LASERS

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

Laser light differs from ordinary source light by having properties like,

1. Directionality
2. Monochromaticity
3. Intensity
4. Coherence

1. Directionality: Conventional light sources emit photons in all direction 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 sources photons will be 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 measure of monochromaticity. For ordinary light sources it is of the order of 1000 Å , however for laser light it is of the order of 10Å to 10^{-4} Å
3. Intensity: The laser gives out light into a narrow beam and its energy is concentrated in a small region. Intensity of 1 mW power laser is 10,000 times bright than light from the sun at the earth's surface.
4. Coherence: The light waves emitted by the laser source will be in phase and of same frequency so it will be 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:

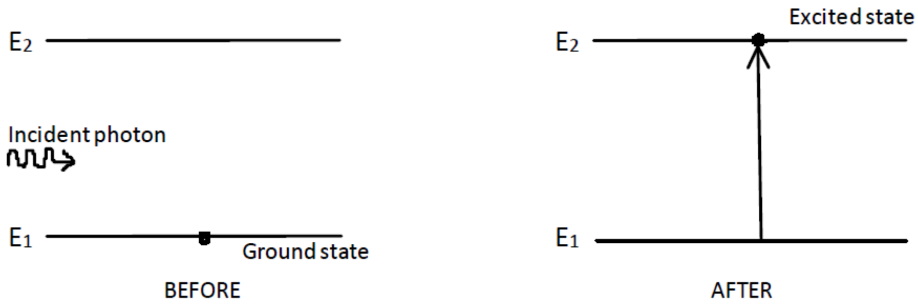
The process of absorption of incident photon by an atom and hence the excitation of the atom to the higher energy state is called induced absorption wherein the energy of incident photon is exactly equal to the difference in energies of two states.

Explanation: Consider two energy levels E_1 and E_2 such that $E_2 > E_1$ as shown in the figure. Consider an atom in the lower energy state E_1. When a photon of energy equal to the energy difference between E_1 and E_2 is incident on the atom in the state E_1, it absorbs the photon. Due to the absorption of photon, the energy of the atom increases to the value of E_2. Therefore the atom gets excited to the energy state E_2.

It can be represented by:

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

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



2) **<u>SPONTANEOUS EMISSION:</u>**

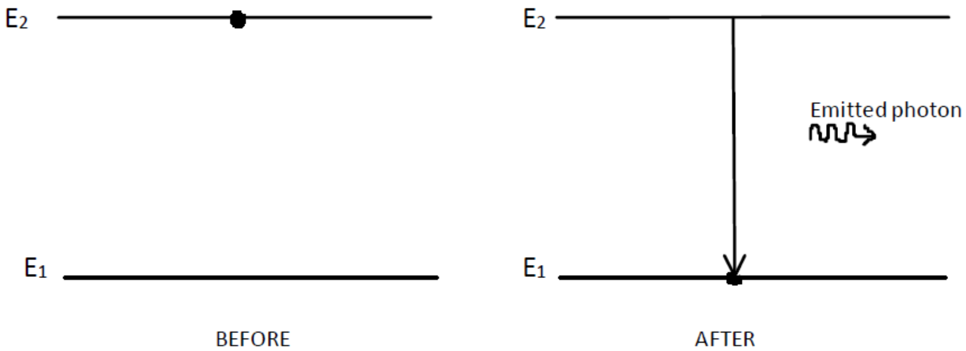
The process of emission of a photon of suitable frequency by an atom due to the transition from a higher energy state to a lower energy state without any supply of external energy is called spontaneous emission.

<u>Explanation:</u> Consider an atom in an excited state E_2. Let E_1 be its ground state energy. In the excited state the atom is unstable and hence it stays in the state E_2 only for 10^{-8} seconds and then undergoes transition to the ground state E_1 by emitting a photon whose energy is equal to the difference between the energy states E_1 and E_2. 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:

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

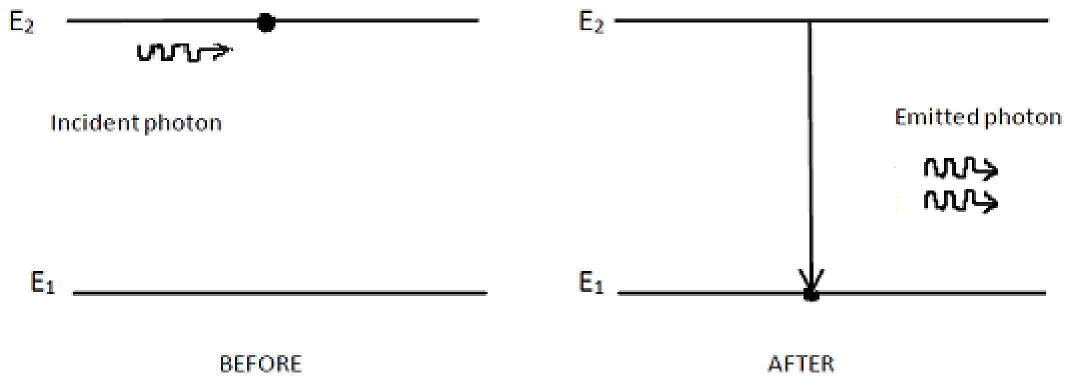
$$A^* = A + h\nu$$



3) **<u>STIMULATED EMISSION:</u>**

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.



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 E_1 and E_2 with population densities N_1 and N_2 respectively such that $E_2 > E_1$.

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.

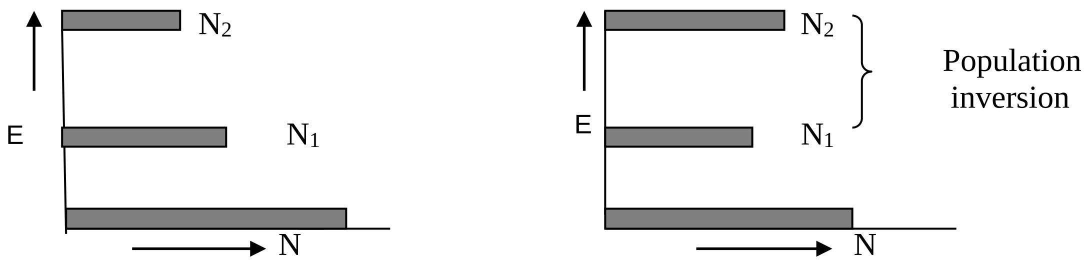
Therefore,

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

$$N_2 < N_1$$

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 population inversion.



EXPRESSION FOR ENERGY DENSITY OF RADIATION IN TERMS OF EINSTEIN'S COEFFICIENTS

Consider two energy levels E_1 and E_2 of an atomic system such that $E_2 > E_1$. Let the population densities of E_1 and E_2 be N_1 and N_2 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 E_1, it absorbs the energy and makes a transition to the energy level E_2. 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 $R_{12} \propto N_1U_\nu$

$$R_{12} = B_{12}N_1U_\nu$$

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

In case of spontaneous emission, an atom in the higher energy level E_2 undergoes transition to the energy state E_1, voluntarily by emitting a photon. The rate of spontaneous emission depends only on population density N_2.

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

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

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 E_2, 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 $R^*_{21} \propto N_2U_\nu$

$$R^*_{21} = B_{21}N_2U_\nu$$

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

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

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

But $\Delta E = h\nu$

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

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

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

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 photons are produced due to stimulated emission. Three processes are possible when radiation interacts with matter.

1)For laser action, that is produce coherent photons, ratio of Rate of Stimulated emission to the Rate of spontaneous emission should be high.

$$\frac{Rate\ of\ stimulated\ emission}{Rate\ of\ spontaneous\ emission} = \frac{N_2 U_\nu B_{21}}{N_2 A_{21}} = \frac{U_\nu B_{21}}{A_{21}} \text{ should be high}$$

From above equation it is clear that **stimulated transition will dominate the spontaneous emission if density of radiations is large**. Further, stimulated transitions will dominate the spontaneous transitions if the value of ratio $\frac{B_{21}}{A_{21}}$ is also large. **To increase the probability of stimulated emission, the life time of atoms at the excited state should be larger** i.e. excited state has a longer life time. or it is a **metastable state**.

2) Also $\frac{Rate\ of\ stimulated\ emission}{Rate\ of\ induced\ absorption} = \frac{N_2 U_\nu B_{21}}{N_1 U_\nu B_{12}} = \frac{N_2}{N_1}$ should be high

Here $B_{12} = B_{21}$ according to Einstein's relation between the coefficients. **The above condition indicates that stimulated emissions will overwhelm the induced absorptions we can achieve the condition $N_2 > N_1$,** hence we can get lasing action.

The condition in which $N_2 > N_1$ is called as **population inversion** which is the required **condition for a laser action.**

REQUISITES OF A LASER SYSTEM

The following are the three requisites of a laser system

Active medium:

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) Gas lasers: They consist of a mixture of gases as the active medium.
Example: He-Ne laser, CO_2 laser

b) Solid-state lasers: They consist of crystals as the active medium,
Example: Ruby laser, Yttrium Aluminium garnet (YAG) laser

c) Semiconductor lasers: They consist of semiconductors as the active medium.
Example: Gallium Arsenide (GAS) laser

d) Liquid lasers: They consist of chemicals as the active medium.
Example: Dye lasers

Pumping: 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) Optical pumping: Intense light source is used to supply luminous energy and raise the atoms.
Eg: Ruby laser.

b) Electric Discharge: In this process electric discharge is used for the excitation of atoms.

