CHAPTER 3: LASER SOURCE

Light Amplification by Stimulated Emission of Radiation, commonly referred to as "Laser" describes a wide range of devices. The lasers can function as oscillators (sources of light) and as amplifiers. Lasers have revolutionized various fields of science and technology, and are being used in a wide range of applications in medicine, communications, defense, measurement, and as a precise light source in many scientific investigations. Commercially available lasers can be categorized based on the characteristics:

Wavelength: Lasers span the entire light spectrum from infrared to ultraviolet.

Power: The power output from a laser ranges from a milliwatt to millions of watts.

Output beam: The laser output may be a continuous wave, where the lasers emit light in a continuous manner or it might be pulsed, where the lasers emit light in short bursts.

3.1 Principle of operation

The principle of operation remains the same though there is a wide range of lasers. Laser action occurs in three stages: photon absorption, spontaneous emission, and stimulated emission. The above three processes are represented in the Figure 3.1, where E_1 is the ground-state or lower energy level and E_2 is the excited-state or higher energy level. The particle of the material, which undergoes the process of excitation, might be an atom, molecule, or ion depending on the laser material.

Photon absorption: In any material, during thermal equilibrium the number of particles in the excited state is very small and is negligible. When the number of particles in the excited state is greater than the number of particles in the ground state, the material is in a state of "Population Inversion". Population inversion is a prerequisite for laser action. Energy can be transferred into a laser medium to achieve population inversion by several mechanisms including absorption of photon, collision between electrons (or sometimes ions) and species in the active medium, collisions among atoms and molecules in the active medium, recombination of free electrons with ionized atoms, recombination of current carriers in a semiconductor, chemical reactions producing excited species, and acceleration of electrons [14].

In photon absorption, the laser material is optically excited to achieve population inversion based on Planck's law. According to Planck's law, the change of energy level from E1 to E2 or vice versa, results in the absorption or emission of photon respectively.

