LASERS

LASER is the acronym for Light Amplification by Stimulated Emission of Radiation. LASER is a device which is used to produce a parallel and highly coherent light beam of high intensity.

Characteristics properties of Laser light

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

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

1. Unidirectionality: Conventional light sources emit photons in all direction but in laser, photons are emitted in one direction, generally along the optical axis of the system which is achieved by means of stimulated emission and the direction of optical resonating cavity. 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 can give 100% monochromatic light, 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 A^o , however for laser light it is of the order of 10A^o to 10^{-4} A^o
3. High Intensity: Light intensity can be expressed in terms of power. There are different types of laser, whose output power varies from mW to 10^7 W. Intensity of 1 mW power laser is 1000 times bright than intensity of sun's light at the earth's surface.
4. High 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 methods by which the radiation interacts with matter. The three methods are

(1) Induced absorption

(2) Spontaneous emission

(3) Stimulated emission.

1) INDUCED ABSORPTION:

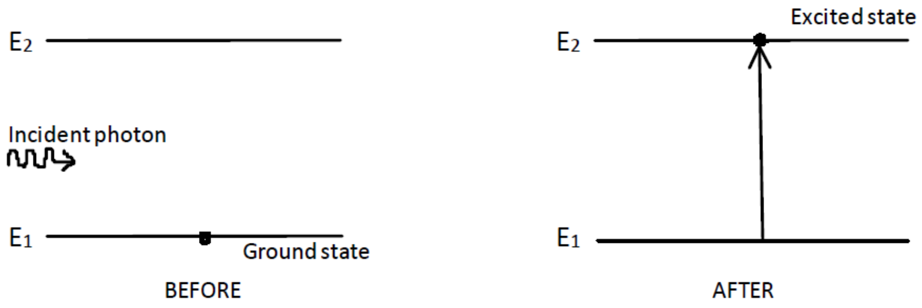
The process of absorption of incident photon by an atom and hence the excitation of the atom to the high-energy state is called Induced Absorption.

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. This process is known as induced absorption because the photon induces its energy to the atom.

It can be represented by:

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

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



2) SPONTANEOUS EMISSION:

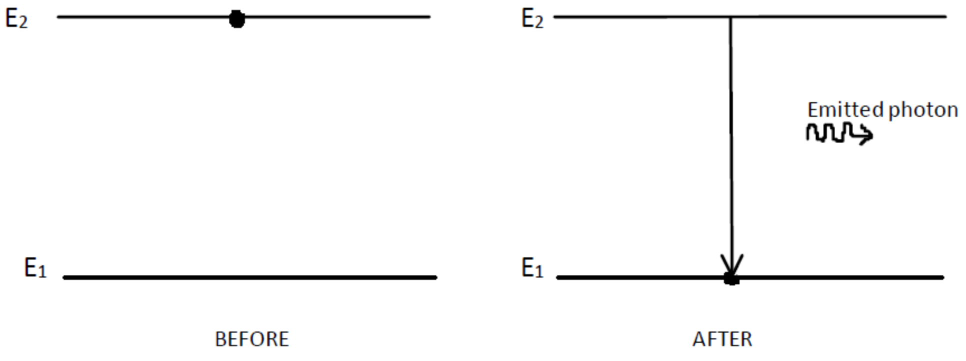
The process of emission of a photon of suitable frequency by an atom due to the transition from a higher energy state to a lower energy state without any supply of external energy is called spontaneous emission.

Explanation: Consider an atom in an excited state 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 and their directions also may be different. 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:

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

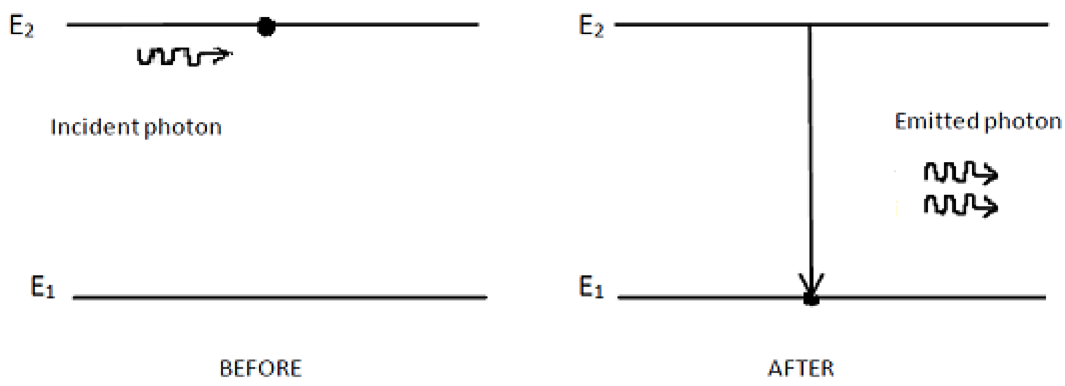
$$A^* = A + h\nu$$



3) STIMULATED EMISSION:

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

Explanation: 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 and the photons are coherent photons. This kind of emission is suitable for laser action.



Boltzman relation for ratio of Population of two atomic States:

The number of atoms in an energy state is known as the population of that energy state.

The population 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 populations N_1 and N_2 respectively such that $E_2 > E_1$.

The relation between the two is given by Boltzmann factor,

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

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

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,

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

$$N_2 < N_1$$

Or $\quad N_1 > N_2$

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 of the higher energy states is made more than the population of any of its lower states then **population inversion** is said to be achieved, or the system is said to have population inversion.

EXPRESSION FOR ENERGY DENSITY

Einstein's Coefficients

Einstein proposed three constants of proportionality to explain the transfer of energy of atoms during the interaction of radiation with matter. These constants are called by his name as Einstein's constants and are denoted as A_{21}, B_{12}, and B_{21}. Their origin is explained in the following way.

Consider two energy levels E_1 and E_2 of an atomic system such that $E_2 > E_1$. Let the population 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 per unit volume 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 is proportional to N_1U_ν

Rate of absorption = $B_{12}N_1U_\nu$

Where, B_{12} is called 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 number of atoms (N_2) in the energy state E_2.

Rate of spontaneous emission is proportional to N_2

Rate of spontaneous emission = $A_{21}N_2$

Where, A_{21} is called 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 number of atoms (N_2) in the energy state E_2, and the incident energy density U_ν

Rate of stimulated emission is proportional to N_2U_ν

Rate of stimulated emission = $B_{21}N_2U_\nu$

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

At thermal equilibrium,

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

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

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

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

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

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

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

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

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.

$$\frac{Rate\ of\ stimulated\ emission}{Rate\ of\ spontaneous\ emission}=\frac{N_2U_\nu B_{21}}{N_2A_{21}}=\frac{U_\nu B_{21}}{A_{21}}\ \text{should be high}$$

From above equation it is clear that **stimulated transition will dominate the spontaneous emission if density of radiations of our interest 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 $\frac{Rate\ of\ stimulated\ emission}{Rate\ of\ induced\ absorption}=\frac{N_2U_\nu B_{21}}{N_1U_\nu B_{12}}=\frac{N_2}{N_1}$ 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.**

<u>Metastable State:</u>

An intermediate energy state between an excited state and the ground state of the atomic energy levels, in which the atoms stay for a long period of time the order 10^{-2} to 10^{-3} seconds, is called a metastable state.

<u>Population Inversion:</u>

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.

For achieving population inversion, the atomic energy levels should have a metastable state.

<u>REQUISITES OF A LASER SYSTEM</u>

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

2) **Energy Source:**
(Pumping: The process of exciting atoms from a lower energy state to a higher energy state, by supplying energy from an external source is called pumping**)**

The population inversion in the laser action is achieved by pumping the atoms from the lower energy state by supplying energy from an external energy source.

