Chapter 2
Laser Basics and Laser Material Interactions

Abstract LASER is an acronym termed Light Amplification by Simulated Emission of Radiation. The development of laser has evolved since its inception and its application has spanned every aspect of human Endeavour. Laser is a phenomenon that has revolutionized the human world. The unique properties of laser such as monochromaticity, directionality and coherency, are responsible for its being favoured in all its areas of application. The application areas span from the smallest laser found in the compact disc player to the large laser found in the industries. The brief history of laser and the basic principle of laser generation are presented in this chapter. Properties of laser, different types of laser, laser safety and their areas of applications are explained. The types of laser that are used in material processing are also presented. The laser material interaction and how important these lasers are in material processing and their use in additive manufacturing technologies, a revolutionary manufacturing process, are also presented.

Keywords Laser · Laser applications · Laser history · Laser material interaction · Laser safety

2.1 Introduction

Laser is an acronym that is used to describes the process of Laser. The full meaning of this acronym is Light Amplification by Simulated Emission of Radiation [1]. Laser is a technology that is based on light. It is generated from light source that has been amplified in a way similar to how a microphone is used to amplifies sound. The amplification of the light is achieved by a process referred to as simulated emission which is also known as the optical amplification [2].

The beam of light that is emitted from a light source is used to create an excitation in the atoms that is present in the lasing medium [3]. The lasing medium could be solid (e.g. Ruby), liquid (e.g. hydrogen fluoride) or gas (e.g. Co_2) [1]. The atoms of this materials in these lasing medium becomes excited which results in the

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emission of coherent type of light. The optical amplification is achieved by the resonance of these atoms through arrangement of mirrors in this chamber. The excited atoms bounce back and forth between these mirrors which results in a powerful amplified beam of light that is coherent, this is called a 'Laser' [1, 4]. This process can best be visualized by placing an object in between two parallel mirrors, the image of the object bounces back and forth thereby producing a countless number of images of the object. This is what is referred to as an optical amplification that has resulted in the generation of countless images of the object between the two mirrors. The same thing happens when a single light is placed between two mirrors.

The laser light is characterized by a single wavelength, a single colour light beam that is known as monochromaticity, same phase position known as coherency as well as low divergence, that is the beam that is spread out in parallel lines [1]. All these properties of the laser make the intensity of the laser beam that is produced to be concentrated thereby producing a high intensity laser beam. This unique properties of laser is responsible for its application in all the areas where it is used. The ability to direct the laser beam only to the point of interest makes laser to be mostly favoured. Laser has really revolutionized the world we live in, by making possible a number of things that were not achievable in the past.

In order to appreciate the technology of laser and its importance, the history of laser, properties of laser, principle of lasers, types of lasers and the areas of application of lasers are presented in this chapter. The development of laser through various evolutions are highlighted. The use of laser in the material processing is one of the major achievement of laser and it is also explained in this chapter. The laser material interaction in material processing are also explained in detail.

2.2 History and Development of Laser

The understanding provided by the work of Max planck in the late 1890s and early 1900s was a major breakthrough in science as his theory is what the revolutionary technology called laser is based [5–9]. It all started when Planck first proposed solution to the black body radiation problem in the year 1899 from the principle of elementary disorder. He derived what he called Wien-Planck's law from assumptions about entropy of an ideal oscillator. This law was found to be in no agreement with experimental results. Planck revised this law by including the energy quantization, and statistical mechanics, to derive a new law called the Planck black-body radiation law. The new law was found to be in good agreement with the experimental data [5]. The law was revised using the Boltzmann's statistical to interpret the second law of thermodynamics to further understand the principles behind his black body radiation law. He discovered that electromagnetic energy could be emitted only in quantized form. Planck discover the relationship that existed between radiation energy and the radiation. He found that energy could only be emitted or absorbed in a discrete chunks that he called ‘quanta’. He provided the understanding that light is a form of electromagnetic radiation. His discovery of the elementary energy quanta was used to explain why the blackbody did not radiate all frequencies of light when heated up and compared to the way the same blackbody will absorb all the different wavelength of light and hardly reflect any. It was expected that blackbody should reflect radiation when heated the same way it will absorb when not heated. Planck became the originator of quantum theory with this discovery which provides a turning point in Physics and has since revolutionized the human understanding of the atomic and subatomic processes [10]. This understanding is responsible for what is now known as laser.

Albert Einstein continues this research in line with the work of Mac Planck and he first proposed the photoelectric effect in the year 1905 [11, 12]. He further supported the Plank’s work through his work which proposed that the light delivers its energy in chunks form which is now referred to as photons. The work was referred to as the quantum theory of light and photons. Later in the year 1917, Einstein also proposed a process called the stimulated emission process. The research work explained the mechanism of stimulated emission. He hypothesized that it was possible to simulate electrons to emit light energy of a particular wavelength through the spontaneous absorption and emission of light [13]. He achieved this using the probability coefficients for the spontaneous emission, absorption, and emission of electromagnetic radiation. The work provide the theoretical background for the fundamental principle of laser. The theory of simulated emission explained how possible it was to amplify stimulated emission from an incident radiation by creating a population inversion between the upper and the lower energy levels in an atomic system. The amplified simulated emission produced would have the same frequency and phases [13]. The phenomena of the simulated emission and negative absorption, as well as how stimulated emission can be used to amplify short waves were also confirmed by a number of researchers [14, 15]. Optical pumping was also proposed in the year 1950 by Alfred Kastler and in the year 1952 it was experimentally validated [16].

Microwave amplification of simulated emission of radiation (Maser) was presented by Charles Towner in the early eighties [17] after the Joseph Weber described how simulated emission can be used to amplify microwave radiation [18]. The first microwave amplifier was produced, the difference between this device and the present laser is that the device was used to amplify the microwave radiation, an invisible radiation. The maser produced was not able to deliver a continuous radiation. It was suggested by other researchers in the field that if optical pumping can be produced, population inversion of the photons can be achieved [19]. The study was continued using a visible light and discover what was termed optical maser. The optical maser was a device that was used to produce a powerful beams of light using higher frequency energy to stimulate the beam of light. This discovery was then patented in the year 1958 by Arthur Schawlow and Charles

Towner [20]. The word laser was coined out by Gordon Gould in 1959 which has been used till date [21]. Although the laser was invented in the year 1958, but there was no possible application of this laser at that time, it was Gould that proposed the possible areas of applications for the laser [21]. The applications proposed include the spectrometry, radar, and nuclear fusion.

