LASER

LASER is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. It is a device which is used to produce a unidirectional, extremely intense and coherent beam of light.

➢ CHARACTERISTICS /PROPERTIES OF LASER LIGHT

The characteristic properties of Laser light are,

1. Unidirectionality
2. Monochromaticity
3. High Intensity
4. Coherence

1. Directionality: Conventional light sources emit photons in all directions but in LASER, photons are emitted in one direction i.e. along the optical axis of the system. This is achieved by means of stimulated emission. In ordinary light sources, photons are emitted in all directions by means of spontaneous emission.
2. Monochromaticity: Laser beam consists of photons of almost same wavelength which gives single colour to the light. There are no light sources which is ideally monochromatic, but compared to ordinary light sources, laser light is highly monochromatic. Line width is a measure of monochromaticity. For ordinary light sources it is of the order of 1000Å, whereas for laser light it is of the order of 10Å to 10^{-4} Å
3. Intensity: LASER gives out light in a narrow beam and its energy is concentrated in a small region. Intensity of 1mW power laser is 10,000 times bright than light from the sun at the earth's surface.
4. Coherence: Light waves emitted by the laser source are in phase and of same frequency so it is highly coherent.

➢ INTERACTION OF RADIATIONS WITH MATTER

The production of laser light is a consequence of interaction of radiation with matter. There are three processes by which the radiation interacts with matter.

(1) Induced absorption

(2) Spontaneous emission

(3) Stimulated emission.

1) **Induced Absorption:**

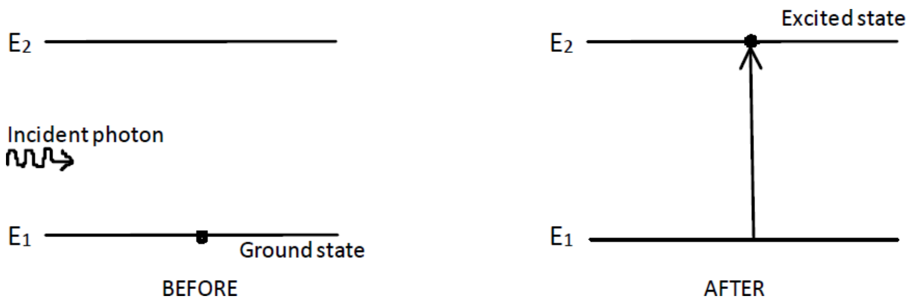
The process of absorption of incident photon by an atom and hence the excitation of the atom to the higher energy state is called induced absorption wherein the energy of incident photon is exactly equal to the difference in energies of two states.

Explanation: Consider two energy levels $E1$ and $E2$ such that $E2 > E1$ as shown in the figure. Consider an atom in the lower energy state $E1$. When a photon of energy equal to the energy difference between $E1$ and $E2$ is incident on the atom in the state $E1$, it absorbs the photon. Due to the absorption of photon, the energy of the atom increases to the value of $E2$. Therefore, the atom gets excited to the energy state $E2$.

It can be represented by:

$$\text{Atom} + \text{Photon} = \text{Atom}^*$$

$$A + h\nu = A^*$$



2) **Spontaneous Emission:**

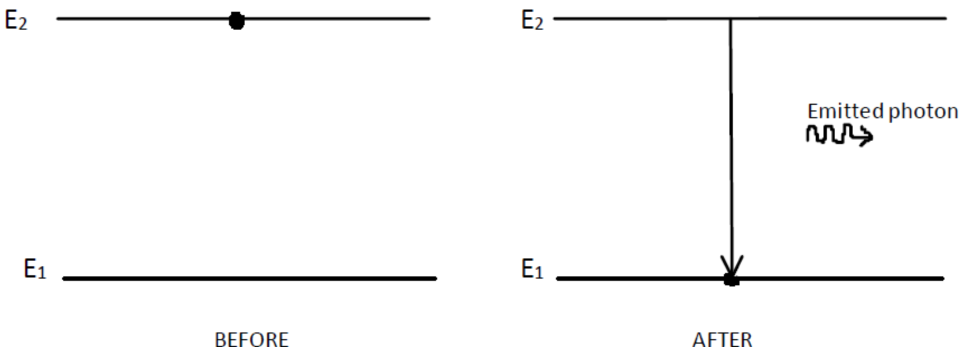
The process of emission of a photon of suitable frequency by an atom due to the transition from a higher energy state to a lower energy state without any supply of external energy is called spontaneous emission.

Explanation: Consider an atom in an excited state $E2$. Let $E1$ be its ground state energy. In the excited state the atom is unstable and hence it stays in the state $E2$ only for 10^{-8} seconds and then undergoes transition to the ground state $E1$ by emitting a photon whose energy is equal to the difference between the energy states $E1$ and $E2$. For this emission, the atom does not require any aid (extra energy). Therefore, the emission is known as spontaneous emission. The atom can emit photon in any direction. Two such photons emitted by two different atoms may or may not be in phase. Therefore, the spontaneous emission is considered as incoherent emission. This kind of emission is observed in glowing electrical bulb, and candle flame.

