3.1 Introduction to Lasers

Laser is a monochromatic coherent light source that emits light through a process of optical amplification based on the stimulated emission of electromagnetic (EM) radiation. Laser emits light at particular wavelengths and amplifies that light, typically producing a very narrow beam of radiation. The term "laser" originated as an acronym for ***L***ight ***A***mplification by ***S***timulated ***E***mission of ***R***adiation. However, laser is not just amplifier of light, it is a generator of intense (amplified), monochromatic and coherent light.

3.2 Absorption of radiation

Absorption is an upward transition (lower energy state to higher energy state). Suppose an atom is in the lower energy state (ground state) level (E_1). If photon of energy ΔE ($\Delta E = hv = E_2 - E_1$) is incident on the atom, it transfers its energy to atom (i.e. atom absorbed the incident photon). As a result of this, atom jumps to excited state (E_2). Such a transition is called absorption.

The probability of absorption (P_{12}) is proportional to the photon density (ρ). Thus,

$$P_{12} \propto \rho$$

$$P_{12} = B_{12}\,\rho$$

where B_{12} is the Einstein's coefficient of absorption.

The rate of absorption transitions in the material will be equal to the product of the number of atoms at level E_1 and the probability of absorption (P_{12}). Thus,

$$rate\ of\ absorption = N_1 P_{12} = N_1 B_{12}\,\rho$$

where N_1 is the number of atoms in the energy level E_1.

Absorption is sometime called as excitation or pumping.

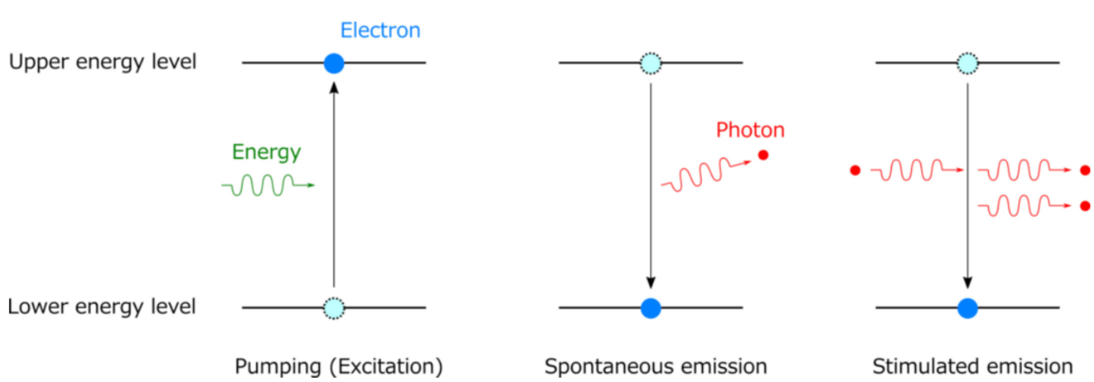


Figure 3.1 Absorption and emission

3.3 Emission of radiation

Emission is a downward transition (higher energy state to lower energy state). When an atom is excited in higher energy level, it cannot stay there for longer time. Within 10^{-9} s, the atom returns to lower energy. During this transition, it emits energy ($\Delta E = E_2 - E_1$). Such process of transition is known as emission of radiation.

Spontaneous and Stimulated emission of radiation

Emission of photon without any interaction with any external impetus is called *spontaneous emission*.

The probability of spontaneous emission $(P_{21})_{spont.}$ depends only on the properties of energy states E_1 and E_2 and is independent of the photon density (ρ). Thus,

$$(P_{21})_{spont.} = A_{21}$$

where A_{21} is the Einstein's coefficient of spontaneous emission.

The rate of spontaneous emission transitions in the material will be depend only on the number of atoms at level E_2 and the probability of spontaneous emission $(P_{21})_{spont.}$. Thus,

$$rate\ of\ spontaneus\ emission = N_2(P_{21})_{spont.} = N_2A_{21}$$

where $N_2$is the number of atoms in the energy level E_2.