The first working laser was built and patented by Theodore Maiman in the year 1960 using ruby as a lasing medium which was stimulated using a high energy flashes of light [22]. The development of laser since the year 1960 has since been an explosive achievement in the history of science and engineering. The laser was able to produce different type of systems with a wide range of applications in a number of fields. The earlier work during this period were focused on the improvement of laser such as how the power can be improved by testing different types of lasing medium which has resulted in the different types of lasers that are being used today and a number of modifications and improvements has also been achieved through various research works [20, 23–42]. The different types of lasers are explained in the next section.

2.3 Types of Lasers

Since the time that the first working laser has been built, different types of lasers has be developed. The search for improving the first laser has resulted in a large number of lasers that is now being used in various field of human Endeavour. Lasers are grouped into five main categories which is based on the state of the lasing medium that the laser employed. These main categories are the solid state lasers, the liquid state lasers, the gaseous state lasers, the chemical laser and the semiconductor or diode laser. These lasers are presented in the following subsections.

2.3.1 Solid State Laser

Solid state laser are lasers in which the gain medium is solid at room temperature [1]. Solid state laser use crystalline solids or glass rod that is doped with ions. The solid state lasers are usually optically pumped using a flash tube or another laser with a shorter wavelength than the lasing medium wavelength. In the solid state laser, the electrons in the lasing medium are first excited to higher energy states through the absorption of photons that pumped on the electrons. The excited electron losses photons in order to be relaxed from their excited states. The quality of the photons released by the excited electrons will determine the quality and the quantity of laser light produced.

Neodymium-(Nd), is the most commonly used dopant that is used for solid state laser crystals such as yttrium orthovanadate (YVO_4), yttrium lithium fluoride (YLF) and yttrium aluminium garnet (YAG). Solid state laser are capable of producing high powers in the infrared light spectrum at a wavelength of 1064 nm. They are usually applicable in the cutting of metal and in the welding of metals and other materials. They are also used in spectroscopy and for pumping of dye lasers. The main limitation of solid-state lasers is the high temperature in the lasing medium which is produced from the excess pump power that heats up the lasing medium and reduces the quantum efficiency. Ruby Laser, the first built laser, is a solid state laser. The other types of solid state lasers include: the Ytterium Aluminium Garnet (YAG) based lasers such as Neodymium based YAG laser—Nd: YAG laser, Thulium based YAG laser—Tm: YAG laser, Ytterbium based YAG laser—Yb: YAG laser, Holinium YAG laser—Ho: YAG laser, Tunable Solid State Lasers, Alexandrite Laser, Ti: Sapphire Laser, Colour Center Lasers, Fiber Lasers, Ytterium doped glass laser (rod, plate/chip, and fiber), Chromium ZnSe (Cr: ZnSe) laser, Divalent samarium doped calcium fluoride ($Sm:CaF_2$) laser, Trivalent uranium doped calcium fluoride ($U:CaF_2$) solid-state laser, NdCrYAG laser, Er: YAG laser, Nd:YLF laser, Neodymium doped Yttrium orthovanadate ($Nd:YVO_4$) laser, Neodymium doped yttrium calcium oxoborate $Nd:YCa_4O(BO_3)_3$ or Nd: YCOB, Neodymium glass—Nd: Glass Lasers, and Titanium sapphire (Ti:sapphire) laser.

2.3.2 Gaseous State Laser

In gas lasers, the lasing medium is a gas. Helium-Neon laser was the first gas laser to be produced and since its invention, a number of gas lasers has also been developed [1]. Gas lasers generate stimulated emission from the low-energy transitions between vibration and rotation states of the gas molecular bonds. The main advantage of gas lasers is that they are relatively cheaper than other types of lasers. Gas lasers are also produced from vaporized metal ion to generate deep ultraviolet wavelengths, e.g. Helium-silver (HeAg) and neon-copper (NeCu). Other types of gas lasers apart from the first Helium–neon laser are the Argon laser, Krypton laser, Xenon ion laser, Nitrogen laser, Carbon dioxide laser, Carbon monoxide laser and Excimer laser.

2.3.3 Liquid State Laser

A liquid state laser is a type of optically pumped laser that its lasing medium is liquid at room temperature [26]. The optical pump that is used with this type of laser include the arc lamps, flash lamps, or other type of lasers. The liquid state laser allows a wide selection of the emission wavelength and polarization from the lasing medium. The spectrum spans from the near ultraviolet to the near infrared radiation which depends on the type of dye that is employed. The liquid used in this type of laser is basically a dye that is doped into the liquid crystal that produces a continuous spectrum of lasing that is also tunable. It is also possible to operate a liquid state laser in a pulse mode. When the dye that is placed in the flow cell is excited with the optical pump, the organic molecules excited at higher frequencies making this type of laser to have the characteristic broad band. The main advantages of liquid state lasers are the higher efficiency, and they can be tuned to various frequencies that makes them ideal for scientific, medical, and spectroscopic applications. The main drawbacks of this type of laser are the liquid instability as a result of high heat intensity and the change of refractive index of the active substance resulting from the heating that causes degenerated ray in the lasing medium.

2.3.4 Chemical Lasers

In chemical lasers, the lasing medium is powered by a chemical reactions that permit large amount of energy to be released quickly [1, 3]. Chemical lasers can produce as high as megawatt power levels. They are of most importance in the industries and in the military. Some of the examples of this laser include the oxygen iodine laser, all gas-phase iodine laser, deuterium fluoride laser, the hydrogen fluoride (HF) and deuterium fluoride (DF) lasers. There is also a deuterium fluoride–carbon dioxide laser.

2.3.5 Semiconductor Lasers

Semiconductor lasers are the type of lasers that the lasing medium is made up of semiconductor [25]. These type of lasers are usually excited by electrically pumping the lasing medium, that is, the interband transition under the conditions of a high carrier density in the conduction band. It involve different physical processes. Semiconductor lasers are also referred to as diode laser. The optical gain is achieved by the recombination of electrons and holes that were created by the applied current. Semiconductor lasers are cheaper to make and can be produced as small as require. The low to medium power laser used in laser pointers, laser printers and CD/DVD players are all made of semiconductor lasers. They can also be made as larger as required such as industrial semiconductor laser with high power output. The properties of laser are presented in the next section.

2.4 Properties of Lasers

Laser is a form of electromagnetic radiation with unique properties that cannot be found elsewhere. From the acronym, the operation of laser is fully captured in this acronym and it is responsible for the exciting properties of the laser [1]. Looking at the full meaning of laser- *light amplification by stimulated emission of radiation,* simply means that light or any electromagnetic radiation is magnified by a process of simulated emission of radiation. The process of achieving this magnification comes along with the characteristic of laser that makes it to be useful in a number of applications. This magnification of light is explained later in this chapter. The three basic properties that differentiate laser from any other forms of light or radiation and which are what makes this type of radiation (laser) an important one are explained in the following subsections.