It can be represented by:

$$\text{Atom}^* = \text{Atom} + \text{Photon}$$

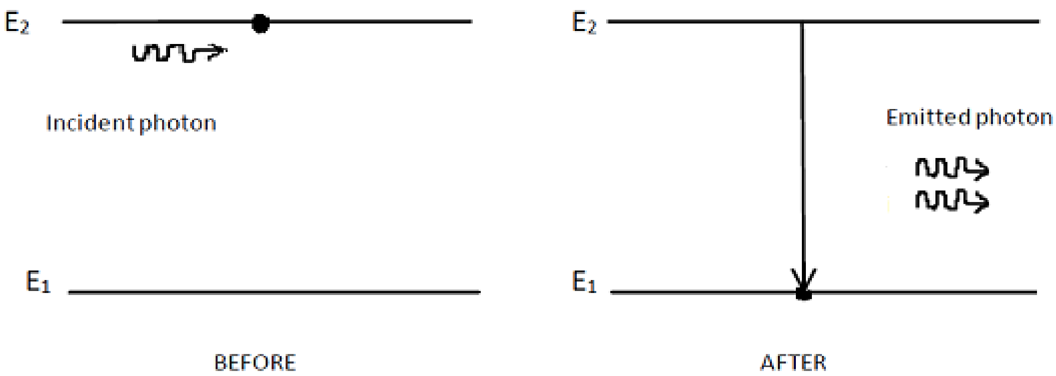
$$A^* = A + h\nu$$



3) **Stimulated Emission:**

The process of emission of a photon by an atom in the excited state under the incidence of a passing photon of right energy on the atom and hence the transition of the atom to a lower energy state is called stimulated emission.

<u>Explanation:</u> In this process the incident photon stimulates the atom to emit an identical photon. Hence this process is known as stimulated emission. In this process both incident photon and stimulated photon travel in the same direction and will be in phase. Hence, stimulated emission is called coherent emission. This kind of emission is suitable for laser action.



$$A^* + h\upsilon \longrightarrow A + 2\,h\upsilon$$

➢ Boltzman relation for ratio of population of two atomic states:

The number of atoms per unit volume in an energy state is known as the population density of that energy state. The population densities of different energy states are related to each other if the system is in thermal equilibrium.

Consider two energy states E1 and E2 with population densities N1 and N2 respectively such that E2 > E1.

The relation between the two is given by Boltzmann factor,

$$\mathbf{N} \propto e^{-\frac{E}{kT}}$$

$$\frac{N_2}{N_1} = e^{\frac{-(E_2 - E_1)}{kT}}$$

But $\quad E_2 - E_1 = \Delta E$

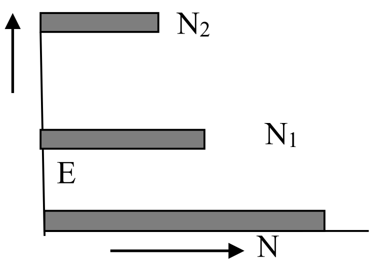
$$\frac{N_2}{N_1} = e^{-\frac{\Delta E}{kT}}$$

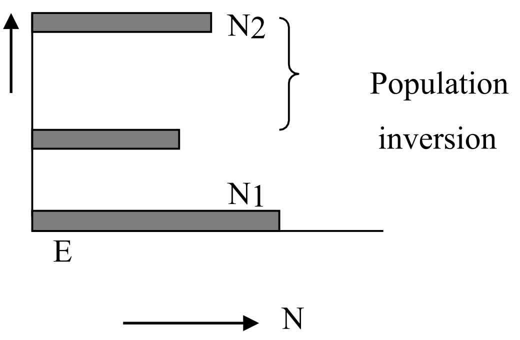
$e^{-\frac{\Delta E}{kT}}$ is always less than unity because ΔE is always positive. Therefore,

$$\frac{N_2}{N_1} < 1 \qquad\qquad N_2 < N_1$$

Thus, under ordinary conditions the population of any higher energy state is less than the population of its lower energy states.

If the population of any higher energy state is more than the population of any specified lower energy state, then it is called <u>population inversion</u>.





- **Expression for energy density of radiation in terms of Einstein's coefficients:**

Consider two energy levels E1 and E2 of an atomic system such that E2 > E1. Let the population densities of E1 and E2 be N1 and N2 respectively. Let radiations with continuous spectrum of frequencies be incident on the atomic system. Then U_ν represents energy density (energy per unit volume of the frequency range) of frequency ν. In case of induced absorption, when this energy is incident on an atom in the energy level E1, it absorbs the energy and makes a transition to the energy level E2. The number of such absorptions per second is called rate of absorption. The rate of absorption depends on the number of atoms in the lower energy state and the energy density U_ν of the incident radiation.

Rate of absorption, $\quad R_{12} \propto N_1 U_\nu$

$$R_{12} = B_{12} N_1 U_\nu$$

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

In case of spontaneous emission, an atom in the higher energy level E2 undergoes transition to the energy state E1, voluntarily by emitting a photon. The rate of spontaneous emission depends only on population density N_2.