Eg: He-Ne laser

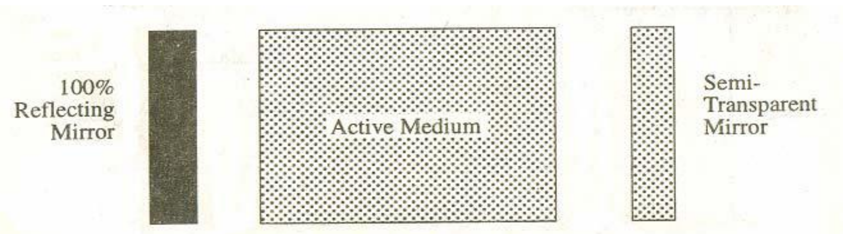
c) Direct Conversion: Electrical energy is directly converted into radiation in devices like LEDs and semiconductor lasers.

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

Resonant cavity:

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.

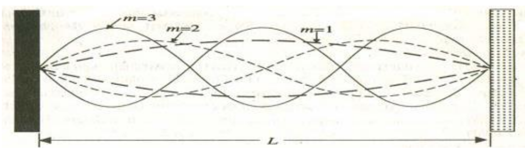


Only those photons emitted parallel to the axis of resonant cavity suffer multiple reflections by the opposite mirrors and gain in strength while other photons are lost.

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.



. **Metastable State:**

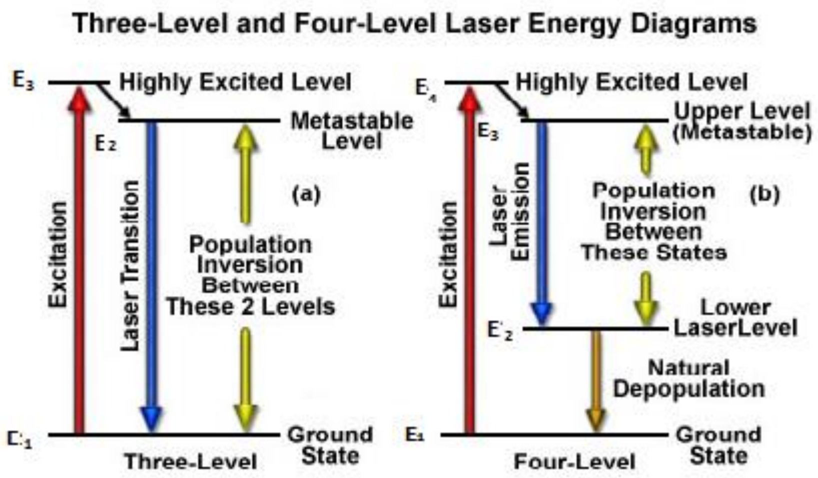
The higher energy state of an atom (or molecule) in which it stays for unusually longer duration of time (of the order of ms or more) is called metastable state.

Population Inversion (The process in which the number of atoms in a higher energy state of an atomic system is made more than the number of atoms in any of its lower energy states is called population inversion.

Three level pumping scheme

The three level scheme first excites the atoms to an excited state higher in 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 fig. Consider three energy levels E_1, E_2 and E_3 of an atomic system, in such a way that $E_1 < E_2 < E_3$. Let E_2 be the metastable state. Under normal conditions the atoms remain in the lower energy state E_1. But when suitable amount of energy is supplied to them they start undergoing excitation to the state E_3.The excited atoms in the state E_3 stay for a period of 10^{-8} seconds and then undergo non-radiative transition to the metastable state E_2, where they stay for a long duration of the order 10^{-2} seconds. If the pumping of atoms from E_1 to E_3 is maintained continuously, then the population of E_1 decreases continuously. The atoms excited to the state E_3 undergo immediate downward transition to E_2, as a result of which the population of E_2 increases more. Due to this process a stage will reach at which the population of E_2 will be more than that of E_1. This stage of operation is known as population inversion. Now a chance photon can trigger stimulated emission.

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 pump power. The three level scheme produces light only in pulses.



For level pumping scheme

A typical four level pumping scheme is shown in fig.

