of the beam (generated photons) out of the cavity. The complete reflector surface ensures generated and stimulated photons repeatedly travel back and forth through the cavity, stimulating even more photons, and the semi-reflector surface emits part of the generated beam.

However, if the generation of new photons is to be maintained, electrons must be continuously excited, or "pumped" to the excited state. If most electrons have returned to their ground states, no stimulated or spontaneous emissions will be achieved. This pumping is achieved by connecting an external energy source (such as a light source – sometimes other lasers, electrical discharges, chemical reactions, etc.) to the cavity. If excited electrons emit radiation, spontaneous or stimulated, they can be returned to the excited state.

With appropriate parameters, the probability of stimulated emission can be kept very high within the cavity and a laser beam will be produced. Thus, to create and sustain the optimum conditions within the cavity, it is necessary to feed the active medium with energy so that the inversion of population remains, and to keep redirecting the photons to the active medium, to maintain a positive feedback and sustain the stimulated emission. Figure 1.7 represents one possible configuration for a laser. The atoms/molecules in the medium form the active medium; the 100% and the 98% mirror complete the laser cavity.

From the moment the pump is turned on (low input energy), the atomic systems are excited and start to emit spontaneously; only a few atoms may be stimulated to emit. Once energy input reaches a certain level (the threshold), the stimulated emissions outnumber the spontaneous emissions; the former are suppressed and almost all the atoms in the active medium are stimulated to emit. Hence, the output light beam, which is released from the cavity by the semi-reflector mirror, is composed of photons that share the same characteristics: energy (wavelength and frequency), direction, and phase coherence.

The active medium may be solid, liquid or gaseous. Common materials are sapphire or ruby crystals (a ruby crystal rod was the active medium for the first laser ever constructed), dye solutions, and argon ion, nitrogen or neon gases. Active media should maintain electrons in the excited state for as long as possible (10^{-10} seconds is the usual lifetime – the duration of the excited state before decay), so that as many electrons as possible may achieve the excited state, allowing the stimulated emission of a massive number of photons. This is also necessary to compensate for photons absorbed by the medium and maintain a positive balance of photons in the laser cavity.

Since light wavelength is related to the photon energy, to obtain a laser beam with a specific wavelength, the active medium must allow energy transitions corresponding exactly to the energy of the desired photons. Additionally, the length of the cavity must be a multiple of the desired wavelength if light is to be released from the cavity and control of the coherence is to be maintained within the cavity. If it is not, light will repeatedly be reflected within the cavity and photons will lose their relative phase coherence; thus, the positive balance within the cavity will be lost. The reasons why this happens will not be discussed in detail, but briefly it should be appreciated that a light wave propagates as continuous cycles of its wavelength, and if a wavelength is not a multiple of the length of the cavity, light will not be emitted. From this it follows that the length of the cavity is a determinant of the wavelengths of the output.

In summary, a laser device needs to achieve an inversion of population and start spontaneous emission. Each spontaneous photon then promotes the stimulated emission of another identical photon. A cascade of photons is obtained as mirrors at the extremities of the optical cavity deflect photons back into the active medium. Electrons are constantly pumped back to excited states by an external energy source. Millions of cycles of this process produce a huge number of identical photons (light amplification). Finally, the semi-reflective mirror releases part of the light from the cavity – the laser beam.

This complex process is worthwhile because a laser beam is not "just" light: it is a very special kind of light! A laser beam has important characteristics that give it several technological and scientific applications. The light emitted by lasers is different from that produced by more common light sources such as incandescent bulbs, fluorescent lamps, and high power arc lamps. Laser light is nearly monochromatic, coherent, and its beam has directionality; a very high power output is achieved as a result.

All common light sources emit light of many different wavelengths. As mentioned previously, white light contains all, or most, of the colors of the visible spectrum. Ordinary colored light, such as that emitted by colored lamps, consists of a broad range of wavelengths covering a particular portion of the visible light spectrum. The beam of a laser, on the other hand, is a very pure color. It consists of an extremely narrow range of wavelengths. It is said to be nearly "monochromatic."

Monochromaticity (or near monochromaticity) is a unique property of laser light. This characteristic is associated with photon frequency and hence photon energy, and is unique because it reflects the specific transitions of the electrons that are excited to obtain those photons. Perfectly monochromatic light cannot be produced even by a laser, but laser light is many times more monochromatic than the light from any other source.