Rate of spontaneous emission, $\quad R_{21} \propto N_2$

$$R_{21} = A_{21} N_2$$

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

If the energy density U_ν is incident on an atom in the energy state E2, it undergoes stimulated emission. The rate of stimulated emission is proportional to the population density N_2 and the incident energy density U_ν

Rate of stimulated emission, $\quad R^*_{21} \propto N_2 U_\nu$

$$R^*_{21} = B_{21} N_2 U_\nu$$

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

At thermal equilibrium,

Rate of absorption = Rate of spontaneous emission + Rate of stimulated emission

$$R_{12} = R_{21} + R^*_{21}$$

$$B_{12}N_1U_\nu = A_{21}N_2 + B_{21}N_2U_\nu$$

$$B_{12}N_1U_\nu - B_{21}N_2U_\nu = A_{21}N_2$$

$$U_\nu\{B_{12}N_1 - B_{21}N_2\} = A_{21}N_2$$

$$U_\nu = \frac{A_{21}N_2}{\{B_{12}N_1 - B_{21}N_2\}}$$

$$U_\nu = \frac{A_{21}N_2}{B_{21}N_2\left\{\frac{B_{12}N_1}{B_{21}N_2} - 1\right\}}$$

$$U_\nu = \frac{A_{21}N_2}{B_{21}N_2}\left\{\frac{1}{\left\{\frac{B_{12}}{B_{21}}\left(\frac{N_1}{N_2}\right) - 1\right\}}\right\}$$

$$U_\nu = \frac{A_{21}}{B_{21}}\left\{\frac{1}{\left\{\frac{B_{12}}{B_{21}}\left(\frac{N_1}{N_2}\right) - 1\right\}}\right\} \quad ----- \quad (1)$$

From Boltzmann's law for thermal equilibrium of an atomic system we have

$$\frac{N_2}{N_1} = e^{-\frac{\Delta E}{kT}}$$

$$\text{or} \qquad \frac{N_1}{N_2} = e^{\frac{\Delta E}{kT}}$$

But $\quad \Delta E = h\nu$

$$\therefore \frac{N_1}{N_2} = e^{\frac{h\nu}{kT}}$$

Substituting this result in equation (1) we get

$$U_\nu = \frac{A_{21}}{B_{21}}\left\{\frac{1}{\left\{\frac{B_{12}}{B_{21}}\left(e^{\frac{h\nu}{kT}}\right) - 1\right\}}\right\} ----- \quad (2)$$

From Planck's law of energy distribution, the energy density is given by,

$$U_\nu = \frac{8\pi h\nu^3}{c^3}\left\{\frac{1}{e^{\left(\frac{h\nu}{kT}\right)} - 1}\right\} ------ \quad (3)$$

Comparing equations (2) and (3), we find

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

$$\frac{B_{12}}{B_{21}} = 1$$

These two equations are called Einstein's relations. Then Equation (2) becomes

$$\boxed{U_\nu = \frac{A_{21}}{B_{21}}\left[\frac{1}{e^{\frac{h\nu}{kT}} - 1}\right]}$$

From, $B_{12} = B_{21}$ we see that the rate of induced absorption is equal to the rate of stimulated emission, at thermal equilibrium.

➢ CONDITIONS FOR LASER ACTION

LASER action is nothing but production of coherent photons. Laser photons can be produced only by stimulated emission.

In a LASER source, stimulated emission should dominate spontaneous emission & induced absorption.

Therefore, the conditions for LASER ACTION are:

1. Rate of stimulated emission / Rate of spontaneous emission should be high.

i.e., $(R_{21})^* / R_{21} = [B_{21}\ N_2 / A_{21}\ N_2]\ U\nu$

$= [B_{21}\ / A_{21}]\ U\nu$ should be high.

Since, $[B_{21}\ / A_{21}]$ is a constant, $U\nu$ should be high.

This is achieved by using appropriate Optical Resonator.

2. Rate of stimulated emission / Rate of induced absorption should be high.

i.e., $(R_{21})^* / R_{12} = [B_{21}\ N_2\ U\nu / B_{12}\ N_1]\ U\nu$

$= [B_{21}\ / B_{12}]\ [N_2\ /\ N_1]$ should be high.

Since, $[B_{21} = B_{12}]$, $[N2\ /\ N1]$ should be high.

The condition, $[N_2 > N_1]$ is called as Population Inversion.

So, population inversion has to be achieved.

➢ REQUISITES OF A LASER SYSTEM

The following are the three requisites of a laser system.

1) <u>Active medium</u>:

A material medium in which the population inversion and hence the lasing action can be achieved is called active medium. Active medium provides energy levels for atomic transitions and helps for lasing action. A material will be chosen as active medium only if it possesses metastable states and by which we can achieve population inversion from which we can have more stimulated emissions.

Depending on the type of active medium used, the lasers are classified into four groups in the following way

a) <u>Gas lasers:</u> They consist of a mixture of gases as the active medium.

Example: He-Ne laser, CO_2 laser

b) <u>Solid-state lasers:</u> They consist of crystals as the active medium,

Example: Ruby laser, Yttrium Aluminium garnet (YAG) laser

c) <u>Semiconductor lasers:</u> They consist of semiconductors as the active medium.

Example: Gallium Arsenide (GAS) laser

d) <u>Liquid lasers:</u> They consist of chemicals as the active medium.