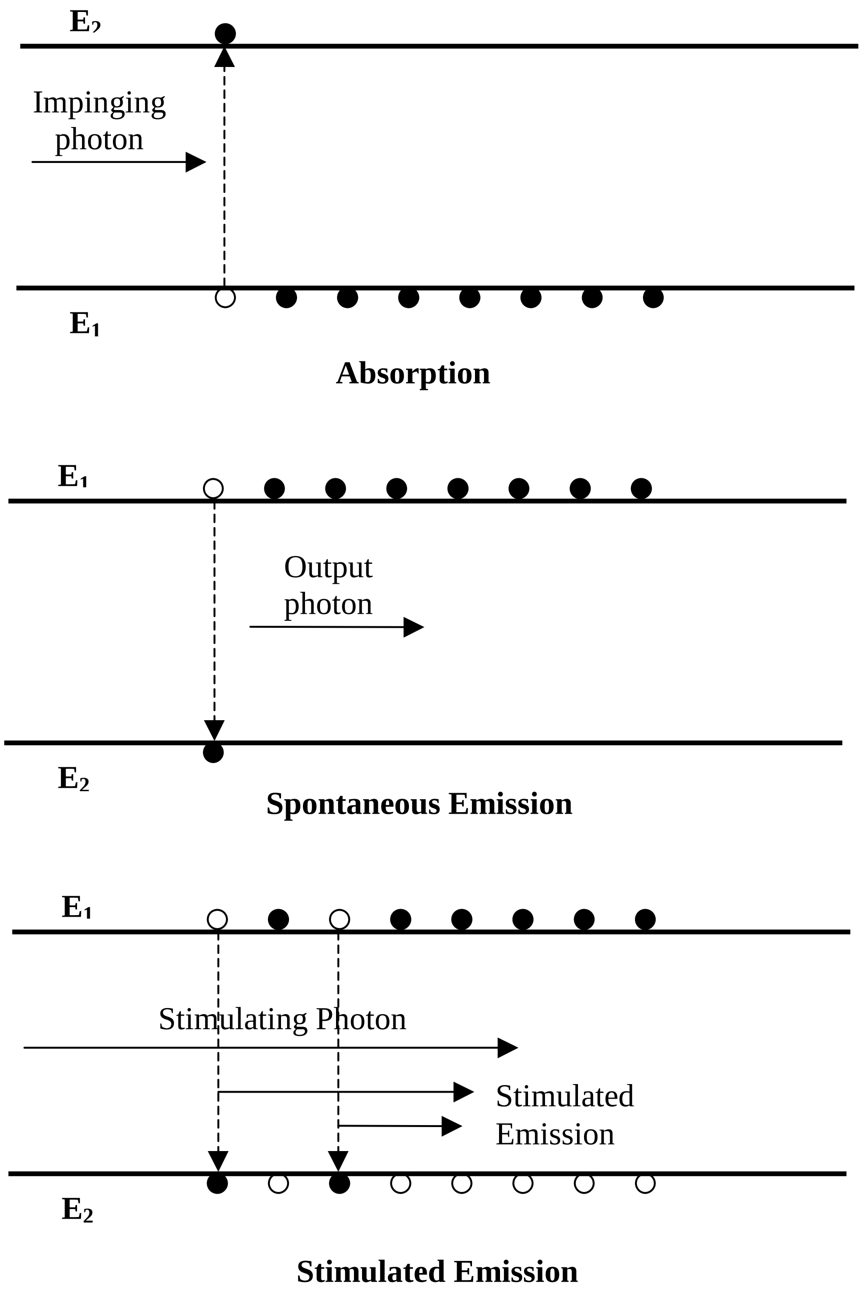

Figure 3.1 Laser Action

Spontaneous emission: The excited particles resulting from population inversion are unstable. They release their excess energy by non-radiative process, such as collisions with other excited particles or by photon emission (Planck's law), and return to the stable ground state. The emission of a photon can be spontaneous or stimulated. Spontaneous emissions occur without any external stimulus, when the laser material drops to its ground state after a characteristic delay time. Spontaneous emissions are random and isotropic in nature.

Stimulated emission: The excited particles can be made to return to the ground-state through an external stimulation. When an external photon having the same energy as the energy difference between the ground state and excited state, impinges on the excited laser material, the particles will drop to the ground-state and emit a photon. A photon having the exact energy necessary to cause stimulated emission is made available by the spontaneous emission. These photons from spontaneous emission trigger stimulated emission of other photons resulting in a cascade of stimulated emission. The photons due to stimulated emission are

1. highly monochromatic (single wavelength),
2. coherent (all the waves have the same phase), and
3. collimated (parallel rays) or appear to originate from a point source

If during the process of stimulated emission, the population inversion is maintained by continuous pumping of energy, the laser action continues indefinitely and the result is a continuous wave laser. On the other hand, if the pumping cannot be maintained the output is a pulsed laser.

3.2 Construction of a laser

A laser consists of an active laser material, a source of excitation energy, and a resonator or feedback mechanism to perform the three stages of laser action. The general construction of a laser is shown in Figure 3.2.

Laser material: The lasing material can be a solid (Ruby, YAG and glass lasers), liquid (Dye lasers), gas (Helium-neon, argon and carbon dioxide) or a semi-conductor (InGaAlP). A material is said to be in "Normal State" if the number of atoms in the lower energy level is more than the number of atoms in the higher energy level. The material is said to be in a excited state if population inversion has been achieved. The laser material is one in which population inversion is possible. The downward transition from the excited to the normal state is triggered by stimulated emission. The lasers are classified depending on the number of energy levels used for the excitation and the stimulated emission process. Commercial lasers are 3 level and 4 level systems, while the simple 2 level system is not used in practice, as it is difficult to achieve population inversion in a 2 level system.