Depending on the type of energy source used for pumping, there are four types of pumping as follows

a) Optical pumping: optical energy
b) Electrical pumping: electrical energy
c) Heat pumping: thermal energy
d) Chemical pumping: chemical energy

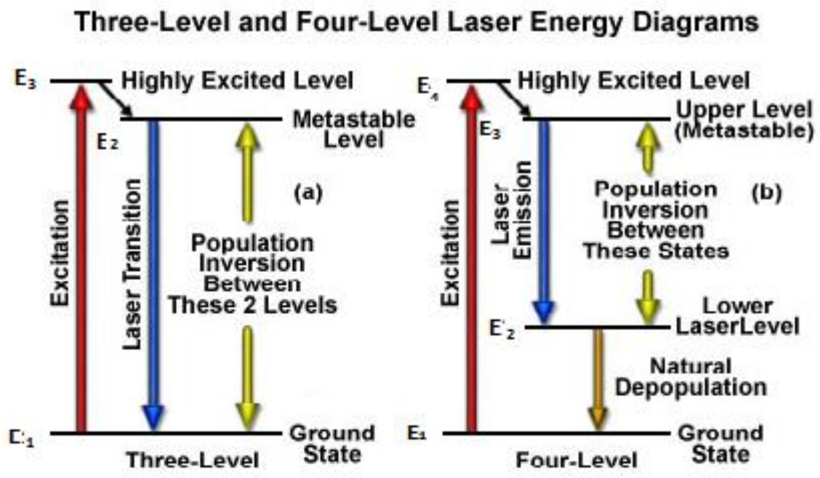
The energy supplied is used not only for pumping, but also for stimulated emission in some cases.

3) **Resonant cavity:**
An arrangement used in a laser device to increase the emitted photon energy density is called resonant cavity. It consists of two mirrors fixed on either side of the length of the active medium oriented in particular direction. One of the mirrors is completely silvered and contributes only to the reflection of the emitted photons. The other is partially silvered and it acts as both a reflector and exit for the laser beam. Mirrors are separated by a distance L for a particular emitted wavelength **λ,** satisfying relation $L = m\,\lambda/2$**,** where m =1,2,3… determines order of modes. These mirrors acts like a optical resonating cavity. Only the photons which are parallel to the axis of the optical resonator are reflected back into active medium while others escape the active medium. So only the photons which are parallel to axis of resonator increase in number thereby producing coherent photons.

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.

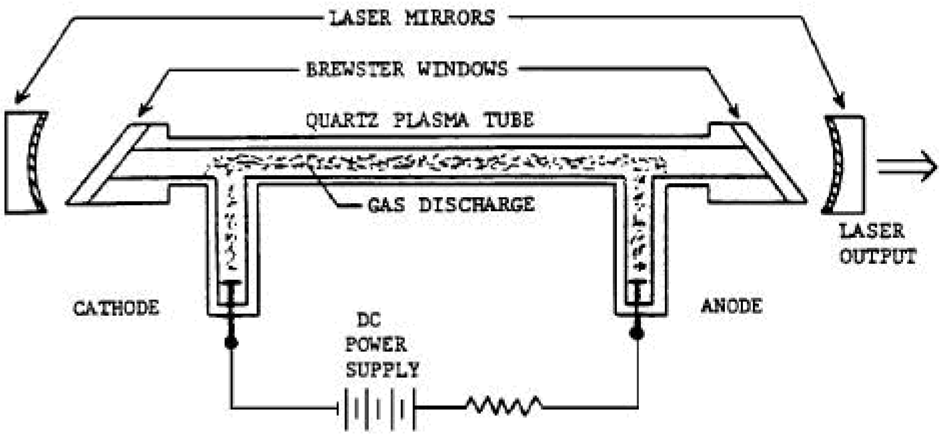
Four level systems follow roughly the same process as that of 3-level scheme except that population is moved from the lowest state E_1 to the highest fourth level E_4 where they stay for only about 10^{-8}s. Then it decays to the third level E_3 which is metastable upper lasing level. As spontaneous 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