Example: Dye lasers

2) <u>Pumping</u>:

To raise the atoms from a lower to a higher energy state by supplying sufficient energy is called pumping. There are different types of pumping techniques.

a) <u>Optical pumping</u>: Intense light source is used to supply luminous energy and raise the atoms. Eg: Ruby laser.

b) <u>Electric Discharge</u>: In this process electric discharge is used for the excitation of atoms. Eg: He-Ne laser

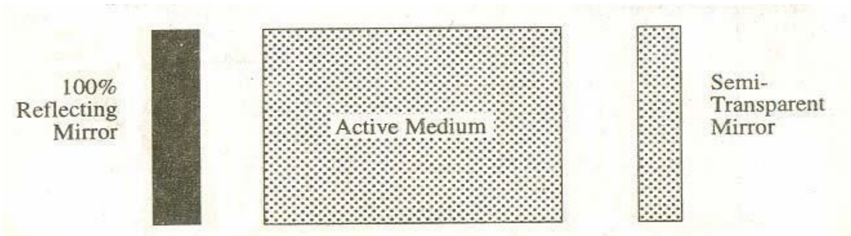
c) <u>Direct Conversion</u>: Electrical energy is directly converted into radiation in devices like LEDs and semiconductor lasers.

d) <u>Chemical Reactions</u>: In this, energy for excitation comes from chemical reactions without any need for other energy sources.

3) **<u>Resonant cavity:</u>**

In order to generate a coherent and amplified light output, it is necessary that photons with a specific direction are selected while others are rejected. Also these stimulated photons are to be made to pass through the active medium a number of times. These requirements are met with an optical resonant cavity.

Optical resonant cavity consists of two parallel mirrors facing each other with active medium placed in between them. One of the mirrors is 100% reflecting while the other is made partially reflecting.

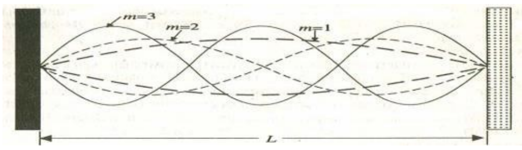


Only those photons emitted parallel to the axis of resonant cavity suffer multiple reflections by the opposite mirrors and gain in strength while other photons are lost.

In order to sustain the standing wave pattern in the resonator, the distance between the mirrors is made to be equal to n (λ/2).

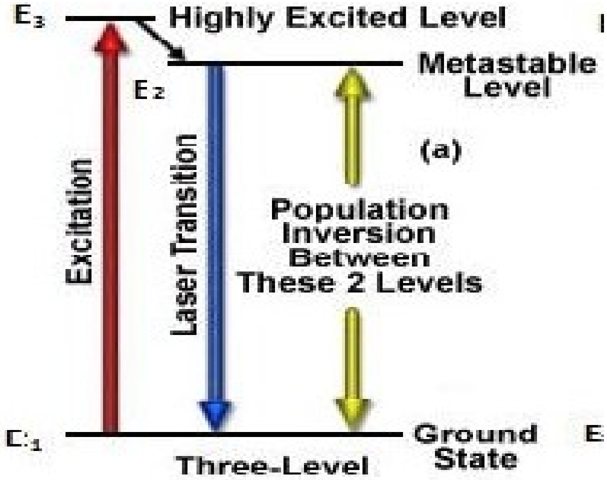
i.e. L = n λ/2 (This is called resonance condition).

where n = 1,2,3,…., L is the distance between the mirrors and λ is the wavelength of light.



- **Three Level Pumping Scheme:**

The three level scheme first excite the atoms to a higher energy than the upper laser state. The atoms then quickly decay down into the upper laser state. A typical three level pumping scheme is shown in the figure.

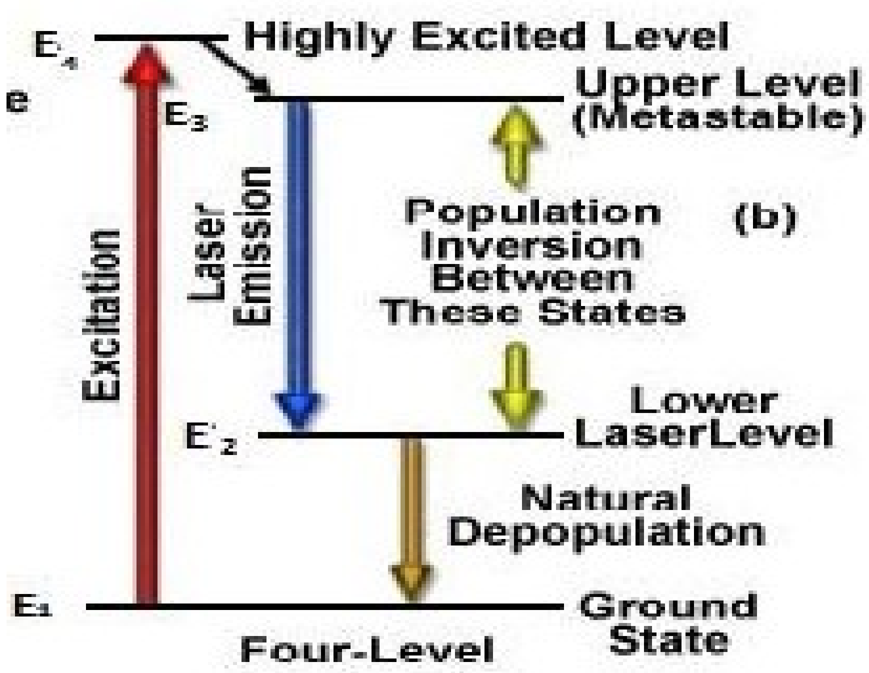


Consider three energy levels E1, E2 and E3 of an atomic system, in such a way that E1 < E2 < E3. Let E2 be the metastable state. Under normal conditions the atoms remain in the lower energy state E1. But when suitable amount of energy is supplied to them they start undergoing excitation to the state E3. The excited atoms in the state E3 stay for a period of 10^{-8} seconds and then undergo non-radiative transition to the metastable state E2, where they stay for a long duration of the order 10^{-2} seconds. If the pumping of atoms from E1 to E3 is maintained continuously, then the population of E1 decreases continuously. The atoms excited to the state E3 undergo immediate downward transition to E2, as a result of which the population of E2 increases more. Due to this process a stage will reach at which the population of E2 will be more than that of E1. This is known as population inversion. Now a chance photon can trigger stimulated emission from E2 to E1.