2.4.1 Monochromaticity

An ordinary light sources emit light with a broad range of wavelengths which results in the many colours seen in this type of light. The White light contains all the seven colours of rainbow because it is made up of wavelengths in the range of 700 nm (red light spectrum) and 400 nm (violet light spectrum). Laser only emit a very narrow range of wavelength and is normally considered as being a single wavelength electromagnetic radiation [1, 4]. This important property of laser is responsible for the high intensity energy achievable in laser. This is because, all the energies are concentrated at this single wavelength. Other types of light apart from laser are referred to as polychromatic light while the laser is termed monochromatic light because of its single wave length and hence one colour property seen in the laser. The light that is coming out of a laser is typically from single atomic transition with one precise wavelength. This is what gives the laser the characteristic single spectral color that is, the purest monochromatic light ever created. Figure 2.1a shows the conventional light and a typical laser light is shown in Fig. 2.1b. Figure 2.2 shows a light from a candle, displaying the different colours including the white light.

The conditions that make the monochromaticity of laser possible are as follows:

- The laser light is originated from the stimulated emission process which is from a set of atomic energy levels, because laser transition can only occur in a well-defined energy levels.
- The generation of laser light involves the oscillation of the light in a resonant system which helps to sustain the laser oscillation at the cavity frequencies that results in narrowing of the laser light line width. This also helps to promote the production of the laser light single and pure wavelength leading to one colour light called monochromatic light.

Although, lasers light are termed monochromatic, but the degree of this monochromaticity was found to vary from one of laser to the other. The degree of chromaticity is dependent on the wavelength bandwidth or the frequency bandwidth of the laser. All lasers generate light in a narrow bandwidth around a single

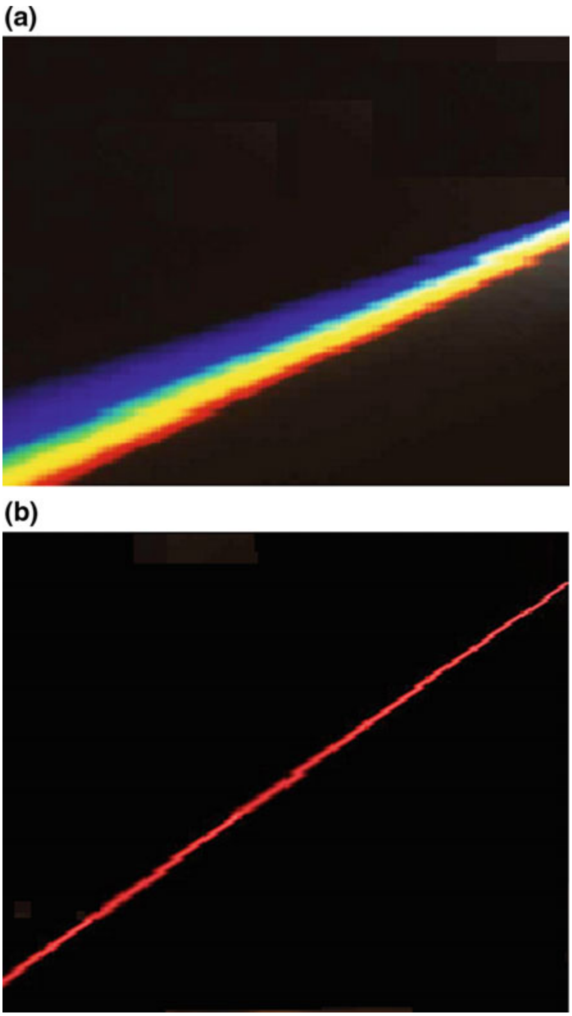

Fig. 2.1 **a** a light from traditional light source **b** a light from laser

wavelength but this band width still varies. The narrower the this bandwidth, the higher is the degree of monochromaticity of the laser. Monochromaticity is also referred to as the high frequency stability. This property is of most importance in some laser application because it has a great influence on the accuracy of such system. An example of such application is in the interferometric measurements. This property is highly needed in high-resolution spectroscopy for observing specific transitions in a medium. The wavelength is used to measure length and distance which must be known with extreme accuracy and precision and must not change with time. Also in scientific analysis applications for quality control. A very narrow line width of less than 0.05 percent of the central wavelength is important for applications such as sensors and in communications.

Fig. 2.2 A candle light showing different colours of light

2.4.2 Coherency

Coherency is another important property of laser that no other light possesses [1]. This is a same phase property of the electromagnetic radiation wave. All the electromagnetic waves in any laser are in the same phase. Laser waves have both temporal and spatial coherence. Spatial coherence is the ability to predict the amplitude of the wave at any given point in space and at any given time. If a wave has a given amplitude over a range of length, then such wave is said to be spatially coherent. The difference between the temporal coherence and the spatial coherence is that, for a temporal coherence, there is correlation between the waves at any given point along the path of a beam at any given time while for the spatial coherence there is correlation between different waves even in space. The process of generating laser beam is responsible for the production of beam that is coherent. The stimulated emission process is responsible for the emission of photons with a definite phase relationship with the photos that cause such emission resulting in coherent beam or same phase beam of light. Figure 2.3a shows a coherent light waves and Fig. 2.3b shows an incoherent light waves.

The atoms in the excited state are made to emit photons which are in phase with the incoming photons that stimulated such emission. When the emitted wave is joined with the incidence waves and the two waves are in phase, they produce a magnified wave that is even brighter that the incidence ones [25]. This process is explained later in detail in this chapter. The Photons are also produced from atoms of the traditional light but without any phase relationship with one another and hence are not coherent. In this ordinary light source, the photons are produced as a result of natural decaying of the atoms and are spontaneous, so the photons are emitted at irregular pattern and therefore out of phase with one another. The emitted photons are supposed to maintain this fixed phase relationship (coherency)

