# 7 LASERS

## (1) INTRODUCTION

The word LASER is an acronym for 'Light Amplification by Stimulated Emission of Radiation'. It is a device, that amplifies light and produces a highly directional, high-intensity beam, that most often has a very pure wavelength or frequency (*i.e.* Laser light is nearly monochromatic). Due to these properties, Laser has become a very special source of light, which finds its applications in a lot of areas like holography, spatial frequency filtering, communication, surgery etc. Various Lasers have been developed for different wavelengths and frequencies, which extend from microwave region (frequency $\approx 10^{11}$ Hz) to soft X-ray region (frequency $\approx 10^{17}$ Hz). The optical power output of different Lasers can extend from $10^{-9}$W to $10^{20}$ W. An ordinary source of light emits light radiations in all directions, having no phase relation between various emitted rays. A laser concentrates all radiations in a narrow region along one direction only and all rays in that region bear a definite phase relation. However for doing this, certain special conditions are required, which are not met by ordinary sources of light. Thus it is not possible to convert every source of light into a Laser.

In 1954, Charles Townes successfully produced coherent, monochromatic and highly intense beam of microwaves of wavelength 1.25 cm using ammonia vapours. The device was termed as MASER, which means 'Microwave Amplification by Stimulated Emission of Radiation'. In 1960 first Laser was successfully developed by T. Maiman using a Ruby Crystal as amplifier and Xenon flash lamp as energy source. Since then, Laser action has been obtained in a variety of materials including liquids, ionized gases, dyes, semiconductors and so on.

## (2) EINSTEIN'S THEORY OF RADIATIONS

We know that an atom consists of discrete energy states or levels *i.e.* any two consecutive energy levels have a finite energy gap. At room temperature the energy of an atom is lowest so that it is a stable entity. Thus most stable state of an atom is called Ground State. If external energy is given to the atom by some external source then an electron from the valence shell can jump to some higher energy level by absorbing the external energy if energy absorbed is exactly equal to the difference in energies of two levels involved in transition. This process of transferring electron from ground level to higher level is called excitation. The source giving energy to the electrons is called Stimulant. It is clear that excitation is always a stimulated process (*i.e.* it requires external energy) and cannot take place by itself (*i.e.* spontaneous excitation is a meaningless term).

However an excited atom may de-excite to some lower energy state and in the process it will lose out energy equal to energy difference between levels involved in transition. This process is called Emission. The emission of light can take place in two entirely different ways :

(*i*) The atom may de-excite to some lower energy state after spending some time in excited state without requiring any external aid. A photon of light is emitted in this case. This is called spontaneous emission. The rate of spontaneous emission depends only on the number of atoms in the excited state. Although energy of each spontaneous photon is same corresponding to same transition, however there is no constant phase relation between them & their directions are random.

(*ii*) An atom in the excited state can de-excite to some lower state when a photon of energy equal to difference in energy of two levels is incident on it. This kind of emission is called Stimulated Emission. The amplification process due to stimulated transition is phase coherent *i.e.* energy delivered by molecular system has same field distribution & frequency as stimulating radiation. A beam of photons emitted due to stimulated emission is produced in one direction because of resonant cavity used in it. The resonant cavity excites only those modes, which are along a particular direction. The rate of stimulated emission depends on number of atoms in excited state as well as the energy density of incident radiations, which triggers it.

Let $E_1$, $E_2$ be the energy values of an atom in the ground state and excited state respectively. Let $N_1$, $N_2$ be number of atoms per unit volume corresponding to energy states $E_1$ & $E_2$ respectively.