In this scheme, population inversion is achieved only when more than half of ground state atoms are pumped to upper state. Thus, scheme requires very high pumping power. The three level scheme produces light only in pulses.

- **Four Level Pumping Scheme**

  A typical four level pumping scheme is shown in the figure.



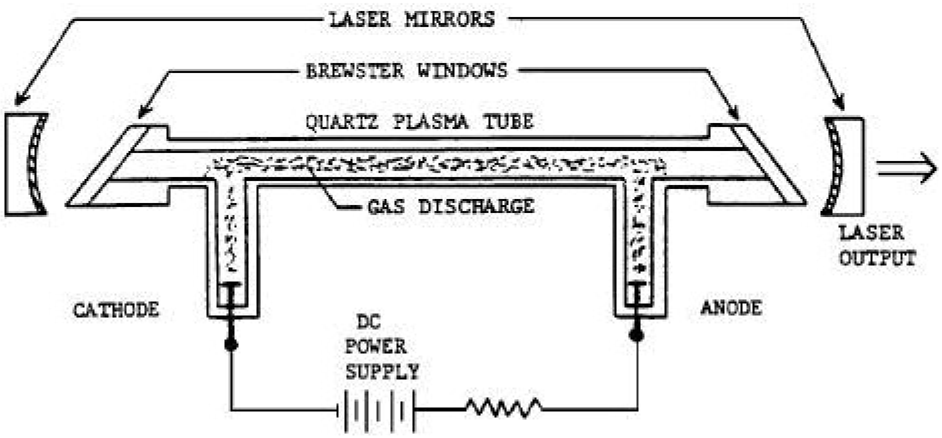
Four level systems follow roughly the same process as that of 3-level scheme except that population is moved from the lowest state E1 to the highest fourth level E4 where they stay for only about 10^{-8}s. Then it decays to the third level E3 which is metastable upper lasing level. As spontaneous transitions from the level E3 to level E2 cannot take place, the atoms get trapped in the state E3 and population grows rapidly here. The level E2 is well above the ground state so that at normal temperature atoms cannot jump to level E2. As a result, level E2 is virtually empty. Therefore, population inversion is attained between the states E3 and E2 and lasing happens when the incident light matches the energy between the third (E3) and second level E2 which is lower lasing level. After lasing, atoms from state E2 subsequently undergo non-radiative transitions to ground state E1.

The lower laser transition level in this scheme is nearly vacant. Therefore, less power is sufficient to achieve population inversion. Four level lasers operate in continuous wave mode.

- **Helium-Neon Laser**

Construction:

- Helium-Neon laser is a **gas laser**.
- The **active medium** is a mixture of Helium and Neon gases in the ratio 10:1with pressure inside the tube is maintained as 1: 0.1 torr.
- The **resonant cavity** (or discharge tube) is a sealed **quartz** tube of 1m length and 1 cm diameter. The ends of the glass tube are sealed with Brewster windows to reduce reflection losses. The quartz tube is placed between two mirrors, one completely silvered and one partially silvered.
- Two **electrodes** are provided in the tube which are connected to external potential source of the order of 1KV, to excite the He-Ne mixture.



Working:

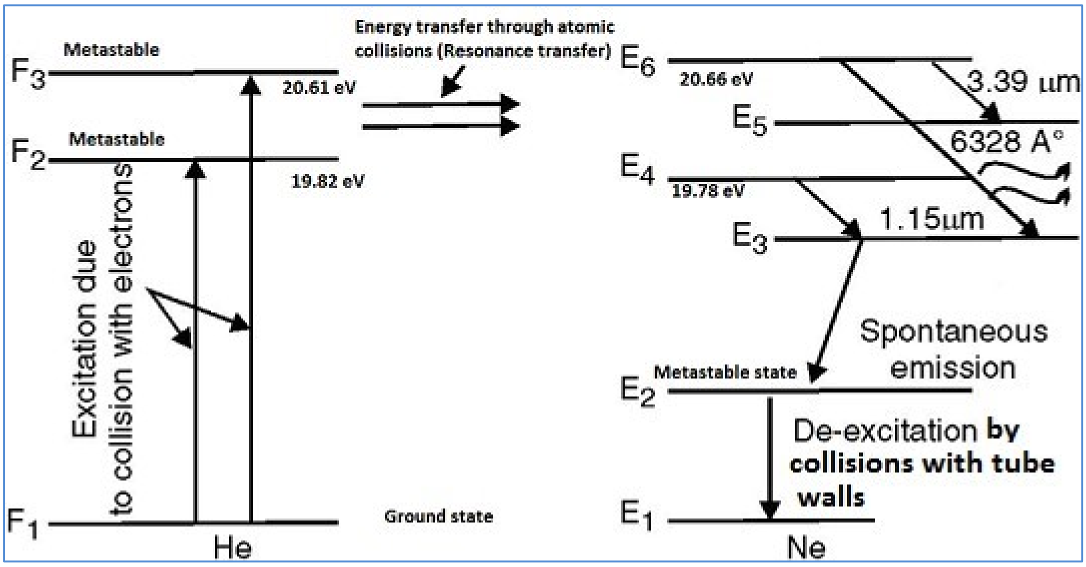
- The energy level diagram of a He-Ne laser is as shown in the figure.
- When a suitable voltage of the order 1000 V is applied to the electrodes, the gaseous mixture of He and Ne undergoes electrical discharge producing free electrons and ions.
- The electrons get accelerated by the applied voltage and collide with the He and Ne atoms due to which the atoms are excited to the higher energy states.
- Since the proportion of Helium atoms is greater, a large number of Helium atoms are excited to F2 and F3 levels, which are metastable.
- Levels F2 and F3 of Helium have approximately the same energy as levels E4 and E6 of Neon. Thus when a Helium atom in the metastable state collides with a Neon atom in the ground state, it transfers its energy to the Neon atom. This transfer is called **resonance transfer**. By gaining the transferred energy, the Neon atom gets transferred to E4 or E6 level.
- The population of E4 and E6 states of Neon increases rapidly and **population inversion** is achieved.
- The atoms in E4 and E6 undergo **radiative transitions** to their lower E3 and E5

levels. Three wavelengths of light are emitted.

- **E6** → **E5** level which gives rise wavelength **3.39 μm**.
- **E6** → **E3** level which gives rise wavelength **6328 Å**.
- **E4** → **E3** level giving rise to 1**.15 μm**.

➢ E3 and E5 are not metastable states and so the atoms undergo **spontaneous transition** to the metastable state E2 by emitting photons.

➢ Since E2 is a metastable state, atoms tend to stay in this state for a longer duration. This has an **adverse** effect since the atoms in this state may be excited to the E5 or E3 levels again due to the photons from the spontaneous emission. This is **counteracted** by making the diameter of the discharge tube very small (order of a few millimetres), since atoms in this metastable state immediately come down to the ground state when they collide with the walls of the laser tube.



He-Ne laser gives light output of wavelength **6328 Å.** Since electrical discharge takes place continuously, population inversion is maintained continuously and the laser emission is continuous. Therefore, He-Ne laser is a **continuous wave laser**.

Salient Features of He-Ne laser

1. Use Four level pumping scheme
2. The active centres are Ne atoms.
3. Electrical discharge is the pumping agent.
4. operates in continuous wave(CW) mode

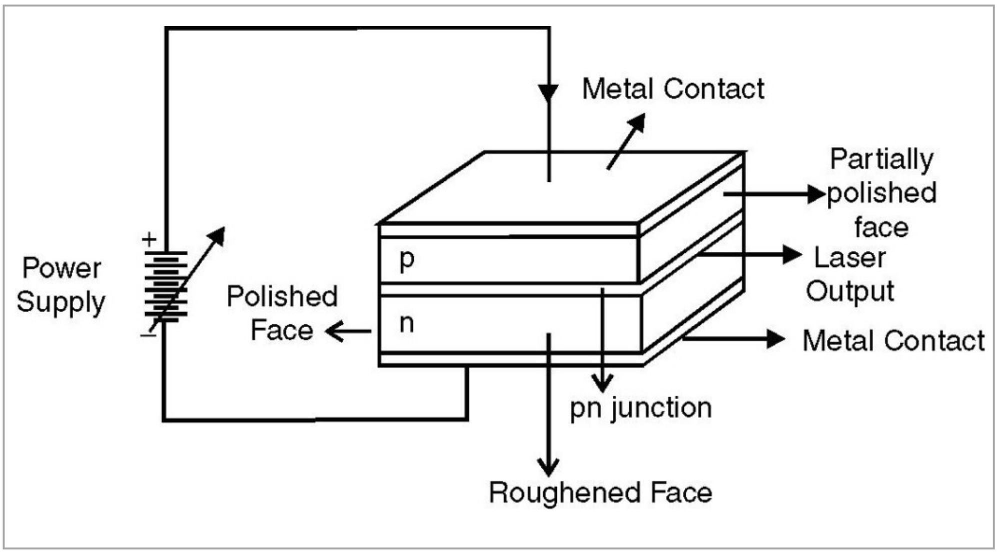
➢ SEMICONDUCTOR LASER

Principle

Semiconductor laser is based on the principle of electron hole recombination in a direct band gap semiconductor which results in emission of photons.

Construction:

- It consists of a p-n junction in which p- and n- regions are heavily doped.
- Each side of the laser is of the order of 1 mm. The p-n junction layer width is ~ 1µm.
- The top and bottom faces are provided with metallic contacts to pass current through the diode.
- The front and rear faces are polished parallel to each other and perpendicular to the plane of the junction. The polished faces constitute the optical resonator.
- The other two opposite faces are roughened to prevent lasing action in that direction.