Why is monochromaticity important? As discussed earlier, both atomic absorption and emission have an intrinsic relationship with the photon energy (color). If one needs to excite a specific electronic transition within a medium, the effect will be much more efficient if the photon used has the same energy as (or is very close to) the energy of the transition, because otherwise a great amount of energy is wasted in generating photons that are not used for the desired transition. The efficiency will impact on the amount of power necessary to obtain the desired effect. If excitation can be efficiently achieved, less power is needed to obtain the same results. For example, when comparing a colored lamp and a laser, both in the same color range, to obtain excitation of the transition for 633 nm (red photons), a laser emitting at a wavelength of 633 nm will be fully utilized in excitation, while only a very small portion of light from a lamp's emission spectrum (hundreds of wavelengths between, say, 610 and 660 nm) will achieve the same effect, requiring much more energy to be provided by the lamp for 633-nm emission.

Conventional light sources, such as an incandescent bulb, usually emit light in all directions. Even though one can use lenses, reflectors, and other kinds of optical systems to collimate the emitted light, such that it is emitted in a directed beam, this beam always diverges (spreads) more rapidly than the beam generated by a laser. This leads to a decrease in light intensity with increasing distance from the light source.

Directionality is the characteristic of laser light that makes it travel in a single direction, with only a narrow cone of divergence. Collimated light, that is a perfectly parallel beam of directional light, cannot be produced even by a laser, but laser light is many times more collimated than the light from any other source. Because of the intrinsic characteristic of the stimulated photons (twin photons), they are almost all emitted in the same direction; therefore all photons in the beam deviate minimally from the beam axis. A laser device can produce a light beam that is approximately collimated for kilometers! This is the property which makes laser light suitable for so many uses, from telecommunications to medical applications, due to the possibility of delivery through optical fibers. Because the output photons of a laser travel mostly in the same direction, laser light may be many times more efficient when compared to a usual light source in terms of power output. The high power output of a laser (the amount of energy generated in a certain time interval, which is proportional to the number of photons generated in that time) is a very important feature, since high power lasers can be used to destroy or modify structures. Pulsed lasers can achieve power outputs in the order of terawatts (10^{12} W).

As illustration, consider the red light generated by a red bulb lamp compared to a diode laser (for simplicity, assume that both sources produces the same number of photons per second). The red lamp will emit photons in all directions – in a sphere around the source (isotropic emission), while the laser will emit these in a single direction with a very small cone of divergence. The physical quantity that describes this effect is the intensity, which is the amount of power per area. Therefore, a laser device can achieve very high intensities, which is extremely important in some technological applications.

However, coherence is an entirely different concept from intensity. To understand the coherence property of laser light, we must remember that light waves behave like water waves: if a rock is dropped into a lake, it produces subsequent waves that can be observed propagating from the center in all directions; each crest is followed by a trough, which is followed by a crest, and so on. However, if many rocks are dropped simultaneously but randomly into the lake, the interference between the many waves will mean that the crests and troughs of the individual waves will probably not be recognized. With this picture in mind, think of coherence as the property of waves that behave just like the ones generated by the single rock dropped into the lake: they move continuously and are synchronized.

The photons generated by stimulated emission are equal, which means they are also "in phase" with each other: they are synchronized and, if represented as a wave, this means their crests and troughs are aligned, both in time and space. This is the case because during the stimulated emission, the photons "drag" other photons with them, forcing them to "behave" in the same way. Remember also that stimulated emission generates a cascade effect, which means that the photon that starts the process dictates the behavior of all the subsequent photons, and they are synchronized with it. With that in mind, we can introduce new concepts: *coherence length* and *coherence time*.

For the same reasons it is not possible to construct a perfectly monochromatic or collimated source, it is not possible to have a perfectly coherent laser. All these concepts are connected, but it is beyond the scope of this chapter to provide further discussion. The photons that exit a laser can only be synchronized for a certain amount of time – the "coherence time." The light is traveling during that time and the distance covered during that time is the "coherence length." In other words, the coherence time/length is the time/distance between two photons generated by the same source during which they will be synchronized; after this time/distance, they no longer "recognize" that they were generated by the same source and will no longer be synchronized.