Stimulated emission is the process by which an incoming photon of a specific frequency can interact with an excited atomic electron (or other excited molecular state), causing it to drop to a lower energy level.

The probability of stimulated emission $(P_{21})_{stimul.}$ is proportional to the photon density (ρ). Thus,

$$(P_{21})_{stimul.} \propto \rho$$

$$(P_{21})_{stimul.} = B_{21}\,\rho$$

where B_{21} is the Einstein's coefficient of stimulated emission.

The rate of stimulated emissions in the material will be equal to the product of the number of atoms at level E_2 and the probability of stimulated emissions $(P_{21})_{stimul.}$. Thus,

$$rate\ of\ stimulated\ emission = N_2(P_{21})_{stimul.} = N_2B_{21}\,\rho$$

where N_2 is the number of atoms in the energy level E_2.

3.4 Population Inversion

Conditions for stimulated emissions to dominate spontaneous emission

1. There should be large number of photons in the active medium (which results in more absorption transitions).
2. The ratio B_{21}/A_{21} should be larger (which increases lifetime of excited state atoms).

3. There should be more number of atoms present in the higher energy level than lower energy level (i.e. $N_2 >> N_1$)

A medium amplifies light only when the above three conditions are fulfilled. Therefore to achieve high percentage of stimulated emissions, an artificial situation (known as population inversion) is to be created in the medium.

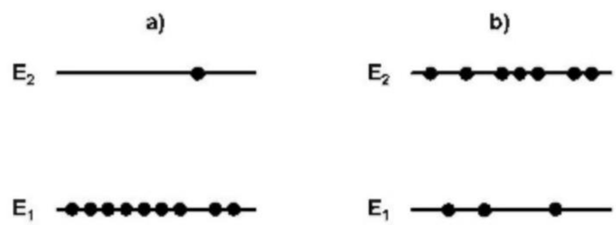


Figure 3.2 (a) Equilibrium state and (b) Inverted state

When material is in thermal equilibrium, the population ratio is governed by the Boltzmann factor,

$$\frac{N_2}{N_1} = e^{-[E_2-E_1]/kT}$$

where k is Boltzmann's constant ($=1.3807 \times 10^{-23}$ J·K^{-1} or 8.629 eV·K^{-1}).

The condition in which there are more atoms in the lower energy state and relatively lesser number of atoms in the higher energy state is known as equilibrium (or stable or normal) state. Thus, under thermal equilibrium condition, $N_1 >> N_2$.

Population inversion is the condition of the material in which population of atoms in the higher energy level (N_2) far exceeds than the population of the lower energy level (N_1),

That is $N_2 >> N_1$.

In this condition the population distribution between the energy level E_1 and E_2 is inverted and hence it is known as inverted state. This is non-equilibrium state and exists only for a short time.

3.5 Metastable states

An atom can be excited to a higher level by supplying energy to it. Generally, excited atoms have short lifetimes and release their energy quickly (~10^{-9} s) through spontaneous emission. As a result of this, even though the pumping agent continuously raises the atoms to the excited state, they undergo spontaneous transition and rapidly return to the lower energy state. Population inversion cannot be established under such cases. In order to establish the condition for population inversion, excited atoms has to 'wait' at the higher energy level till a large number of atoms accumulate at that level. Such an opportunity would be provided by metastable states. Atoms excited to a metastable state remain excited for appreciable time (~10^{-6} to 10^{-3} s). This is ~10^{3} to 10^{6} s times the lifetimes of the ordinary excited energy level. Therefore metastable state allows population of large number of excited atoms at that level. Thus, the condition of population inversion is established in the lasing medium. It would be impossible to create a state of population inversion without a metastable state. Metastable state can be readily obtained in a crystal by incorporating impurity atoms.

Importantly, if metastable states do not exist, there could be no population inversion and hence no lasing action.