Working

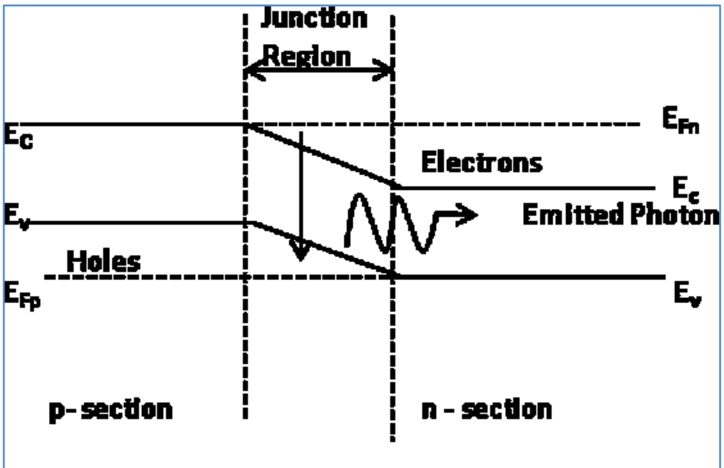
- When the laser diode is forward biased, electrons move to p-region and holes to n-region.
- These electrons and holes recombine in the junction region and photons are emitted.
- At low forward current only spontaneous emission takes place. As the current increases and reaches a threshold value, the depletion region contains high concentration of electrons within the conduction band and a large concentration of holes within the valence band. This is the state of population inversion.
- Thus the forward bias plays the role of pumping source. At this stage, any

spontaneously emitted photon triggers stimulated emission and laser beam is produced.

- The emission wavelength depends on doping and threshold current.

For example, the energy gap of GaAs semiconductor is 1.4 eV.

From the equation, $E_g = hc / \lambda$, we get the wavelength of emitted photon $\lambda = 8400$ Å.



Energy band diagram for a semiconductor laser

Semiconductor lasers have many advantages such as compact in size, lightweight, good reliability, long service life, low power consumption, safe operation and low cost of maintenance.

Semiconductor lasers are used in optical communication, optical data storage, laser pointers, writing or reading from CD and DVD, metrology, spectroscopy, material processing, pumping of other lasers, and medical treatments.

- **Applications of LASER:**

- **LIDAR — Light Detection and Ranging**

LIDAR is a remote sensing method used to examine the surface of the Earth.

Remote sensing means measuring remotely and not physically with our hands. We are using sensors which capture information about a landscape and record things that we can use to estimate conditions and characteristics. To measure vegetation or other data across large areas, we need remote sensing methods that can take many measurements quickly, using automated sensors.

LIDAR, which stands for *Light Detection and Ranging,* is a remote sensing method that uses light in the form of a pulsed laser to measure ranges (variable distances) to the Earth. LIDAR is an active remote sensing system that can be used to measure vegetation height across wide areas. Lidar systems allow scientists and mapping professionals to examine both natural and manmade environments with accuracy, precision, and flexibility.

These light pulses—combined with other data recorded by the airborne system — generate precise, three-dimensional information about the shape of the Earth and its surface characteristics.

Generally, a LIDAR instrument consists of a laser, a scanner, and a specialized GPS receiver. Airplanes and helicopters are the most commonly used platforms for acquiring LIDAR data over broad areas. Two types of LIDAR are topographic and bathymetric. Topographic lidar typically uses a near-infrared laser to map the land, while bathymetric lidar uses water-penetrating green light to also measure seafloor and riverbed elevations.

In a LIDAR system, light is emitted from a rapidly firing laser. This light travels to the ground and reflects off of things like buildings and tree branches. The reflected light energy then returns to the LiDAR sensor where it is recorded. A LiDAR system measures the time it takes for emitted light to travel to the ground and back. That time is used to calculate distance travelled. Distance travelled is then converted to elevation. These measurements are made using the key components of a lidar system including a GPS that identifies the X,Y,Z location of the light energy and an Internal Measurement Unit (IMU) that provides the orientation of the plane in the sky.

Light energy is a collection of photons. As photon that make up light moves towards the ground, they hit objects such as branches on a tree. Some of the light reflects off of those objects and returns to the sensor. If the object is small, and there are gaps surrounding it that allow light to pass through, some light continues down towards the ground. Because some photons reflect off of things like branches but others continue down towards the ground, multiple reflections may be recorded from one pulse of light.

A **Discrete Return LiDAR System** records individual (discrete) points for the peaks in the waveform curve. A **Full Waveform LiDAR System** records a distribution of returned light energy.