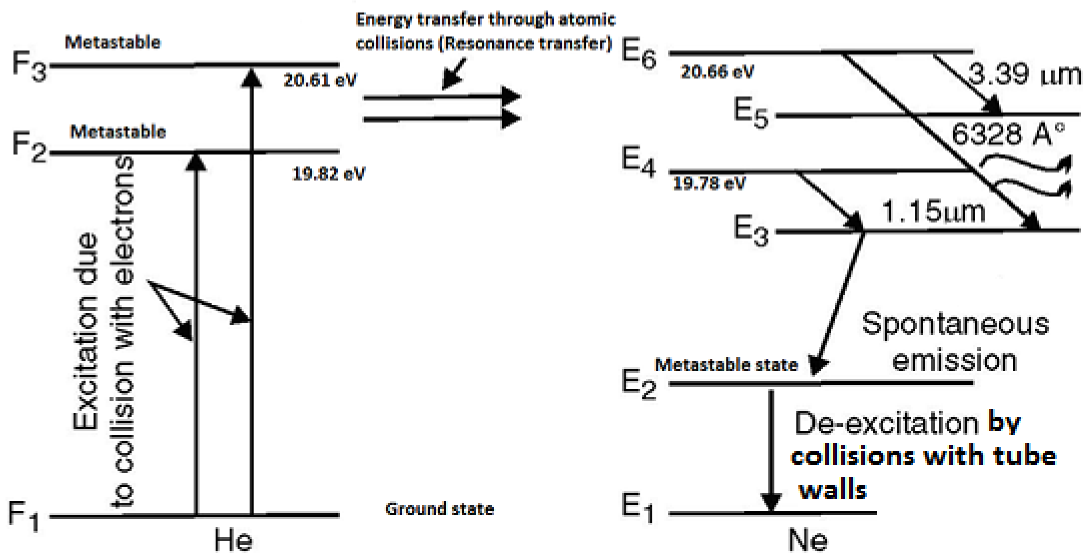
<u>Construction:</u>

1) Helium-Neon laser is a **gas laser**.
2) 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.
3) The **resonant cavity** (or discharge tube) is a sealed **quartz** tube of 1m length and 1.5cm diameter. The ends of the glass tube are fitted with mirrors, one completely silvered that reflects all the incident photons and one partially silvered that acts as a reflector and as a point of exit for the laser beam.
4) 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.
5) **Brewster's windows** are sealed to the tube at both of its ends.



Working:

1) The energy level diagram of a He-Ne laser is as shown in the figure.
2) 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.
3) 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.
4) 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.
5) 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.
6) The number of Neon atoms excited to the E_4 and E_6 is greater than that which remains at the ground state, since the number of Helium atoms in the metastable state is more. Thus, the population of E_4 and E_6 states of Neon increases rapidly and **population inversion** is achieved.
7) 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) Transition from the $\mathbf{E_6}$ level **to** the $\mathbf{E_5}$ level which gives rise to radiation of wavelength **3.39 µm**.
    b) Transition from the $\mathbf{E_6}$ level **to** the $\mathbf{E_3}$ level which gives rise to radiation of wavelength **6328 A°**.
    c) Transition from the $\mathbf{E_4}$ level **to** the $\mathbf{E_3}$ level giving rise to 1**.15 µm**.
8) 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. The population of E_2 level increases rapidly by virtue of its metastability.
9) 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**. The emitted light photons suffer multiple reflections by the parallel mirrors fixed at both the ends of the tube, and result in the emission of highly intense, coherent and monochromatic beam called LASER.

Salient Features

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

SEMICONDUCTOR LASER (Gallium Arsenide Laser)

Principle

Semiconductor laser is one in which the active medium is semiconducting material. Among the semiconductors there are two different groups. They are direct band gap semiconductors and indirect band gap semiconductors. Direct band gap semiconductor is one in which a electron in conduction band directly recombine with the hole in valence band and the recombination process leads to emission of light whereas in indirect band gap semiconductors direct recombination of conduction electron with hole in valence band is not possible and recombination of an electron and hole produces heat in the material.

So in a direct band gap semiconducting material when transition of electron from conduction band to valence band takes place, excess energy may be released in terms of photons. **Thus electron hole recombination is basic mechanism responsible for emission of light.**