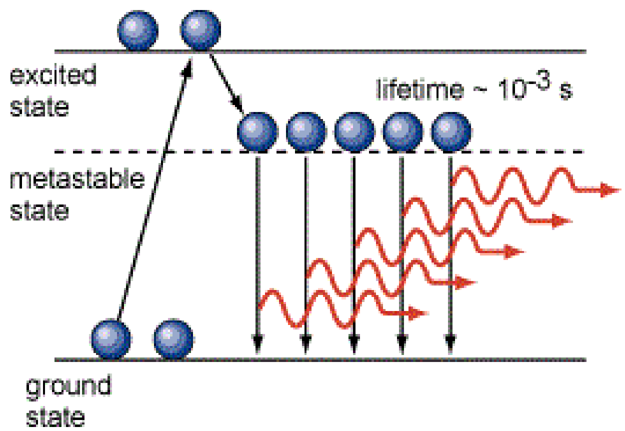


Figure 3.3 Metastable state

3.6 Components of laser

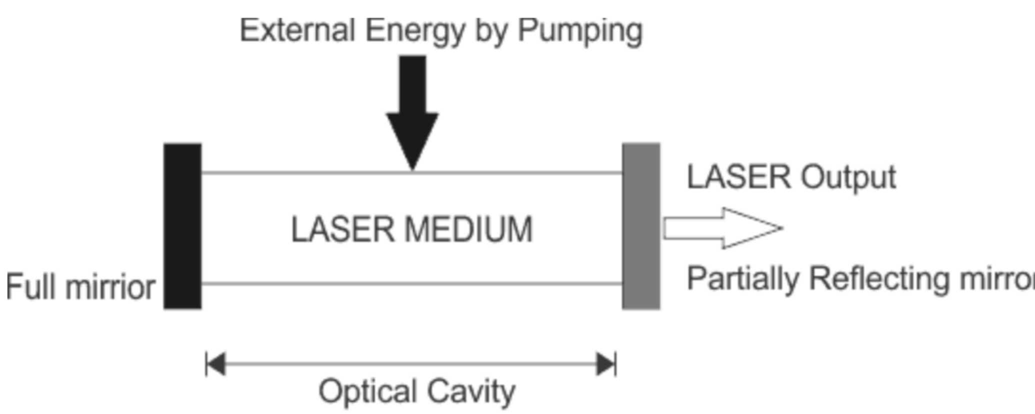


Figure 3.4 Components of laser

Essential components of laser are (1) Active medium, (2) Pumping agent and (3) Optical resonator

1. **Active medium**: Population inversion is the most important phenomenon in lasers. Generally, atoms have large number of energy levels. However, not all atoms are available for lasing action. Out of different atoms, only a small fraction of atoms have energy levels suitable for achieving population inversion. Such atoms can produce more stimulated radiations than spontaneous radiations and causes amplification of light. Those atoms which cause lasing action are called active centers. The medium hosting active centers is called active medium. *Active medium* is a medium which when excited reaches the state of population inversion and promotes stimulated emissions leading to amplification of light.
2. **Pumping agent**: For achieving and maintaining the condition of population inversion, we have to raise atoms from lower energy level to higher energy level continuously. It requires energy to be supplied to the system. The process of supplying energy to the atoms so that they can excite to higher energy level from lower energy level to occur lasing action, is known as pumping. The mediator which supply this energy is called pumping agent.

   Type of pumping:

   There are a number of ways to pump (excite) atoms to higher energy level from lower energy level. Few of them are as follows.

   1. *Optical pumping*: Optical pumping uses photons to excite the atoms. A light source such as flash discharge tube is used to illuminate laser medium and photons of appropriate frequency excite the atoms to higher energy level to create the condition of population inversion. Generally, optical pumping is used in solid-state lasers.
   2. *Electrical pumping*: Electrical pumping is used only in case of laser medium which conducts electricity without destroying lasing property. This method of pumping is limited to gas lasers. In this, high electric field causes ionization of laser medium and raises it to the excited state to satisfy the condition of population inversion.
   3. *Direct conversion*: In this type of pumping, there is direct conversion of electrical energy into light energy takes place.
3. **Optical resonator**: Laser is a light source and it is analogous to electronic oscillator. Electronic oscillator is essentially an amplifier with positive feedback. Positive feedback means a part of output is taken and fed back to its input.