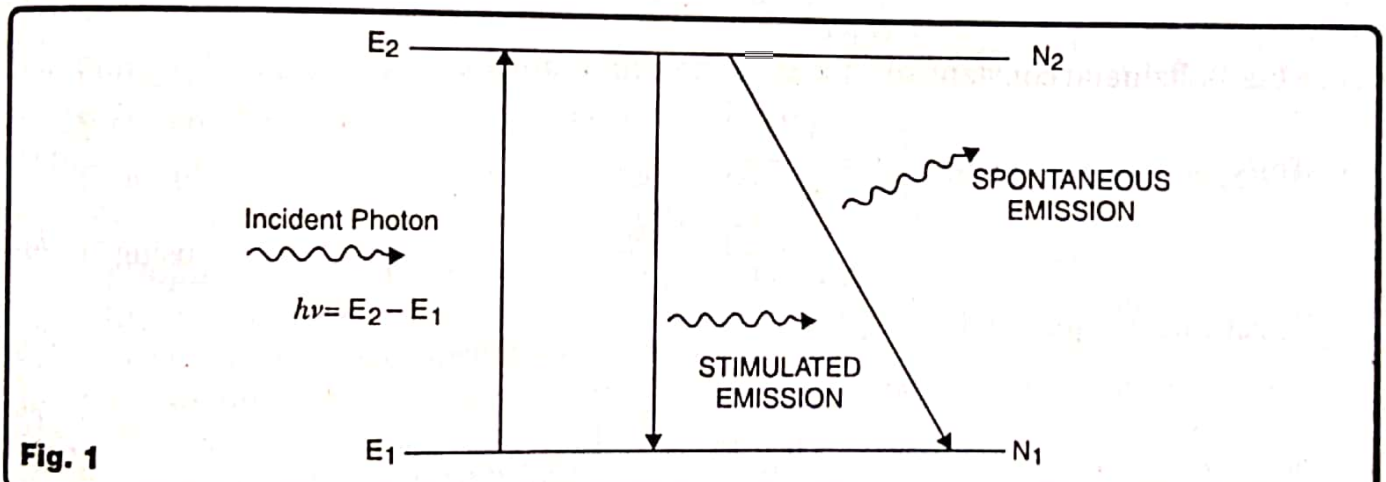



**Fig. 1**

Let $\rho(\nu)$ is the energy density per unit frequency of the beam of incident photons.

If the photon energy $h\nu$ is exactly equal to the energy difference $E_2 - E_1$

*i.e.* $$h\nu = E_2 - E_1 \quad ...(1)$$

then this photon can excite an atom from state $E_1$ to $E_2$.

Let $R_a$ is rate of absorption per unit volume then according to Einstein it depends both on $N_1$ as well as $\rho(\nu)$ *i.e.*

$$R_a \propto N_1 \rho(\nu)$$

$$R_a = B_{12} N_1 \rho(\nu) \quad ...(2)$$

Here $B_{12}$ is constant or proportionality & it is called Einstein's coefficient for stimulated absorption. For given value of $N_1$ & $\rho(\nu)$, if $B_{12}$ is large then $R_a$ will also be large. Thus $B_{12}$ represents the probability of absorption of radiation by a substance.

Let $R_{sp}$ is rate of spontaneous emission per unit volume.

According to Einstein, rate of spontaneous emission is directly proportional to the number of atoms in excited state only.

*i.e.*
$$R_{sp} \propto N_2$$
or
$$R_{sp} = A_{21}N_2 \quad ...(3)$$

$A_{21}$ is called Einstein's coefficient for spontaneous emission. It represents probability of spontaneous de excitation by a substance.

Let $R_{st}$ is rate of stimulated emission per unit volume. Then according to Einstein, it is proportional to $N_2$ and $\rho(\nu)$. *i.e.*
$$R_{st} \propto N_2\rho(\nu)$$
or
$$R_{st} = B_{21}\, N_2\rho(\nu) \quad ...(4)$$

$B_{21}$ is called Einstein's Coefficient for stimulated Emission. It represents probability of stimulated emission by the substance.