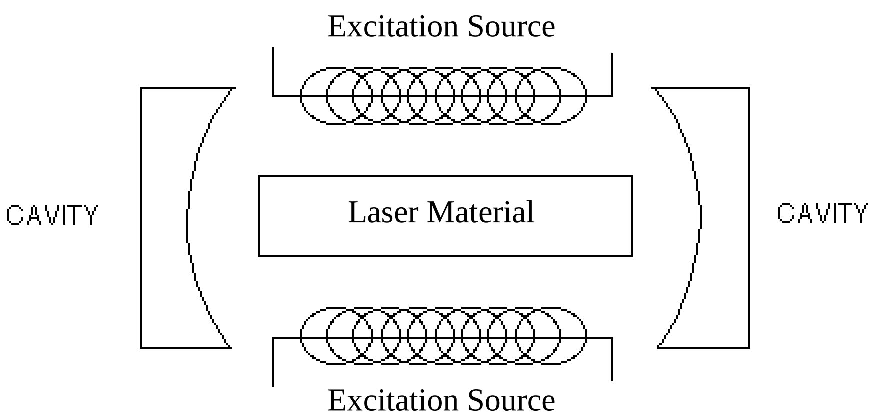

Figure 3.2 Construction Of Laser

Excitation Source: Population inversion is achieved by "pumping energy" from an external source. Depending on the external source, the excitation process is called as optical pumping or electrical pumping. In electrical pumping, an AC or DC electrical discharge is used for excitation. Gas lasers and semiconductor lasers are usually excited using electrical pumping. In optical pumping, light is the source of energy and is used for most of the solid-state and dye lasers.

Resonator: A Fabry-Perot cavity that has a pair of mirrors, one at each end of the laser is used as a resonator in most lasers. One of the mirrors is completely reflective while the other mirror is partially transparent. The reflection of the laser beam between the two mirrors results in increased power. The beam is reflected back for amplification, until a specific threshold power is reached. The portion of the laser beam with the necessary power is coupled as output through the partially transparent mirror.

3.3 Semiconductor lasers

Semiconductor lasers are very similar to Light Emitting Diodes (LED) in structure. Laser diodes and LEDs are p-n junction semiconductors that convert the electrical energy applied across the junction into optical radiation. In both laser diodes and LEDs the wavelength of the output radiation depends on the energy gap across the p-n junction. However, the output from a laser diode is highly coherent and collimated, while the output from an LED has many phases and is dispersed in different directions.

3.3.1 Lasing Action in Diode Lasers

The current carriers in a semiconductor are electrons and holes (vacancies of electron). The semiconductor material is doped with impurities to alter the type and density of charge carriers. Semiconductors having electrons as majority carriers are called n-type materials and semiconductors having holes as majority carriers are called p-type materials.

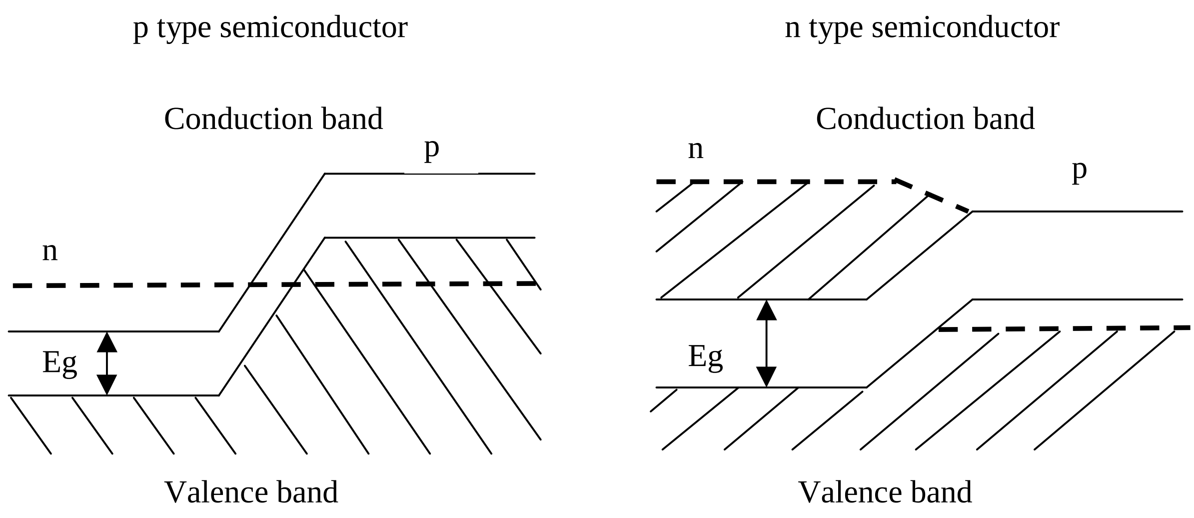

Figure 3.3 Energy Levels Of Semiconductor Laser Material

The energy level diagrams of p-type and n-type semiconductor materials shown in Figure 3.3 illustrate that the energy levels are not distinct and that they merge to form bands of energy. The two bands which participate in the lasing action are the valence band (the highest energy band in which the electrons reside during their ground state) and the conduction band (the higher energy band than the valence band to which the electrons are excited). These two bands are separated by an energy gap "Eg".