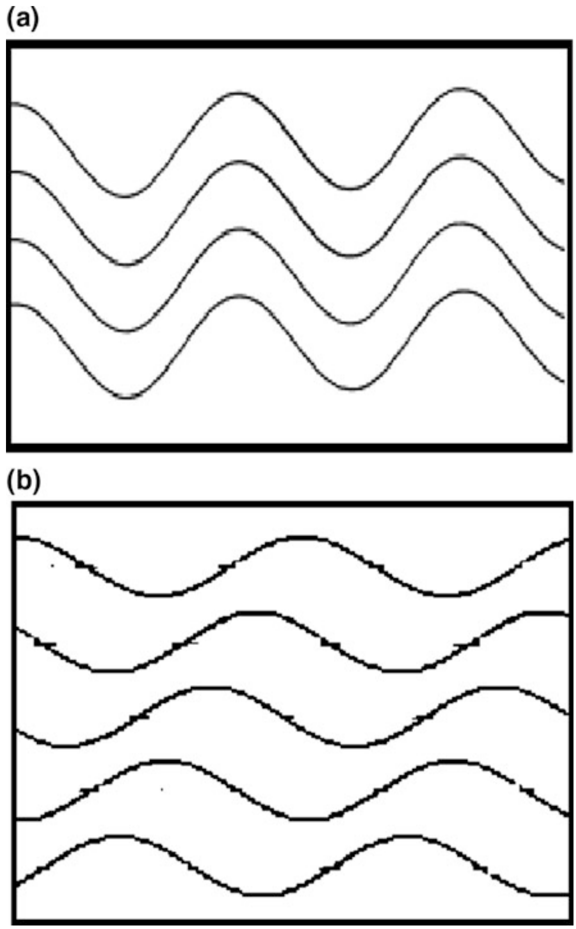

Fig. 2.3 **a** Coherent laser light waves **b** incoherent ordinary light waves

throughout the time they are required to hit their intended target and then return. This property is of utmost importance in applications such as alignment, bar code reader, radar, material processing and communication system. Another important application of this laser property is in the Doppler velocity measurements of a target using the frequency measurements shift of the moving targets. The measurement is taken from this frequency shift obtained from the target-reflected energy which is a function of the target's velocity. If the laser does not have this coherence property, there will be error in the measurement and the frequency shift will be partly from the incoherent light beam and the moving target. Therefore high coherency is required for such measurement.

2.4.3 Directionality

Directionality is the property of laser that described its divergence limited behaviour [1, 4]. To be able to understand this property, the behaviour of an ordinary light is first explained. The conventional light sources emit light in every direction because of the irregular spontaneous emission. This emitted photons are scattered all over and spread out very quickly. Lasers on the other hand emit light that are spread out only very little with distance. Figure 2.4 shows the conventional light beam and a typical laser beam with limited divergence behaviour. Laser beams do diverge as they move through space but the divergence is very limited.

This low divergence property of laser is also referred to as highly collimated beam. Meaning that, the laser light does not lose its intensity with distance unlike in the ordinary light where most of the light rays are scattered far apart as the distance is increased and most of the intensity are lost in the process (as seen in Fig. 2.4). Laser beam is a highly directional beam because the laser beam are produced from the resonant cavity that allows only the propagation of the waves along the optical axis. That is, the mirrors placed at opposite ends of a laser cavity causes the beam to oscillate and travel back and forth resulting in the stimulation of emissions of more photons that are at the same wavelength. This action results in the propagation of only photons that are traveling in a parallel line to the walls of the cavity leading to the production of highly collimated beam. Collimation is the degree to which the beam is parallel with distance. directionality of a laser beam can be described using divergence angle as shown in Fig. 2.5.

A perfectly collimated beam is shown in Fig. 2.6 which has a zero divergence angle, This is an ideal beam. This diffraction angle is small in laser as shown in

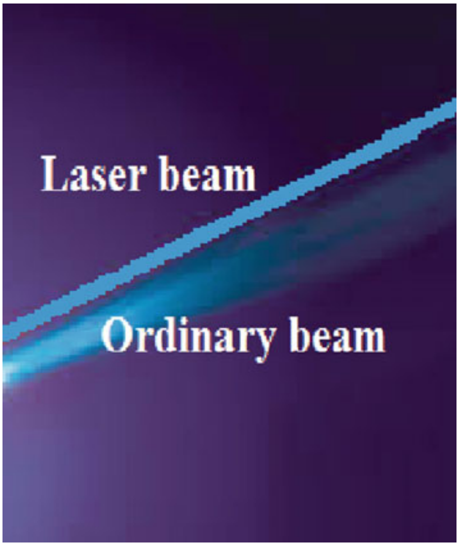

Fig. 2.4 Diagram showing the collimated laser beam and scattered light beam

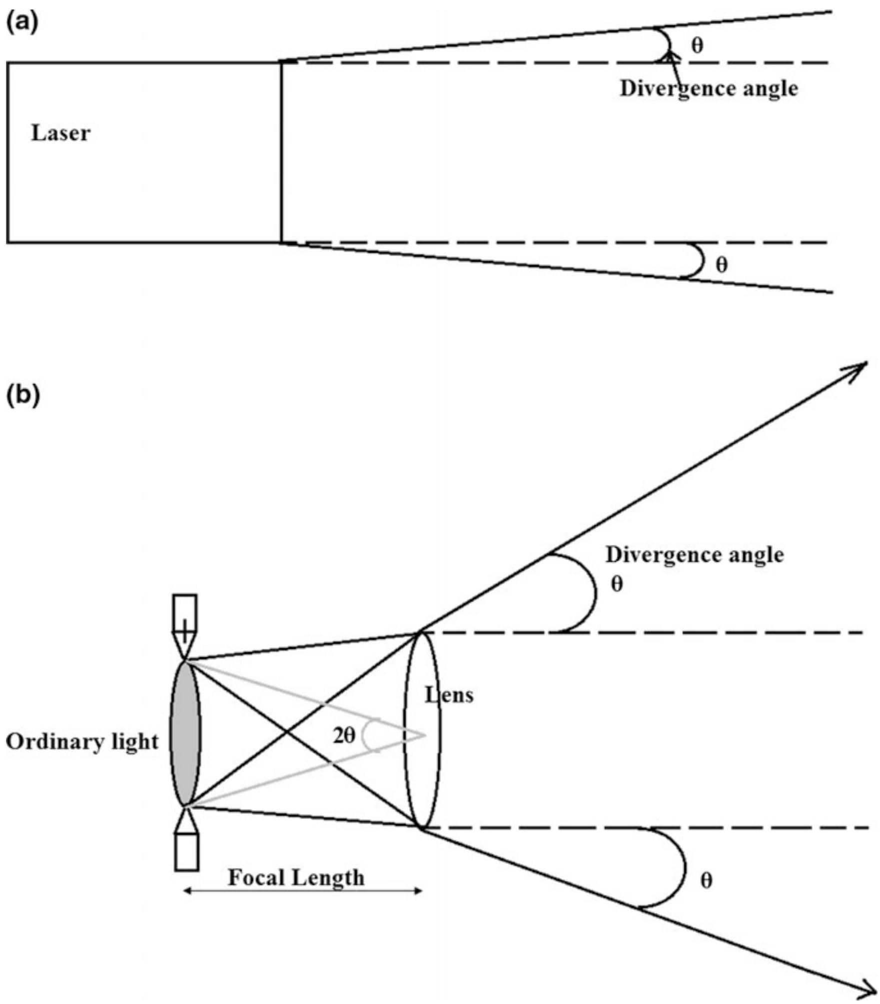

Fig. 2.5 **a** schematic diagram showing divergence angle of a (**a**) laser beam light and **b** an ordinary light

Fig. 2.5a while the value is large for an ordinary beam as shown in Fig. 2.5b. The diffraction property of a laser beam plays an important role in the determination of the laser spot size that is achievable over a given length. The directionality of laser is responsible for the high intensity of laser and helps to maintain this intensity over a large distance which is useful in applications such as material processing like drilling, welding and additive manufacturing. This property is also very important in space applications as well as in medicine.