At thermal equilibrium the rate of absorption and emission are equal *i.e.* $R_a = R_{sp} + R_{st}$

or
$$N_1B_{12}\rho(\nu) = N_2A_{21} + N_2B_{21}\rho(\nu)$$
or
$$\rho(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{N_1}{N_2}\right)\left(\frac{B_{12}}{B_{21}}\right) - 1} \quad ...(5)$$

According to Maxwell Boltzmann Statistics, the occupancy of an energy level having energy E is given as
$$N \propto e^{-\frac{E}{kT}}$$
where $k$ is Boltzmann constant and T is absolute temperature.

Thus
$$\frac{N_1}{N_2} = \frac{e^{-E_1/kT}}{e^{-E_2/kT}}$$
$$= e^{\frac{E_2 - E_1}{kT}} = e^{\frac{h\nu}{kT}} \quad \text{(using 1) ...(6)}$$

Substitute in equation (5), we get
$$\rho(\nu) = \frac{A_{21}/B_{21}}{\left(\frac{B_{12}}{B_{21}}\right)e^{h\nu/kT} - 1} \quad ...(7)$$

According to Planck's Radiation Law, the energy density per unit frequency range is given by
$$\rho(\nu) = \frac{\frac{8\pi h\nu^3}{c^3}}{e^{\frac{h\nu}{kT}} - 1} \quad ...(8)$$

Comparing (7) and (8), we get
$$\frac{B_{12}}{B_{21}} = 1$$
or
$$B_{12} = B_{21} \quad ...(9)$$
and
$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3}$$

or
$$B_{21} = \frac{c^3}{8\pi h\nu^3} A_{21} \qquad ...(10)$$

Dividing (4) by (2) and using (9), we get

$$\frac{R_{st}}{R_a} = \frac{N_2}{N_1} \qquad ...(11)$$

## Discussion

(*i*) From (7) we have

$$\frac{R_{st}}{R_{sp}} = \frac{\rho(\nu)\, B_{21}}{A_{21}} = \frac{1}{e^{\frac{h\nu}{kT}} - 1} \qquad ...(12)\ (\because B_{12} = B_{21})$$

Normally the temperature of a source emitting light radiations is $\approx 10^3$K. Also energy of visible light corresponding to green colour is $\approx 2.5$ eV. If we substitute these values in (12), we get

$$\frac{R_{st}}{R_{sp}} \approx 10^{-10}$$

Thus at optical frequencies, the emission of radiations from ordinary light source is spontaneous. The rate of spontaneous & stimulated emission from an optical source can be equal if $e^{\frac{h\nu}{kT}} = 2$

or
$$\frac{h\nu}{kT} = \ln(2) = 0.693$$

Putting $h\nu = 2.5$ eV for mean wavelength of visible spectrum, we get $T \approx 33500$ K

Such a high temperature normally exists on stars only.

Thus only stars can produce stimulated emission in the visible region, naturally. However in Lasers the ratio $R_{st}/R_{sp}$ can be significantly greater than unity.

(*ii*) **Population Inversion.** At thermal equilibrium more atoms are in the ground state than in the excited state *i.e.* $N_1 > N_2$ so that $R_{st} < R_a$ (see eq. (11)) *i.e.* rate of stimulated emission is small compared to rate of absorption. Thus to increase stimulated emission as compared to absorption we must break the thermal equilibrium so that $N_2 > N_1$ *i.e.* more atoms are in the excited state, than in the ground state. Thus Laser action occurs when medium is in non equilibrium state and this non equilibrium is continuously maintained. "When the number of atoms is more in excited state than ground state then population distribution between energy levels $E_1$ & $E_2$ is said to be inverted and medium is said to have gone into the state of Population Inversion." From equation (6), we see that when $N_2 > N_1$ then $\frac{h\nu}{kT}$ must be negative, which means T is negative. Thus population inversion is also referred to as negative temperature state. However it only signifies that population inversion is a non equilibrium state. Moreover equation (6) is valid only at thermal equilibrium. In actual practice the state of population inversion is obtained at ordinary temperature by breaking the equilibrium state.