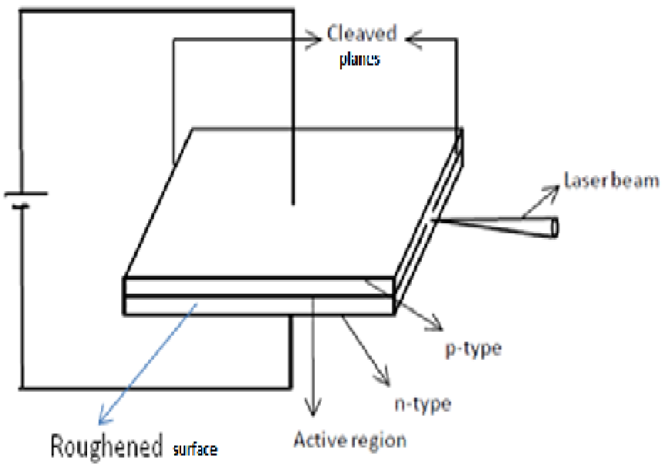
Construction:

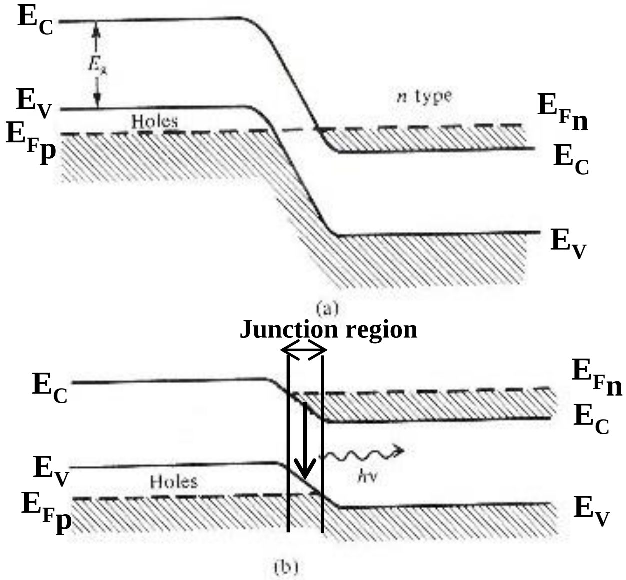
It a single crystal of **GaAs** which consists of heavily doped *n* and *p* sections and doping concentration is of the order of 10^{17} to 10^{19} dopant atom/cm^3.

The n-section is derived by doping GaAs with Tellurium and the p-section by doping GaAs with Zinc.

1) A pair of parallel planes of the crystal is **polished** at right angles to the p-n layer. These planes play the role of reflecting mirror. The other two sides perpendicular to the junction are **roughened** to suppress reflections of the photons.

2) The end surfaces of the p and n sections parallel to the plane of the junction are provided with **electrodes** in order to apply a forward bias voltage.
3) The diode is extremely small in size and each side is of the order of 1mm with junction layer of the order of 1 µm to 100 µm.



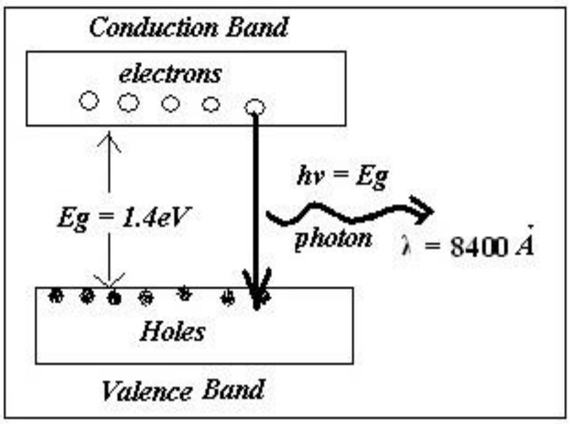


<u>Working</u>

1) Because of very high doping on n-side, the donar levels are broadened and extend into conduction band. The Fermi level is also pushed into the conduction band and electrons occupy the portion of conduction band below Fermi level.
2) Similarly, on the heavily doped p-side the Fermi level lies within the valence band and holes occupy the portion of valence band that lies above the Fermi level.
3) At thermal equilibrium, the Fermi level is uniform across the junction as shown in fig (a).
4) The GaAs laser diode is subjected to a forward bias using a DC source. Electrons from the n-section and holes from the p-section flow across the junction. An **active region** is formed in the junction where electrons and holes recombine and emit photons. This is spontaneous emission.
5) Under normal conditions, the concentration of electrons in the valence band is greater than that in the conduction band. Thus population inversion is not possible.
6) If the current flowing through the diode exceed a certain **threshold** value then the amount of electrons jumping from the valence band to the conduction band is great enough for population inversion to be achieved within junction region as shown in fig (b). Spontaneous emission will take place, and a photon will be released due to recombination. This photon interacts with an electron in the conduction band resulting in a **stimulated emission** which gives the required laser action.