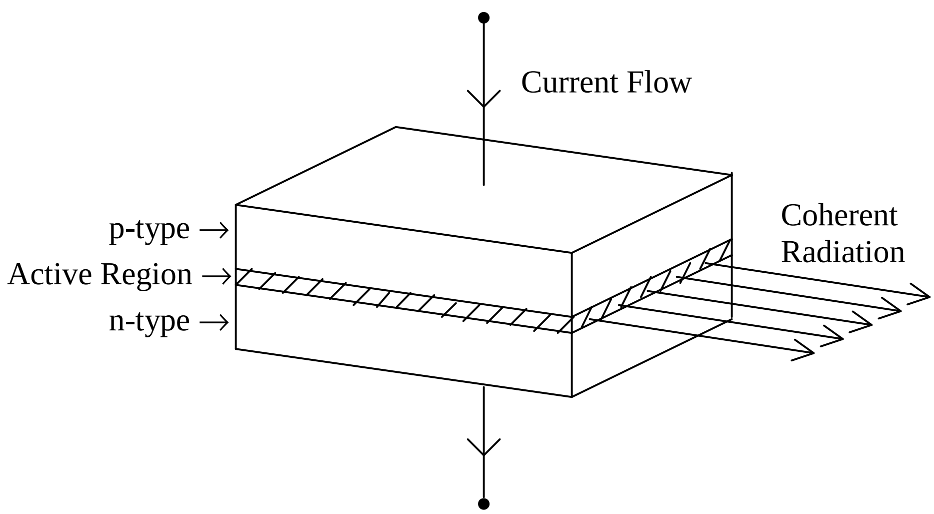

Figure 3.4 Fabry - Perot Laser Diode

A laser diode consists of a junction between a p-type and a n-type material. The construction of a laser diode is show in Figure 3.4. When a positive voltage is applied to the p-type material and a negative voltage is applied to the n-type material, a local excess of minority carriers (electrons for the p-type and holes for the n-type) is formed on each side of the junction. This condition is known as Forward Biasing the diode. It causes the carriers to cross the junction resulting in the electron-hole recombination. The electron-hole recombination generates photons with a wavelength proportional to the band-gap energy at the junction.

As seen earlier, for laser action to take place, population inversion and optical feedback are necessary. Population inversion is achieved by passing a high drive current through the diode, which results in the majority charge carriers to excite to a higher energy level. Voltage is applied across the diode using the electrical contacts attached to the flat surfaces. The semiconductor crystal is cleaved at the ends to obtain flat parallel surfaces to function as the optical cavity. The cleaved ends perform the function of a mirror enabling feedback and output coupling. A coat of metallic films achieves higher reflectivity.

3.3.2 Structure of a Laser Diode

A simple form of a laser diode, as shown in Figure 3.4, consists of a block of semiconductor, one half of which is doped to form a p-type material and the other half is doped to form the n-type material. Based on the energy levels of the valence band and the conduction band the semiconductor materials are classified as direct band gap compounds and indirect band gap compounds. In a direct band gap material the recombination of electrons and holes takes place in a single step, whereas in an indirect band gap material the recombination process requires several intermediate stages. The probability of recombination is more in the direct band gap material since it takes place in one step. Furthermore, in an indirect band gap material the generated photons tend to recombine resulting in reduction of output intensity. As a result of the above properties, direct band gap materials are used in laser diodes.