We know that when a beam of radiations of intensity $I_0$ means passes through a medium, then intensity decreases exponentially according to the law

$$I = I_0\, e^{-\mu x} \qquad ...(13)$$

where $\mu$ is called absorption coefficient and is generally a positive quantity. In a Laser medium the amplification of light takes place and the intensity grows exponentially instead of decaying. Due to this fact a Laser in the state of population inversion is called a medium with negative absorption coefficient, and the process of amplification of light is termed as negative absorption.

(*iii*) Since $B_{12} = B_{21}$. This means that probability of spontaneous and stimulated emission is equal between two levels. This result tells that a photon emitted by stimulated emission from level $E_1$ to $E_2$ can be reabsorbed by some another atom for excitation from $E_1$ to $E_2$. This means photon of light will be trapped and no stimulated emission will be observed out of LASER medium. This process is called radiation trapping. To break this cycle of radiation trapping, we introduce an intermediate state $E_3$ between $E_1$ and $E_2$. This intermediate state is called metastable state because its life time is in between the life time of ground and excited state. Due to metastable state, the stimulated absorption takes place between $E_1$ and $E_2$ while stimulated emission takes place between $E_3$ and $E_1$ such that $B_{31} >> B_{12}$. Thus metastable state helps in increasing probability of stimulated emission. Thus we conclude that a metastable state is necessary for laser action.

(*iv*) From equation (10) we see that $B_{21} \propto \frac{1}{\nu^3}$. Thus chance of stimulated emission is large in low frequencies than in optical and higher frequencies. Thus it is easier to produce stimulated emission of microwaves than optical waves. This is the reason, why MASER was invented earlier than LASER.

## (3) PUMPING

We have discussed above that for stimulated emission to take place, population inversion has to be produced and maintained. For this there must be a source of external energy, which can continuously supply energy to Laser medium, which can bring about population inversion in it. Such a source of external energy is called Pump and the process of supplying external energy to Laser medium so as to achieve population inversion is called Pumping.

Depending upon the type of Laser, different pumping schemes are employed. Some of these are discussed below :

(*i*) **Optical Pumping.** This kind of pumping is used in solid state lasers like Ruby Laser. In this type the Laser medium is exposed to highly intense beam of visible light using a flash lamp source. These radiations excite a number of atoms of Laser medium to higher energy level. If pumping is rigorous enough then soon population inversion is achieved and laser action takes place. For Increasing the efficiency of optical pumping, the rod of Laser medium and flash lamp are placed parallel to each other along the two focal axes of a cylindrical reflector having elliptical cross section. Any ray of light produced from flash lamp will converge on the rod of Laser Medium after reflecting from inner wall of the reflector.