Role of optical resonator:

- To provide positive feedback of photons so that stimulated emission is sustained and laser acts a generator of light.
- It makes laser beam unidirectional.
- It makes photon density very high through repeated reflections of photons.
- It makes laser beam highly monochromatic.

3.7 Types of Lasers

Lasers are classified into different categories based on the active materials and pumping agent used.

1. Solid state lasers: In this type of laser, active medium is in solid form while optical pumping is employed here.

e.g. Ruby laser, Nd:YAG laser, Nd:Glass laser, etc.

2. Semiconductor (diode) lasers: In this type of laser, active medium is in solid form but pumping is electrical.

e.g. GaAs laser, InP laser, etc.

3. Gas lasers: In this type of laser, active medium is in gaseous form while pumping is electrical.

e.g. He-Ne laser, CO_2 laser, Argon ion laser, etc.

4. Liquid lasers: e.g. Organic dye laser.

He-Ne Laser

Gas lasers are the most widely used lasers. They range from the low power helium-neon laser used in college laboratories to very high power carbon dioxide laser used in industrial applications. These lasers operate with rarefied gases as the active media and are excited by an electric discharge. In gases, the energy levels of atoms involved in the lasing process are narrow and as such require sources with sharp wavelength to excite atoms. Finding an appropriate optical source for pumping poses a problem. Therefore optical pumping is not used in gas lasers. The most common method of exciting gas laser medium is by passing an electric discharge through the gas. Electrons present in the discharge transfer energy to atoms in the laser gas by collisions.

The first gas laser was He-Ne laser, which was invented in 1961 by Ali Javan, William R. Bennett, Jr. and Donald R. Herriott.

Construction:

The schematic of a He-Ne laser is shown in Fig. 24.19. Helium –

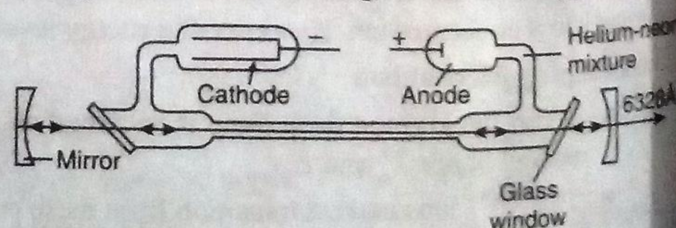


Fig. 24.19

Neon laser consists of a long discharge tube filled with a mixture of helium and neon gases in the ratio 10:1. Neon atoms are the active centers and have energy levels suitable for laser transitions while helium atoms help in exciting neon atoms. Electrodes are provided in the discharge tube to produce discharge in the gas. They are connected to a high voltage power supply. The tube is hermetically sealed by inclined windows arranged at its two ends. On the axis of the tube, two mirrors are arranged externally, which form the Fabry-Perot optical resonator. The distance between the mirrors is adjusted to be $m\lambda/2$ such that the resonator supports standing wave pattern.