Light emitting diode

You certainly use a light emitting diodes (LEDs) many times in your daily life. They are in TV remote controls, clock displays, and TV screens. LEDs were first used as an electronic component in the 1960s. Later, with the development of electronic systems and materials, it was possible to construct high power LEDs, allowing their use as efficient light sources.

To explain how LEDs work, we need to discuss the interaction between atoms in a crystalline array. When atoms are close enough, such as in a crystalline structure, the energy levels of one atom will be slightly disturbed by its neighbors. This effect may result in a near continuum of energy levels. In solids, the ground state corresponds to the electrons occupying the lowest possible energy level. The energy gaps determine whether the solid is an insulating material or a conductor (Fig. 1.8). This is a very simplistic description, since it is the wave nature of the electrons in the crystal that is responsible for generating the energy band; the reader is referred to more detailed books for further insights into this subject if desired.

Conducting materials, such as metals, have high conductivity at the last occupied band as they have a small gap between the electronic bands. Consequently, changes in the electrons states are possible when an electric field is applied, promoting conduction. Some materials, known as semi-metals, have a slightly higher resistance than normal metals. Materials that do not conduct electric current are known as insulators.

It is also possible for enough electrons to be excited thermally so that an applied electric field can produce a modest current; these materials are known as semi-conductors.

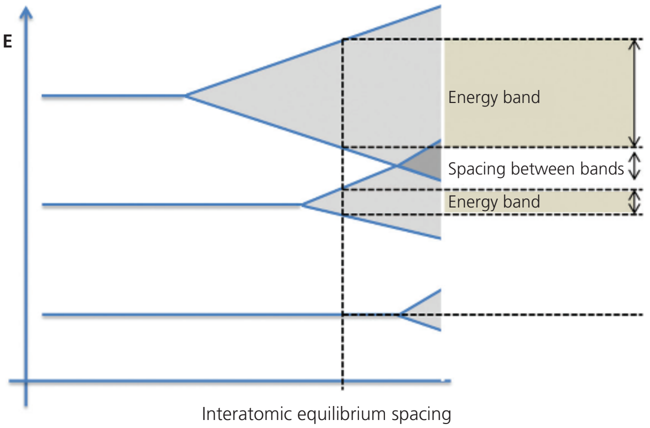

Figure 1.8 Recombination between electrons and holes, which releases energy as emitted photons.

The band structures of insulators and semi-conductors are qualitatively similar. Normally there exists in both insulators and semi-conductors a filled energy band (referred to as the valence band) separated from the next higher band (referred to as the conduction band) by an energy gap. For a semi-conductor, the energy gap is usually smaller than about 1 electron volt. In general, the gap in insulators is at least several electron volts; overcoming this large energy gap to promote sufficient numbers of electrons to the conduction band cannot be achieved with an applied field or by thermal excitation. Therefore, there is high resistance to changing the total electron momentum and allow the electrons to move as they would in a conductor.

In a semi-conductor, the valence band is full at very low temperatures (close to 0 K), but when the temperature increases, electrons acquire sufficient thermal energy to be promoted to the conduction band, which was empty initially. This effect creates the so-called “holes” in the valence band, which correspond to the “vacancies” left by the electrons that leave for the conduction band. These holes are able to generate an electric current when an external electric field is applied, because they represent the absence of negative charges – it is helpful to think of them as positive charges. The conductivity of a material depends on the number of electrons that can be transferred to the conduction band and therefore are “free” to move within the crystalline arrangement.

The main difference between semi-conductors and insulators is the energy gap. The number of electrons in the conduction band changes with temperature. Pure semi-conductors are called “intrinsic,” and because of their dependence on temperature, they are not used in the manufacture of electrical devices (a device that only worked under a specific range of temperature would have limited utility). In order to use semi-conductor materials, manufacturers usually use a technique called “doping,” which means modifying the conductivity of a material by incorporating “impurities.” This enables tighter control of the conduction conditions and allows different electronic devices to be made using the semi-conductor. In the absence of an external electric field, the band gap is large enough for these semi-conductors to act as insulators, but when an external field is applied, the balance of energy changes and the electrons and holes acquire some degree of freedom. In this way, the behavior of semi-conductors can be controlled. Doped materials are usually called “extrinsic” materials.