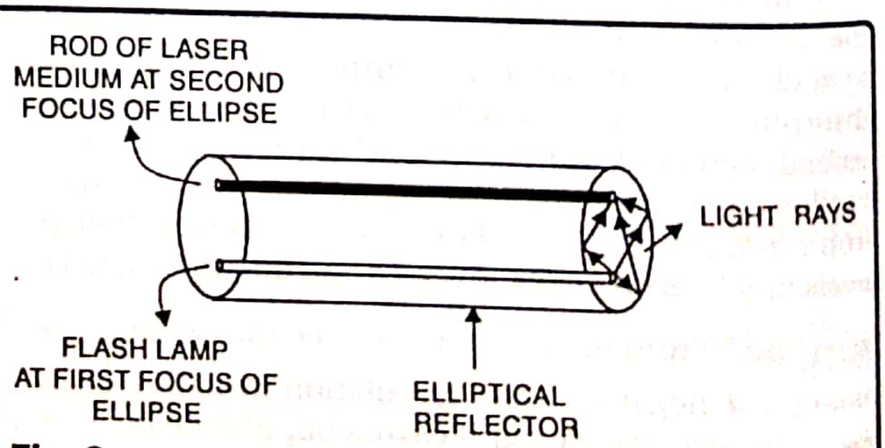



**Fig. 2**

*(ii)* **Electric Discharge Pumping.** This kind of pumping is used in gas lasers like He–Ne Laser and $CO_2$ Laser. In this method the Laser medium (gas) is enclosed in a discharge tube at low pressure. Electrons are produced in the cathode by passing electric current from a low tension battery and a high potential difference is applied between anode and cathode using high tension battery. The electrons get accelerated due to the accelerating voltage. On their way from cathode to anode the electrons suffer elastic collision with gas molecules and transfer their kinetic energy to them, due to which gas molecules go to excited state. The electron after suffering collision comes to rest. However because of potential gradient it is again accelerated and may suffer collision with another molecule & excite it to higher energy state. Thus in going from cathode to anode, an electron can suffer multiple collisions with gas molecules. If the number of collisions is large enough then pumping is efficient so as to bring population inversion in the gas enclosed so that Lasing action can take place.

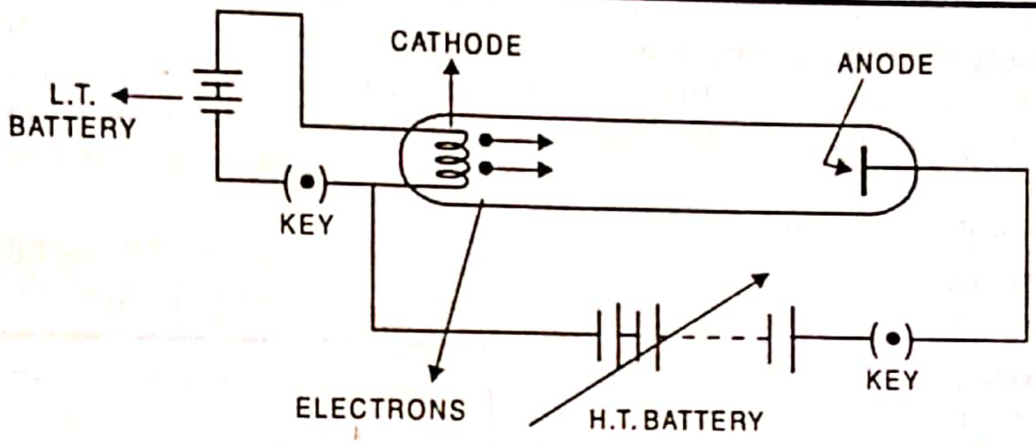



**Fig. 3**

*(iii)* **Electric Pumping.** This kind of pumping is used in semiconductor Laser. When electric current is passed through a *p–n* junction diode so as to give it a forward bias, then electrons drift from *n* side to *p* side of the diode across the junction provided bias voltage is more than barrier voltage. These electrons are free electrons in *n*-side, and possess kinetic energy. Such electrons are shown in conduction band of *n*-type energy diagram in the figure. On crossing the junction these electrons combine with holes in *p*-side and are used in the formation of covalent bond *i.e.* these electrons are now immobile and hence are shown to be going to valence band of *p*-side. Thus an energy equivalent to band gap energy is released in the form of a photon corresponding to every electron hole recombination across the junction. Various photons emitted in this fashion result in spontaneous emission. However due to biasing battery, simultaneously a number of covalent bonds are broken in the valence band of *p*-type, which generates free electrons in *p*-type, and these electrons are attracted by +ve terminal of battery. If the current through diode is large enough then number of electrons just above the lower edge of conduction band along *n*-side