Four level systems follow roughly the same process as that of 3-level scheme except that population is moved from the lowest state E_1 to the highest fourth level E_4 where they stay for only about 10^{-8}s. Then it decays to the third level E_3 which is metastable upper lasing level. As spontaneous transitions from the level E_3 to level E_2 cannot take place, the atoms get trapped in the state E_3 and population grows rapidly here. The level E_2 is well above the ground state so that at normal temperature atoms cannot jump to level E_2. As a result level E_2 is virtually empty. Therefore population inversion is attained between the states E_3 and E_2 and lasing happens when the incident light matches the energy between the third (E_3) and second level E_2 which is lower lasing level. After lasing atoms from state E2 subsequently undergo non-radiative transitions to ground state E_1.

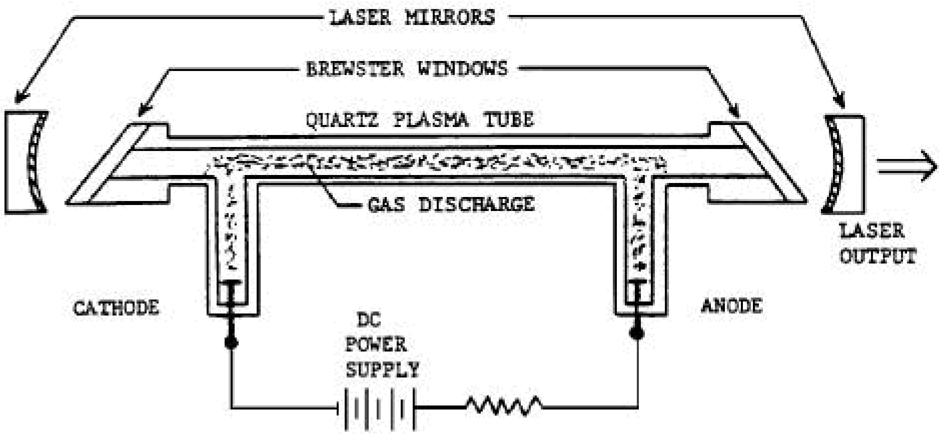
The lower laser transition level in this scheme is nearly vacant. Therefore, les power is sufficient to achieve population inversion. Four level lasers operate in continuous wave mode.

Helium-Neon Laser

Construction:

- Helium-Neon laser is a **gas laser**.

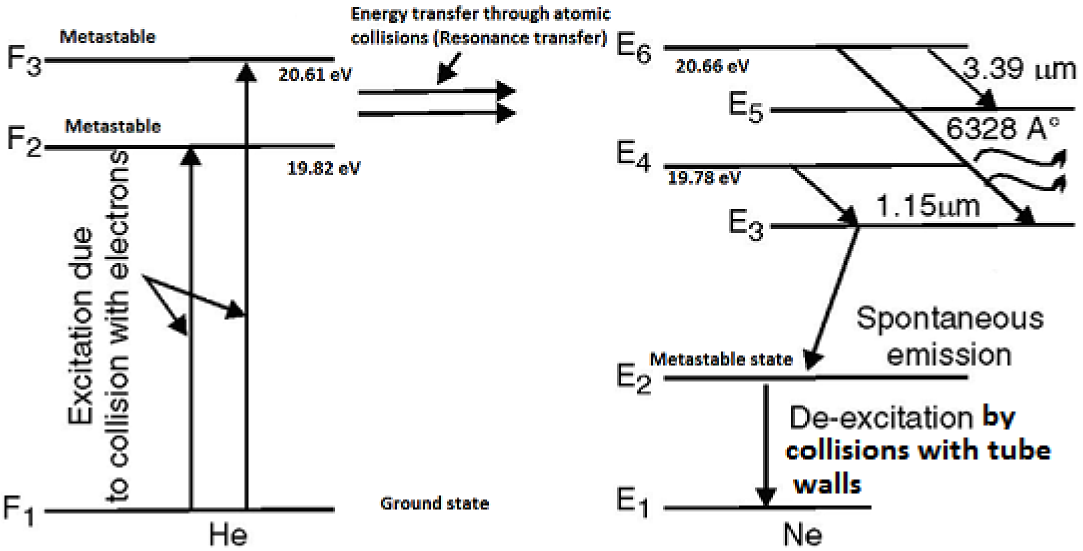
- The **active medium** is a mixture of Helium and Neon gases in the ratio 10:1with pressure inside the tube is maintained as 1: 0.1 torr.
- The **resonant cavity** (or discharge tube) is a sealed **quartz** tube of 1m length and 1 cm diameter. The ends of the glass tube are sealed with Brewster windows 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 F_2 and F_3 levels, which are metastable.
- Levels F_2 and F_3 of Helium have approximately the same energy as levels E_4 and E_6 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 E_4 or E_6 level.
- The population of E_4 and E_6 states of Neon increases rapidly and **population inversion** is achieved.
- The atoms in E_4 and E_6 undergo **radiative transitions** to their lower E_3 and E_5 levels. Three wavelengths of light are emitted.
    a) $\mathbf{E_6 \rightarrow E_5}$ level which gives rise wavelength **3.39 µm**.
    b) $\mathbf{E_6 \rightarrow E_3}$ level which gives rise wavelength **6328 A°**.
    c) $\mathbf{E_4 \rightarrow E_3}$ level giving rise to **1.15 µm**.
- E_3 and E_5 are not metastable states and so the atoms undergo **spontaneous transition** to the metastable state E_2 by emitting photons.
- Since E_2 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 E_5 or E_3 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.