LEDs are made from two types of extrinsic material. The characteristics of the semi-conductor will change depending on the impurities added. If impurities that can donate electrons are added, an “n-type” semi-conductor (“n” for negative) is formed. These are usually made by introducing atoms with five electrons in their valence band, with the fifth electron weakly bound; consequently, these electrons are free to move around the crystal. Impurities in n-type materials are called donator atoms. The other kind of material is called a “p-type” semi-conductor (“p” for positive), which is made by the addition of impurities that have only three valence electrons. In this case, the number of electrons is insufficient to make covalent bonds, creating holes in the crystalline array. Impurities with incomplete covalent bonds are called acceptor atoms.

The transition processes in semi-conductors, either from photon emissions or absorptions, are more efficient when impurities have been added. The impurities facilitate electrons and holes to recombine in the process of photon emission. In LEDs, whenever an electron makes a transition from the conduction band to the valence band (effectively recombining electron and hole) there is a release of energy in the form of a photon. In some materials, the spacing of the energy levels is such that the emitted photon is in the visible part of the spectrum. Figure 1.9 represents the recombination of electrons and holes, which leads to the emission of photons.

The “p–n” junction is at the base of the LED. The junction between a p-material and an n-material forms a semi-conductor diode. The electrons in the “n” side move to the junction and will be projected into the “p” side to produce a high electron concentration in the conduction band, which is larger than when in thermal equilibrium. The same happens on the other side, with the holes. When an electron combines with a hole, energy is released, a fraction as thermal energy and another as a photon (Fig. 1.10a). When an external field is applied to the junction, the electrons and holes have sufficient energy to recombine and eventually emit a photon

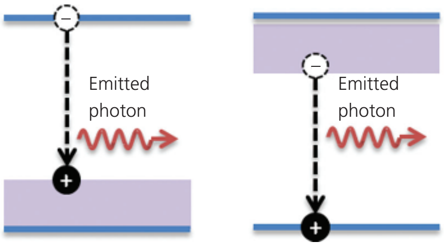

Figure 1.9 Schematic of the overlap of the energy bands, with energy versus interatomic equilibrium spacing. Not all energy levels overlap, only specific ones, depending on the material characteristics.

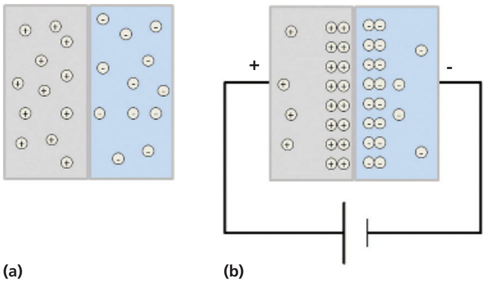

Figure 1.10 P–n junction in an LED. (a) Electrons (material “n”) and holes (material “p”, vacancies of electrons that behave as positive charges) are found in specific materials. (b) If a voltage is applied across the material, electrons and vacancies try to follow the electric field and the energy transfers involved promote light emission.

(Fig. 1.10b). The wavelengths of the emitted photons depend on the materials from which the LED is manufactured. Table 1.1 lists some semi-conductor materials (their names also indicate the impurity used in the manufacture of the device), with the corresponding wavelength (color) of the light they generate.

LED light is neither coherent nor collimated, but it is much more monochromatic than other light sources, excluding laser devices. In contrast to lasers, LEDs consume very little energy to produce light. Additionally, they are durable and, depending on the desired wavelengths, may be very cheap and easily sourced. As such, when light of specific wavelengths is required, they are a better option than lamps, which make them an important tool in science and technology development.

Table 1.1 Some common materials used in LED, with their characteristic wavelength and color.

Material	Wavelength (nm)	Color
GaAs (gallium–arsenide)	904	Infrared
InGaAsP (indium–gallium–arsenide–phosphide)	1300	Infrared
AsGaAl (gallium–aluminum–arsenide)	750–850	Red
AsGaP (arsenic–gallium–phosphorus)	590	Yellow
InGaAlP (indium–gallium–aluminum–phosphide)	560	Green
CsI (caesium iodide)	480	Blue