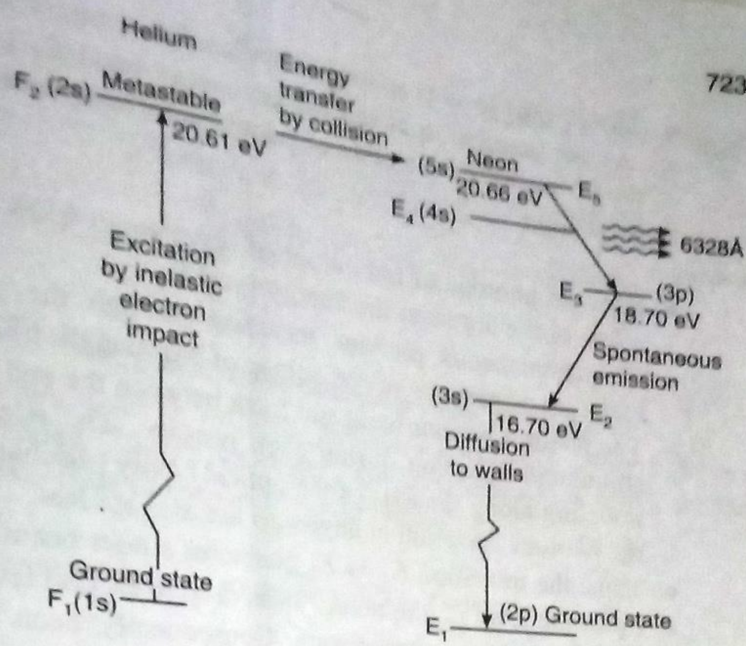


Fig. 24.20

Working:

The energy levels of helium and neon are shown in Fig. 24.20.

The Pumping Mechanism

- When the power is switched on, a high voltage of about 10 kV is applied across the gas mixture. It ionizes the gas.
- The electrons and ions produced in the process of discharge are accelerated towards the anode and cathode respectively. They collide with helium and neon atoms on the way.
- The energetic electrons excite helium atoms more readily, as they are lighter.
- One of the excited levels of helium $F_2(2s)$ is at 20.61 eV above the ground level. It is a metastable level and the excited helium atom cannot return to the ground level through spontaneous emission.
- However, the excited helium atom can return to the ground level by transferring its excess energy to a neon atom through collision. Such an energy transfer can take place when the two colliding atoms have identical energy levels. Such an energy transfer is known as **resonant energy transfer**.
- The neon energy level $E_5(5s)$ is at 20.66eV, which is close to the excited energy level F_2 of helium atom. Therefore, resonant transfer of energy occurs between the excited helium atom and ground level neon atom. The kinetic energy of helium atoms provides the additional 0.05 eV required for excitation of the neon atoms.
- Helium atoms drop to the ground state after exciting neon atoms. This is the pumping mechanism in He-Ne laser.

Population Inversion

- The upper state of neon atom E_5 is a metastable state. Therefore, neon atoms accumulate in this upper state.
- The E_3 (3p) level is sparsely populated at ordinary temperatures.
- As the population at the higher energy level E_5 is greater than the population at the lower level E_3, a state of population inversion is established between E_5 and E_3 levels.

Lasing

- Random photons of red colour of wavelength 6328 Å are emitted spontaneously by a few of the atoms at the energy level E_5.
- The spontaneous photons traveling through the gas mixture prompt stimulated emission of photons of red colour of wavelength 6328 Å.
- The photons bounce back and forth between the end mirrors, causing more and more stimulated emission during each passage. The strength of the stimulated photons traveling along the axis of the optical cavity (discharge tube) builds up rapidly while the photons traveling at angles to the axis are lost.
- Thus, the transition $E_5 \rightarrow E_3$ generates a laser beam of wavelength 6328 Å.
- From the level E_3 the neon atoms drop to E_2 (3s) level spontaneously.
- E_2 level is a metastable state. Consequently, neon atoms tend to accumulate at E_2 level.

- Neon atoms return to the ground state E_1 through frequent collisions with the walls of the glass tube holding the helium-neon gas mixture.
- The neon atoms are once again available for excitation to higher state and participate in lasing action.
- The neon atoms are excited to the upper lasing level continuously through collisions. As the population inversion can be maintained in the face of continuous laser emission, the laser operates in continuous wave mode.

Role of helium atoms

- The role of helium atoms in the laser is to excite neon atoms and to cause population inversion. The probability of energy transfer from helium atoms to neon atoms is more, as there are 10 helium atoms per 1 neon atom in the gas mixture. The probability of reverse transfer of energy from neon to helium atom is negligible.

Necessity of narrow glass tube

- During the operation of the laser, it is necessary that the atoms accumulating at the metastable level E_2 are brought to the ground state E_1(2p) quickly; otherwise the number of atoms at the ground state will go on diminishing and the laser ceases to function. The only way of bringing the atoms to the ground state is through collisions. Therefore, to increase the probability of atomic collisions with the tube walls, the discharge tube is made narrow.