Direct band gap semiconductors like GaAs and InP are used in practice in the manufacture of laser diodes. A commercial laser consists of a number of layers of different materials in addition to the semiconductor material. The advantages of having several layers include ability to vary the wavelength of output, better confinement of laser light, and facilitate lasing action [14]. The layers are added to the binary compound by epitaxial growth of n-type or p-type impurities on the substrate binary compound. The addition of layers can be either vertical or horizontal.

The output wavelength of the diode laser depends on the energy gap or the bandgap of the semiconductor material used. Most of the binary compounds like GaAs and InP have a constant lattice structure and hence a constant bandgap. In order to obtain different wavelength outputs, additional elements like Aluminum are added as a replacement to a portion of the existing elements. This changes the lattice structure, and hence the bandgap and consequently the output wavelength.

Index guiding and gain guiding are two methods by which the lasing action is confined to a narrow stripe or portion of the semiconductor material [14]. The confinement is achieved in the index guided lasers by changing of refractive index along the active material. They have lower threshold current and better efficiency compared to gain guided lasers. Index guided lasers have better frequency stability in the longitudinal mode and have a narrow spectral bandwidth. Gain guided lasers restrict the lasing action to a small portion by restricting current flow to a narrow portion of the laser material and generates output of higher power. Though gain guided lasers are easier to build, they lack stability in the longitudinal mode and the output suffers more divergence compared to index guided lasers. Most commercial lasers are of the index guided type and they are widely used in most of the fiber optic communication applications, laser printer, and compact disc players.

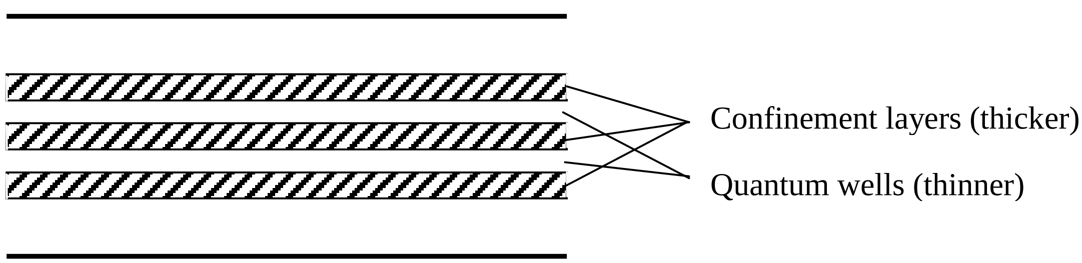

Figure 3.5 Multiple-Quantum-Wells

Though a number of layers are added to the semiconductor, the size of the laser diode is kept to a minimum by arranging the layers in a structure called "Quantum Wells". A quantum well is a three-layer structure with very thin layer of laser material in between layer of higher bandgap material, as shown in Figure 3.5. The quantum well is a development that is a result of the advancement in the epitaxial layer growth technology. The main advantage of the quantum well structure is the vast improvement of the lasing action due to the variation of the energy level distribution of the semiconductor material when its thickness is reduced below 20nm[14]. The high concentration of charge carriers in the narrow strip of the active material reduces the threshold current required to initiate lasing. The high bandgap layers on either side of the active layers perform confinement of charge carriers to the active materials as well as confinement of the laser output to a narrow width. A multiple-quantum-well is a structure consisting of an alternating pattern of active and high bandgap materials.

Another feature used in a commercial laser diode is the use of an internal photodiode known as monitor photodiode. This monitor photodiode is used in the feedback loop to stabilize the output power from the laser. While laser diodes convert electrical energy to optical energy, photodiodes transform optical energy to electrical energy. Absorption of photons of energy greater than or equal to the energy gap of photodiode results in generation of electron-hole pairs. These charge carriers under the influence of an external electric field drift to the electrodes of opposite polarity, creating a net current. The current generated is proportional to the number of incident photons. This current is fed to the circuit which drives the laser diode, and it increases or decreases the output of the diode as the case may be.

3.3.3 Applications of laser diodes[12]

Laser Diodes are used in a wide range of applications. A partial list of those applications include CD players; CDROM drives; laser disc and other optical storage drives; laser printers and laser fax machines; laser pointers; sighting and alignment scopes; measurement equipment; free space communication systems; pump source for other lasers; bar code scanners; high performance imagers; and typesetters.