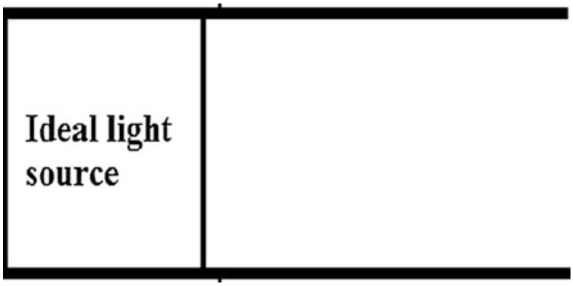

Fig. 2.6 An Ideal beam of light

2.5 Principles of Laser

The word 'Laser' is an acronym that is used to describe the generation of laser: Light Amplification by Stimulated Emission of Radiation. what this phrase means is that an electromagnetic radiation that is monochromatic, divergence limited and highly directional beam is produced from a light beam that is amplified by supplying a gain medium with energy that excites the atoms in the medium also stimulate this exited atoms to emit radiation [1, 3, 4]. Thereby magnifying the light and giving it the characteristic properties mentioned above. In other words a laser is a machine that makes billions of atoms to pump out trillions of photons at once so they are lined up to form a concentrated light beam.

A laser basically consists of three parts: a resonant optical cavity that is called the optical resonator, a laser gain medium (also called the active laser medium) and a pump source that is used to excite the particles in the gain medium. The process of generating laser is explained in this section.

In order to generate a laser beam, three basic components are required. A gain or amplifying medium is needed which could be gaseous, solid or liquid, Something to stimulate the atoms in the gain medium for example, a flash tube or even another laser. Lastly an optical resonance cavity. Each of these components are explained in detail in the following subsections.

2.5.1 Amplifying or Gain Medium

Gain medium is normally made of solid, liquid, or gas [3, 4]. These media are important because they are made up of atoms, molecules, ions or electrons. It is these atoms that are used to produce the exciting laser lights. the atoms will absorb energy, release this absorbed energy in form of light photons that are emitted at wavelength that corresponds to the energy differences between the orbital's energy levels. Electrons in an elements are happy when they are in the lower energy state and they love to remain at this low energy level. This level is called the atom's ground state. If energy is introduced to these atoms at this ground state, the energy is absorbed by these atoms and when the atom absorb enough energy it gets excited and move from the lower energy level to a higher energy level. This process is shown in Fig. 2.7. This process is called absorption process and the atom in this new energy state are said to be excited atoms. This excited state of the atom is an unstable state and the atoms are not comfortable in this state and always ready to return back to its ground state. The excited atoms are ready to give anything it takes to be able to return back to this ground state. This excited atom can be made to return back to the lower energy level in two different ways: either through the natural decay of the atom at the end of its life span of about 10^{-8} s or if the excited atom is impacted with another energy. To understand the absorption process better, the case of heating water in a container can be used as an example. When heat is applied to a container with water at room temperature, the water molecules very close to the bottom of the container gain heat and when enough heat is absorbed by the water molecules, the molecules become excited and move to the top of the water level in the container. These excited water molecules are seen as bubbles and these bubbles are also seen collapsing randomly. This is similar to the process happening in the gain medium of the laser generation process.

When the excited atom is made to return back to the lower energy level by natural decay, it gives up the energy absorbed by giving up photons in a random direction and it is referred to as a spontaneous emission process. The spontaneous emission is the process that takes place in an ordinary light such as electric bulb or candle light. In a candle light, for example, the chemical reaction between the oxygen in the air and the candle wax cause the excitation of the atoms releasing photons in every direction resulting in the glow that we see, that is produced by spontaneous emission process taking place inside this candle flame which does not have the laser properties.

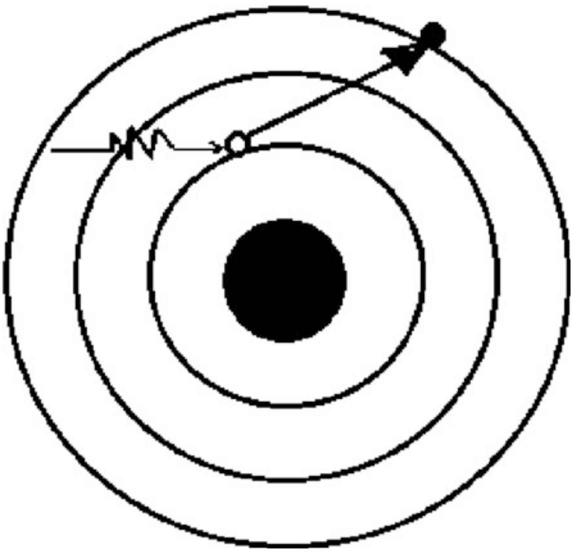

Fig. 2.7 Excitation of electrons

On the other hand, if the excited atom is made to return back to the lower energy level by being hit by another photon, the excited atom is stimulated to release photons that are of the same wavelength with the incident photon and also the two photons are in phase which results in a magnified photons as shown if Fig. 2.8a. This process is referred to as 'stimulated emission' which is what the lasing process needs [25, 26]. Although the spontaneous emission (see Fig. 2.8b) is not good for lasing because of the scattered nature of the photons that is produced, but they are needed to actually start the lasing process and it will be explained later in this chapter.

It can be seen in Fig. 2.8a that the photons that were released during this stimulated emission process, they all travel in the direction of the incoming energy.