Since the energy gap of a GaAs semiconductor is 1.4 eV,
From, $E_g = hc/\lambda$
$\lambda = 8400\ A^o$
This is the frequency of the emitted radiation.

Energy level diagram



Applications of semiconductor diodes:

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

HOLOGRAPHY

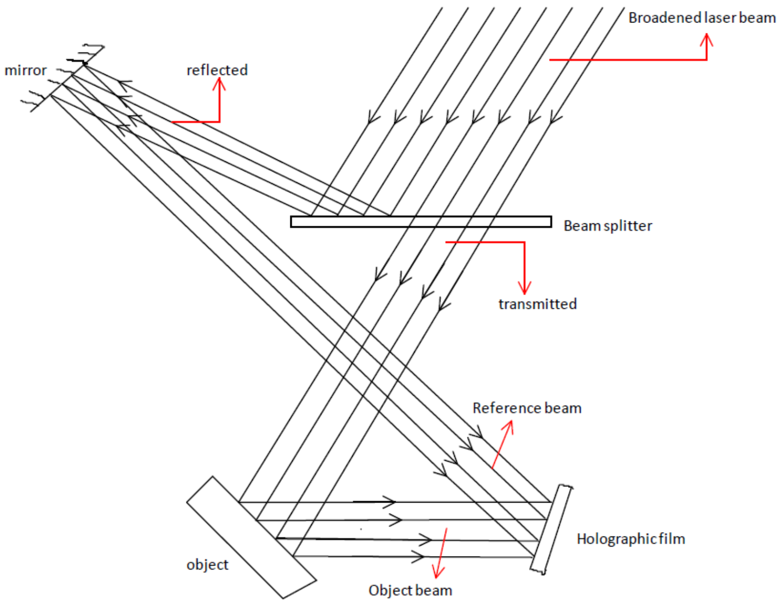
The technique of recording the three dimensional image of an object on a two dimensional recording aid using the principle of interference is known as holography. The Holography requires highly coherent laser light. In conventional photography, the photographic film records only the intensity of light, 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**

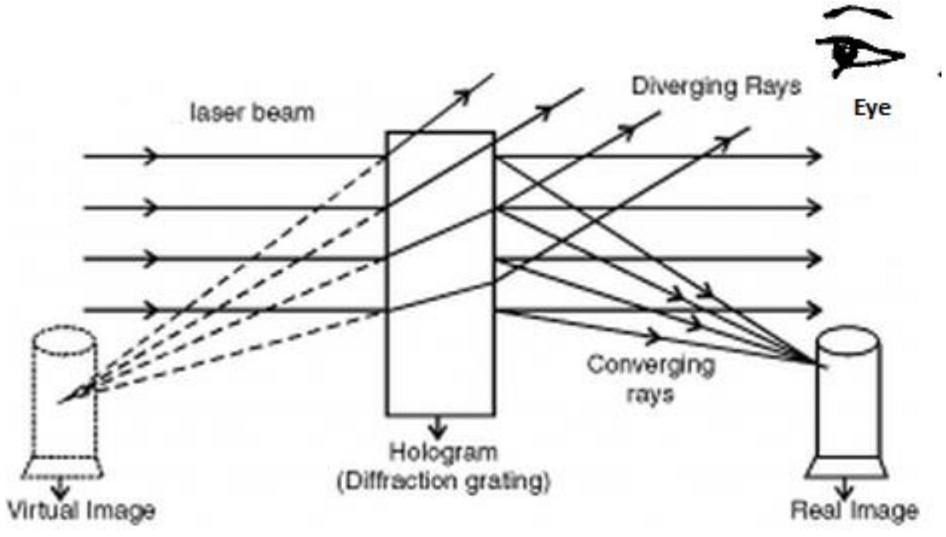
The image of an object can be recorded on a photographic plate using the laser light using Amplitude division technique

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.