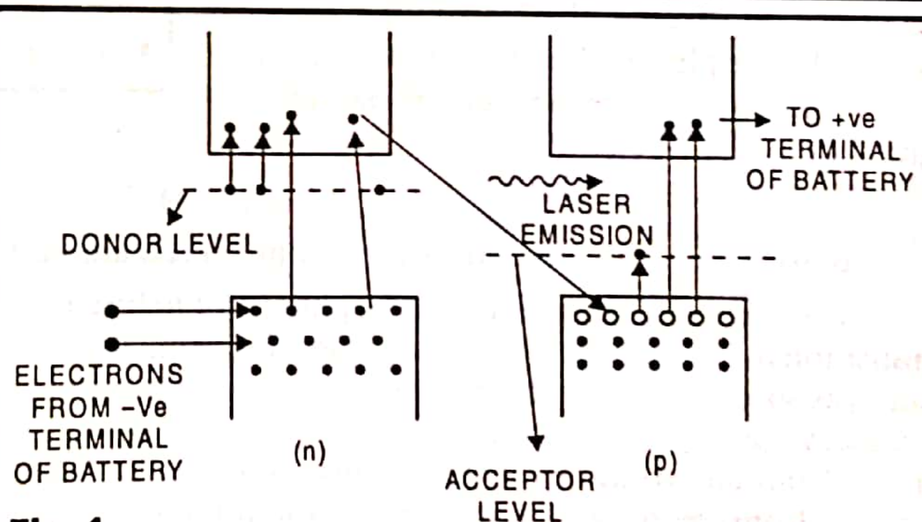



**Fig. 4**

may become more than number of electrons just below the upper edge of valence band in $p$ side, leading to population inversion very close to the junction region (called depletion region) only and hence lasing action may take place.

## (4) CHARACTERISTICS OF LASER BEAM

The quality of a laser beam is characterised by following parameters :

(*i*) **Divergence or Directionality.** An ordinary light source emits light waves in all directions in the form of spherical waves and is highly divergent. However the divergence or angular spread of a Laser is very small. If $d$ is the diameter of the front mirror and $\lambda$ is wavelength of Laser light, then angular divergence is given by

$$\Delta\theta = \frac{1.22\lambda}{d} \qquad \text{....(14)}$$

For gas lasers, the angular divergence can be as low as $10^{-5}$ rad. Thus laser beam is highly directional. It is because of the fact that resonant cavity in a laser supports only those modes, which are along a particular direction. The small divergence of laser beam is because of the diffraction effects caused by the mirror used in optical resonator. This mirror acts as circular aperture for the output laser beam and diffracts it.

(*ii*) **Coherence.** Two or more light waves are said to be coherent if these bear a constant phase relation among themselves. Coherence can be classified in two ways :

(*a*) **Temporal or Longitudinal Coherence.** Consider a light wave travelling along +X-axis as shown in fig. (5)(*a*). Consider two different points A and B along the length of same wave train. Let $\phi_A$ & $\phi_B$ be the phases of points A & B at any time. Then phase difference between these points is given by

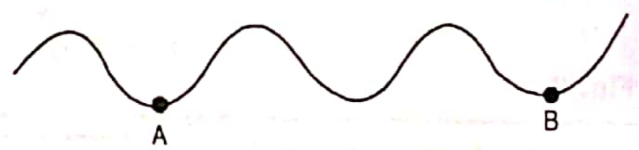


**Fig. 5(a)**

$$\Delta\phi = \phi_A - \phi_B \qquad \text{...(15)}$$

If $\Delta\phi$ is independent of time then points A & B are said to exhibit Temporal Coherence.

We know that an atom emits a photon of light when an electron makes a downward transition from excited level to ground level. The emission of light wave from de-exciting atom starts as soon as electron leaves excited state and stops as soon as it reaches the ground level. This wave can cover some finite distance in space in that time. Obviously it cannot be infinitely long. "A monochromatic wave is defined as a wave of constant amplitude & frequency which extends from $-\infty$ to $+\infty$ *i.e.* it must be infinitely long". In this sense the light wave emitted due to de-excitation of atom cannot be termed as monochromatic wave. In fact it is called Wave Train. Thus when an atom de-excites then a wave train is emitted in space. If a number of atoms are de-exciting frequently, then we can receive one wave train after the other and so on. Any two points on the same wave train bear a constant phase relation and show temporal coherence. Their is always an abrupt change of phase from one wave train to the other. Thus temporal coherence can be maintained by any light source only upto the distance equal to the length of wave train.