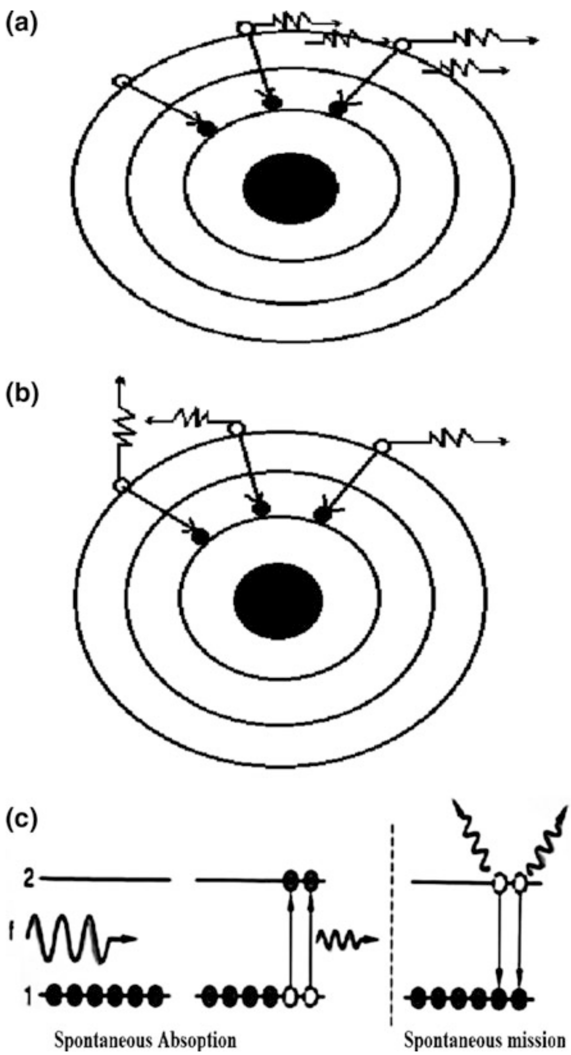

Fig. 2.8 **a** Schematic diagram of (**a**) stimulated emission **b** spontaneous emission **c** spontaneous absorption and emission

This is what helped to multiply the incoming radiation as it can be seen that one photon was used to stimulate the excited atom but two came out of the process. This is not yet regarded as a gain because remember that certain energy was also used to bring the excited atom to the higher energy level. The actual gain is produced through the use of optical resonance that is explained later. For this process to happen as required, there is need to have constant supply of atoms in the excited state and there should also be more atoms in the excited state than in the lower energy level. This is made possible through a pumping process that is introduced in the lasing system and it is explained in the next section.

2.5.2 Pumping System

To introduce energy into the gain medium of a laser system, the process known as pumping is used. This will create the conditions for the light amplification by supplying the necessary energy to excite and keep exciting the atoms during the lasing process [25]. There are different types of pumping system that are used in this process which include: optical pump e.g. tungsten-filament lamps, or other lasers; electrical pump e.g. electric lamp, or semi-conductors; and chemical pump where the exothermic reaction is used to excite the system. In order to have a lasing action, the number of atoms in the higher energy level must always be greater that the number of atoms in the lower energy level and this is made possible by the use of pump as shown in Fig. 2.9. The process of making the population of the atoms in the excited state more than at a lower energy level is referred to as ‘population inversion’.

Population inversion is a necessary condition for stimulated emission to take place which in turn results in the production of laser called ‘lasing’. When there are more excited atoms in the excited state than in the lower energy state, then the next thing is for the lasing to begin. Lasing actually begins through spontaneous emission of at least one of the excited atom. The photo that is released by this decayed atom hits another excited atom which then stimulates the release of another photon from this atom and the process continues. The two photons produced after putting one photon into the system to produce the simulated emission thus effectively doubles the number of photons.

These two photons are further used to stimulate other atoms to release their photons which eventually produce a cascade of photons through the chain reaction. Since these emitted photons from these atoms as a result of the stimulated emission and they have a definite phase relationship with one other, this will result in the production of a brighter beam of pure, and coherent laser light. This process is the amplification of light using stimulated emission of radiation. The two main conditions for the generation of laser are population inversion and stimulated emission, but the real magnification of the input energy into the system is achieved through the process known as optical resonance. This process is explained in the next section.

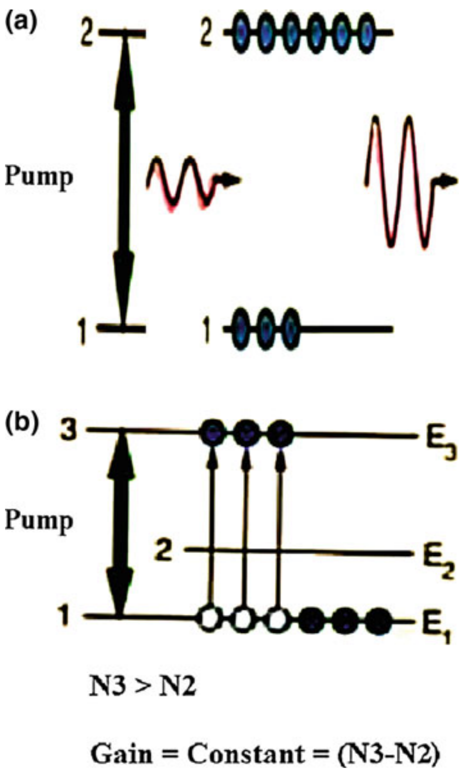

Fig. 2.9 **a** Population inversion. **b** How gain is calculated

2.5.3 Optical Resonance System

In order to achieve the needed magnification in the lasing medium, the gain medium is expanded to include a system that is known as an optical resonance system or a laser oscillator. The optical resonance system is contained of a pair of reflecting mirrors such as plain mirrors or curved mirrors or mixture of the two types of mirror. This mirrors are arranged in such a way that the objects in between these mirror are made to bounce back and forth. This process is similar to what we see when we stand between two mirrors that are parallel to each other, the multiple images we see inside these mirrors are produced from the bouncing back and forth of our image in the two mirrors. One of the two mirrors in the resonance system is made an output beam mirror in which an opening is made to enable part of the light wave in the cavity to be removed as an output bean which are then incident on other lens or mirrors for control purposes. The photons that are released through the stimulated emission are magnified by making these photons to bounce back and forth through the two mirrors in the resonance cavity [1,-4]. The schematic of a gain medium consisting of the resonance cavity as shown in Fig. 2.10. This bouncing back and forth helps to amplify the photons and thus help to compensate for the loss through the output coupler. The stimulated emission process is allowed to take place in this resonance cavity. The main idea of the magnification taking place inside the resonance cavity is that, by allowing the released photons to bounce back and forth, it is used to stimulate other atoms in the excited state at very high rate that prevent other spontaneous emission to take place apart from the one that was used to start the lasing process. A common photon triggers the emission events, which helps to provide an amplified light beam, these emitted photons are 'in step' and also in phase that generates coherent output. The output is exited through the opening on one of the mirrors that is called the output coupler. The implication process with the resonance cavity helps to maintain the phase and direction of the light, giving rise to the light beam output that is directional and coherent called laser. To maintain the efficiency of the gain medium the system needs to be cooled down because the processes taking place in the system results in higher temperature that must be controlled in order not to also damage the components in the system. This can be achieved for example in CO_2 laser, by the circulation of the laser gas that is passed through a heat exchanger to cool the laser medium down as shown in Fig. 2.10. Other laser can be cooled using appropriate cooling systems.