- **HOLOGRAPHY**

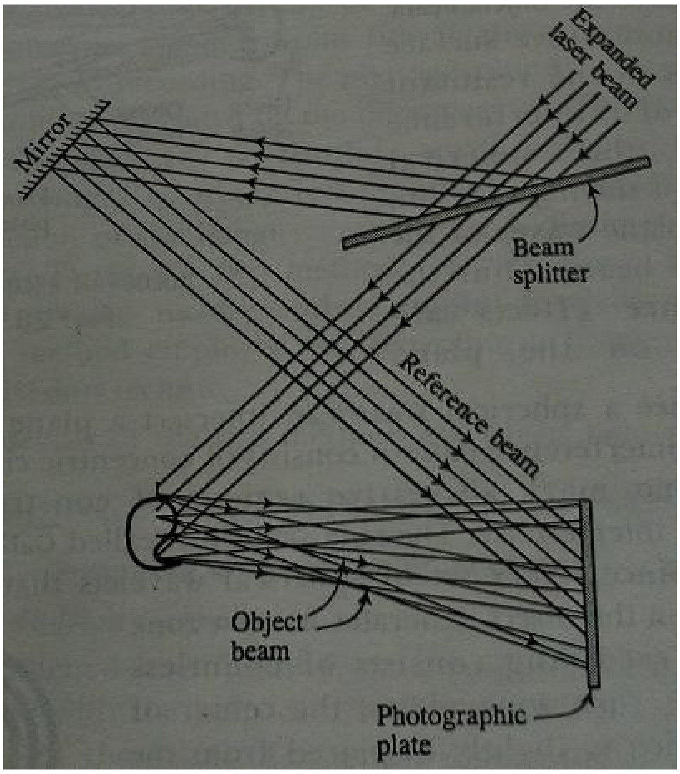
The technique of recording the three dimensional image of an object on a two dimensional recording aid using the principle of interference is known as holography. The Holography requires highly coherent laser light. In conventional photography, the photographic film records only the intensity of light, and not the phase of the wave. Thus it loses the three dimensional nature of the object. But in holography we record both intensity and phase of the wave by making the wave front from the object to interfere with another wave front from a reference source and recording the interference fringes on a conventional photo film. This result in a 3-dimensional picture of the object called a hologram.

Holography involves two steps:

1) **Recording of the image of an object**

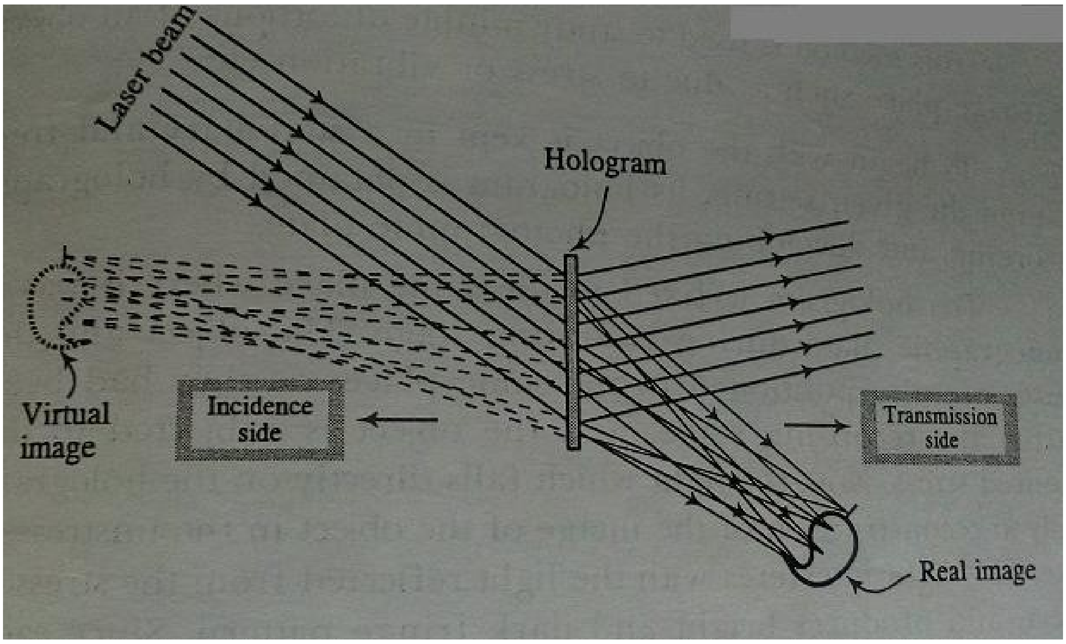
   The image of an object can be recorded on a photographic plate using the laser light using Amplitude division technique

   In this technique, a broadened laser beam is incident on a beam splitter. The beam splitter reflects a part of the incident beam on to a mirror while transmitting the rest to incident on to the object kept at a certain distance from the mirror. The beam reflected from the mirror is called the reference beam, and the beam reflected from the object, the object beam. These two beams interfere on the photographic plate and an interference pattern is recorded. The recorded photographic film, when developed gives the hologram. This method is considered division of amplitude because the transmitted and reflected light beams from the mirrors have different intensities and hence different amplitudes. The interference pattern has recorded both the amplitude variation and phase of the object. The interference pattern does not reveal the image of the object but consists of only dark and bright patterns. It has information of the object in coded form.



2) **Reconstruction of Image**

Reconstruction of the holographic image is the process of extraction of 3-dimensional information about the object. For the reconstruction of the image, the hologram is illuminated by the laser light of same wavelength in the direction, in which the reference beam was incident on it during recording.



When beam illuminates the hologram, it acts like diffraction grating producing secondary wavelets which undergo interference to generate the real image of the object on the transmission side of the hologram, and a virtual image behind the hologram at the original site of the object. When an observer sees the hologram from the transmission side, he receives the rays diverging from the virtual image and it appears as though the original object is lying on the other side.

Holography is not only used to make three-dimensional pictures and it does not confine itself to the visible spectrum. Microwaves are used to detect objects through otherwise impenetrable barriers. Holography is also used to detect stress in materials. Museums keep archival records in holograms. Hologram is a reliable object for data storage, because even a small broken piece of hologram contains complete data or information about the object with reduced clarity. The information-holding capacity of a hologram is very high because many objects can be recorded in a single hologram.