Salient Features

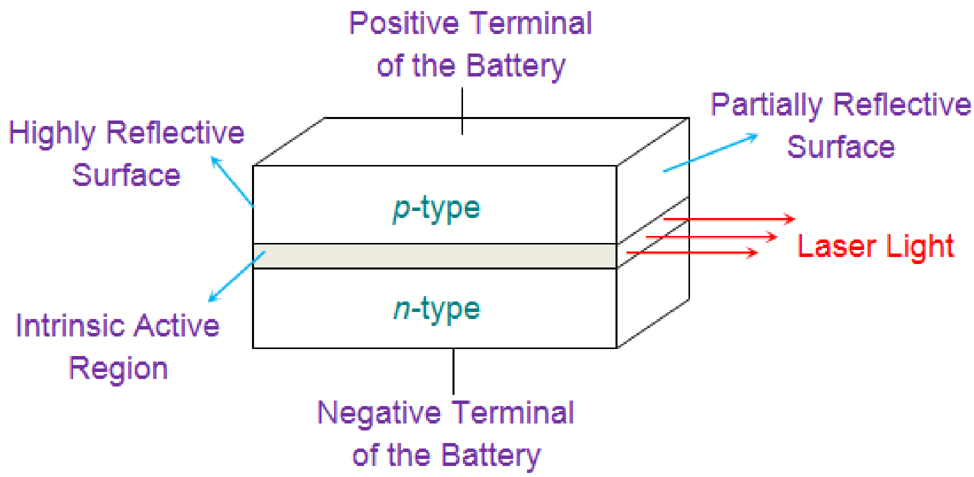
- Uses four-level pumping scheme
- The active centers are neon atoms
- Electrical discharge is the pumping agent
- Low efficiency and low power output
- Operates in CW mode

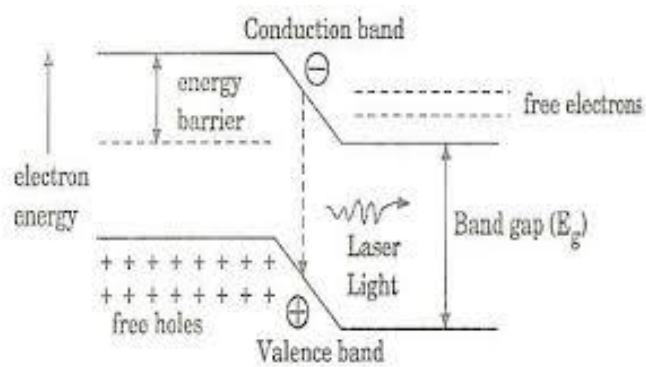
Semiconductor (diode) Laser

Semiconductor laser is specially constructed p-n junction device, which emits coherent light when it is forward biased.

Construction:

These lasers are made with direct band gap semiconductors (e.g. GaAs). Heavily doped n-type and p-type semiconductors are used to form p-n junction diode. Top and bottom surfaces are metalized for electrical connections. Front and rare faces are polished parallel each other. Polished surfaces will acts as a optical resonator. Remaining two sides are roughened to eliminate lasing light.





Working:

Because of heavily doped n and p type semiconductors, there are large number of electrons in conduction band of n-type and large number of hole in valance band of p-type semiconductor. When junction is forward biased, electrons and holes are injected into the junction. Here, charges are pumped by the dc voltage. Thus, there are large number of holes in valence band and electrons in conduction band. As the upper level has high number of electrons and lower levels are large number of holes (absence of electrons), the condition for population inversion is established in the narrow region. This narrow region is active region. Recombination of electrons and holes leads to lasing action.

Features:

Diode lasers are made to emit light almost anywhere in the spectrum from UV to IR region.

Small in size (~0.1 mm length)

High efficiency, operated at low power

Portable, cheaper than any other lasers

3.9 Application of Lasers (Self study)