2.6 Laser Safety

The key important properties of laser that makes them to be an important tool is used in different areas of human endeavour are the same reason why they are extremely dangerous which necessitate that care should be taken when working

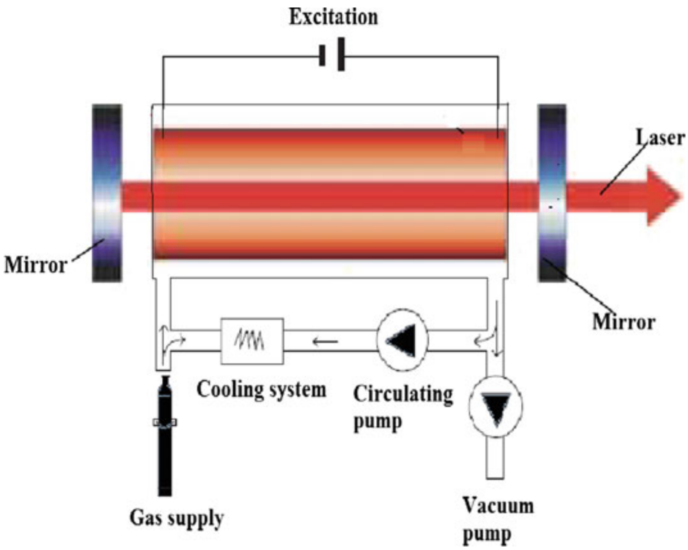

Fig. 2.10 Schematic diagram of a laser gain medium with the resonance cavity

with laser or when in an environment where laser is used [4, 25, 26]. The very first laser produced (Ruby laser) was recognized to be potentially dangerous and that it could burn through a razor blade. The lowest power laser can be hazardous to human eyes. The collimated, directional and coherent beam when hits the eye either directly from laser of from the reflected beam after hitting a reflective surface can be focused by the eye to a very small spot on the retina which would cause a localized burning in this site and result in a permanent damage in a matter of milliseconds. Lasers are classified based on the degree of the potential danger they can produced and are given a safety class number. The safety class label carried by any laser gives an idea of the type of safety rules that must be observed and the type of safety gadget that is required to be worn around such laser. There are basically four classes of laser based on safety.

Class one lasers are the safest class because this type of lasers are in an enclosure. An example of such lasers include the laser CD players and DVD players. Class 1 M laser have moderate risk. The Class two lasers are regarded as being safe during normal use although they are not enclosed like class one lasers. Such class of laser usually have power of up to 1 mW and they cannot cause serious damage to the eyes. A quick blink through the reflex action of the eyes can prevent any damage to the eyes. Example of class two lasers include the laser pointers used in presentations. The class 3R lasers are formerly known as class 3a lasers, they have power of up to 5 mW. This class of laser can cause minimal damage to the eyes within the time of the blink reflex. If this class of laser is stared into, for couple of seconds, will cause damage to the eyes. Class 2 M lasers have a higher risk than class 2 lasers. Another class of laser is the class 3B lasers which are very dangerous to the eyes. Immediate exposure to the eyes can cause permanent damage to the eyes. Class 4 lasers can cause damage to the skin, and eyes. Class 4 lasers can also cause fire. Most industrial and scientific lasers belongs to this class. It is important to wear safety gadget when around any class 3 and class 4 lasers. Lasers that are used in material processing belongs to these classes of lasers. Safety eye goggles with correct safety number that are designed to absorb light of a particular wavelength and that are labeled as such should be worn. Also, Smoke evacuator and good ventilation should be provided where the use of laser resulted in the production of plumes that are hazardous when inhaled, hence nose coverings should also be worn when people are around such lasers. Nose covering such as sub-micrometer surgical filter masks provide some protection against inhalation when they are worn properly.

2.7 Areas of Application of Laser

Application of lasers range from domestic use of laser as small as microscopic diode lasers to industrial and research use of as large as a football field sized neodymium glass lasers that is used for inertial confinement fusion, in nuclear weapons research and other high energy density physics experiments [25]. Lasers are found almost everywhere we are. barcode reader, laser disc player and laser printers are among the early applications of lasers. Some of the application areas of lasers are summarized in Fig. 2.11 and explained as follows:

- Lasers in entertainments: Optical discs e.g. CDs, DVDs and so on, Laser lighting displays; Laser light shows.
- Lasers in product development/commercial: laser printers, barcode scanners, thermometers, laser pointers, and holograms.
- Lasers in defense: lasers are used in weaponry. The use laser-beam to hit a target that causes severe shockwaves that damage the target. Lasers are also used in