The radiation of wavelength **6328 A°** is the output laser light.

Since the electrical discharge is maintained continuously, the population inversion also takes place continuously and the laser emission is continuous. Therefore, He-Ne laser is a **continuous wave laser**.

<u>Salient Features</u>

1. Use Four level pumping scheme
2. The active centres are Ne atoms.
3. Electrical discharge is pumping agent.
4. Low efficiency and low output power.
5. operates in continuous wave(CW) mode

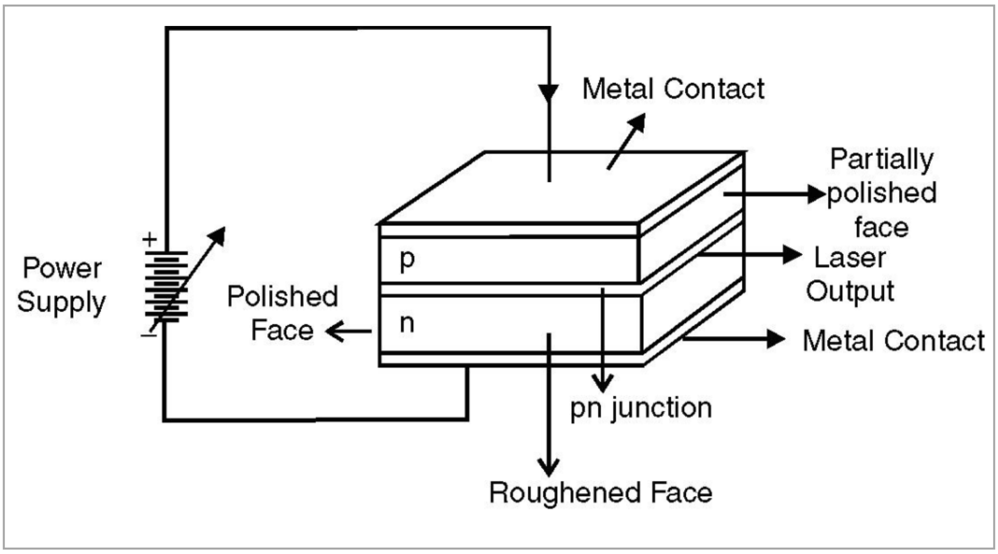
<u>SEMICONDUCTOR LASER</u> (Gallium Arsenide Laser)

<u>Principle</u>

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

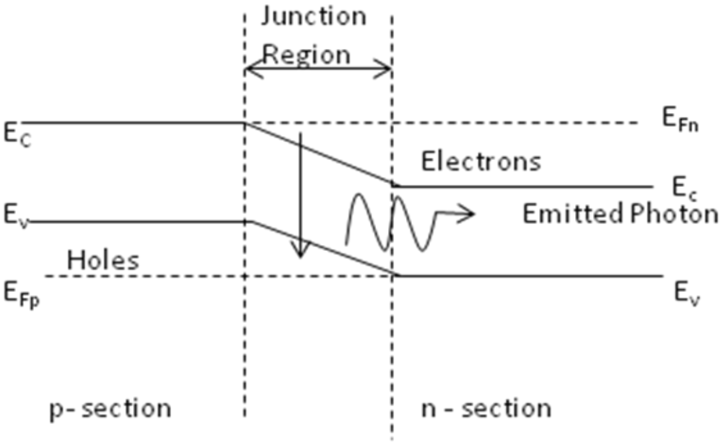
<u>Construction:</u>

- 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.



<u>Working</u>

- 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.



Energy band diagram for a semiconductor laser

The energy gap of a GaAs semiconductor is 1.4 eV,

From, $E_g = hc/\lambda$

Wavelength of emitted photon $\lambda = 8400$ A°

Applications of semiconductor diodes:

1) Optical communication
2) Reading devices for compact disc players, CD- ROM