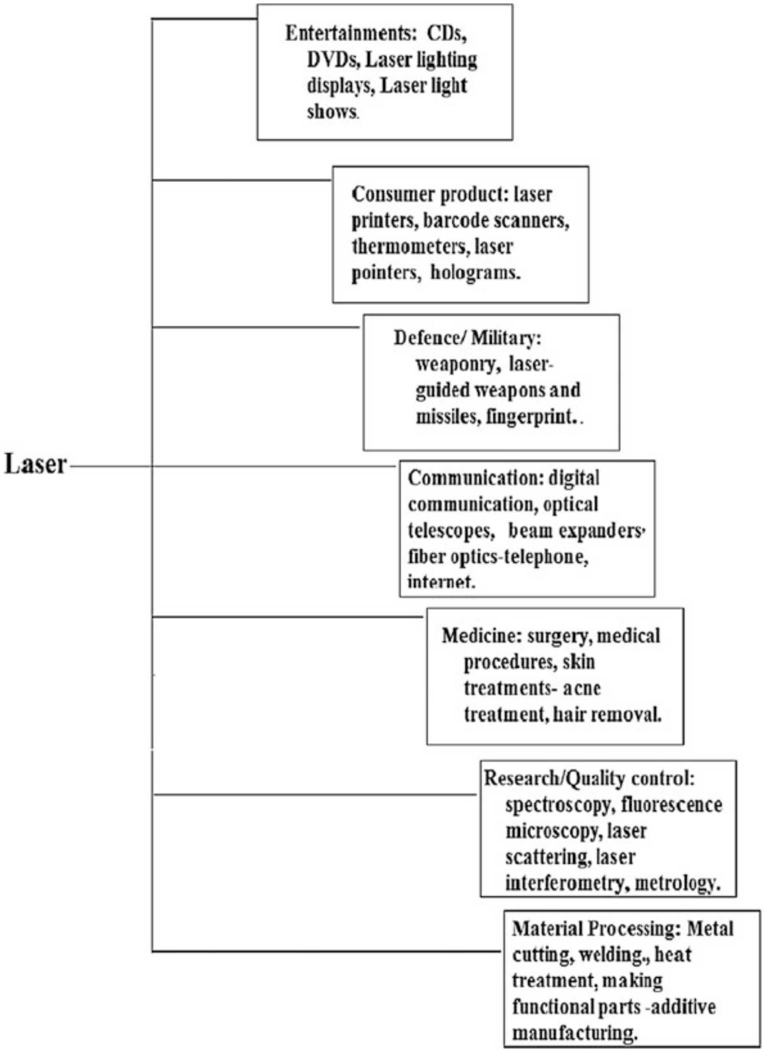

Fig. 2.11 Some of the applications of lasers

laser-guided weapons and missiles. for marking targets, guiding ammunitions, electro-optical countermeasures (EOCM), alternative to radar, and blinding troops. Lasers are also used in latent fingerprint detection for forensic identification.

- Laser in communication It is used for range-finding and precision tools, digital communication, for optical telescopes as beam expanders in space exploration. fiber optics for mobile phones and internet are also part of this applications of lasers in telecommunication.
- Lasers in medicine: surgeries and medical procedures such as: laser healing, surgical treatment, cancer treatment, kidney stone treatment, and in dentistry. Lasers are used for cauterizing blood vessels for correcting problems such as laser-eye surgery, fixing of detached retinas, and in the treatment of cataract. lasers are also used for medical procedures in skin treatments such as: acne treatment, cellulite and hair removal.
- Lasers in Research and Quality control: Lasers are used in the research applications such as spectroscopy, fluorescence microscopy, laser scattering, laser interferometry, and metrology.

Lasers in Material Processing: Metal cutting and welding.

The properties of lasers that allow them to be accurately directed and pointed to where needed allow their use in cutting of metals and the welding of dissimilar metals. lasers are also used for heat treatment, making functional parts (additive manufacturing), laser ablation, laser annealing, and in non-contact measurement of parts. The importance of lasers in material processing is revolutionary and it has helped in the fabrication of part that could not be produced through any other process. How this laser interacts with materials in material process are explained in the next section.

2.8 Laser Material Interaction

The unique properties of laser such as directionality and high power enables a number of material processing to be performed with lasers. The high directionality of laser and small high resolution spot size allows the processing to be achieved without causing any significant alteration to the surrounding bulk material properties. The laser is used to perform operations that it heat up the material to a certain temperature of even cause the material to melt completely depending on the type of material processing being undertaken. In either ways, the material under processing and the laser interact in certain ways depending on a number of factors such as the laser beam parameters such as the laser wavelength, the beam spot size, power etc. and the material properties such as reflectivity, and the thermal conductivity property of the material [43]. The wavelength of laser has a greater influence on the assumption of laser energy in materials depending on the type of material. The behaviour of some lasers in various materials according to the laser's wavelength is shown in Fig. 2.12. The behaviour of laser with materials during laser material processes are analyzed in this section. The laser interact with the material being processed in two basic ways that is, coupling or absorption of the laser rays by the material and heating or melting of the material.

When the laser beam hits the surface of the material being processed, some of this beam are reflected while some are absorbed depending on the property of this material. The beam that are absorbed into the material are said to have coupled or engaged with the material. When the atoms or electrons in this material have absorbed enough energy based on the laser properties and the processing parameters that are employed, the atoms becomes excited. A large number of atoms leave the lower energy state for a higher energy state which causes series of collations between these excited atoms. These atoms release energies during these collisions and return to the lower energy state [1, 3].

The released energies during these collisions are dissipated as heat to the surrounding lattice that causes a rise in the material temperature [44]. The temperature distribution in the material depends on a number of factors such as the material properties- the reflectivity and the thermal conductivity; and if the material is close to a phase change, for example if the material is near the melting point -from solid to liquid [43]. The conversion of the released energy by the colliding atoms into heat occur through energy transfer to the lattice which is described by the energy relaxation time based on the material properties and the laser energy intensity.

Depending on the application that is required from the laser in material processing, the laser may be used to melt, vaporize or to just heat the material as used in additive manufacturing, drilling/cutting or heat treatment respectively. In cutting operation, the laser may be required to remove material in form of liquid, vapour, or

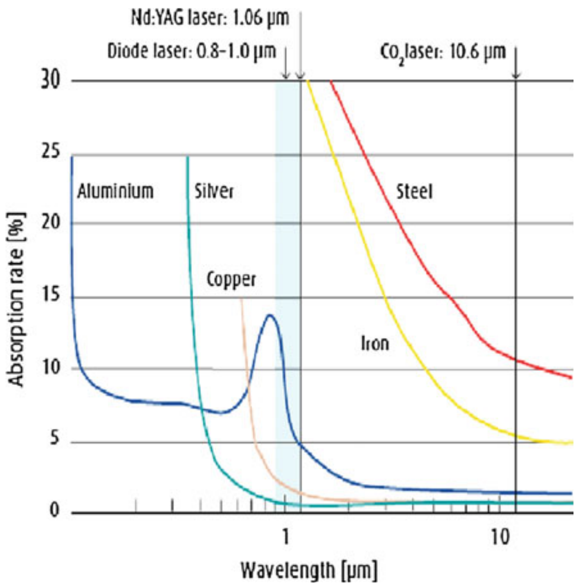

Fig. 2.12 Absorption rate of laser radiations in cold metal [46]

plasma. Plasma is formed at a certain laser intensity as a cloud of vapour from the material [45]. It is important to control the laser intensity or the laser material interaction time during material processing so as not to produce plasma in some material processing application such as laser alloying and additive manufacturing. When melting do occur during laser material interaction the latent heat also come into play. It is not all the energy required to melt the material that needs to be produced by the laser. That is, the amount of heat necessary to melt the material also depends on the volume of material to be melted.

2.9 Summary

The basic principle of laser and brief historical background of laser were presented in this chapter. The unique properties of laser such as monochromaticity, directionality and coherency, that makes it to be useful in different areas of application are also analyzed. The different types of laser that are used are presented and the safety aspect of laser safety are also highlighted. various areas of applications were explained and the use of lasers in material processing are also highlighted. The laser material interaction, its importance in material processing such as welding, cutting and additive manufacturing are also presented.

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