Let $\tau_C$ is time taken by an electron to reach from excited state to the ground state. This time is called coherence time. The length of the wave train emitted in this process is equal to the distance travelled by light in coherence time.

If c is speed of light, then length of a wave train & hence coherence length is given by (see fig. (5)(*b*))

$$l_C = c\,\tau_C \qquad ...(16)$$

The line width of a wave train is defined as reciprocal of the coherence time. It is denoted by $\Delta\nu$.

Thus $$\Delta\nu = \frac{1}{\tau_C} \qquad ...(17)$$

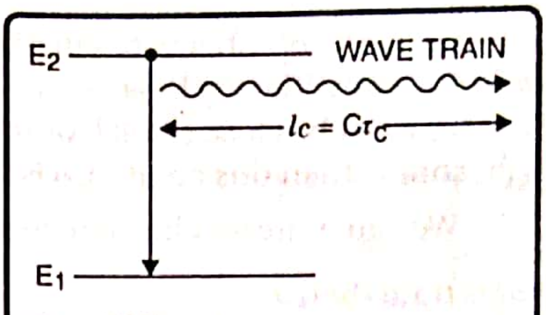


**Fig. 5(*b*)**

We know that any periodic function can be expanded as a linear combination of sine and cosine functions and this series expansion is called Fourier Expansion of the function. Further domain of both sine and cosine functions extend from $-\infty$ to $+\infty$. Thus a wave represented by sine or cosine function is always infinitely long and is said to be monochromatic according to definition given above. Let $\nu$ is the average frequency (called central frequency) of the wave train. Since wave train is also a periodic function covering only a finite region of space, we can express it as a fourier series. It can be shown that this wave train is obtained by superposition (fourier series) of infinitely long harmonic waves, whose frequency lie in the range $\nu - \frac{\Delta\nu}{2}$ to $\nu + \frac{\Delta\nu}{2}$. This result in fact indicates that any wave train always contain a number of monochromatic waves (Infinitely long) and thus is never monochromatic. Further smaller is the value of line width $\Delta\nu$, smaller are the number of monochromatic waves contained in the wave train, more is the monochromatic nature of wave.

We define monochromaticity of a wave train or light source as the ratio of central frequeny to the line width *i.e.*

$$\text{Monochromaticity} = \frac{\nu}{\Delta\nu}$$

It is a dimensionless parameter. Now $\Delta\nu$ can be small only if $\tau_C$ is large.

For ordinary light source $\tau_C \approx 10^{-10}$ s.

$\therefore$ $\Delta\nu \approx 10^{10}$ Hz

For $\lambda = 6000$ Å, we get $\nu = \frac{c}{\lambda} = 5 \times 10^{14}$ Hz

$\therefore$ $\frac{\nu}{\Delta\nu} \approx 5 \times 10^4$

In contrast, for a well controlled laser $\Delta\nu$ can be as low as 500 Hz.

$\therefore$ $\Delta\nu \approx 500$ Hz

Thus monochromaticity for 6000 Å wavelength is $\approx \frac{\nu}{\Delta\nu} \approx \frac{5 \times 10^{14}}{500} = 10^{12}$

which is quite large. Thus a laser beam is highly coherent.

Let us consider coherence length.

For ordinary light source $l_C = c\,\tau_C$

$$= 3 \times 10^8 \times 10^{-10} = 0.03\ m = 3\text{ cm}.$$

For a laser light $l_C = c\,\tau_C$

$$= 3 \times 10^8 \times \frac{1}{500} = 6 \times 10^5\ m = 600\text{ km}$$

Such a long coherence length implies that lasers can be used for performing interference experiments with very large path differences. In lower classes, we used to say that the two light sources must be close to each other for obtaining sustained interference. But if laser is used as light source then this condition is almost insignificant.

We can write an alternate expression for coherence length. If $\lambda$ is central wavelength for wave train then $\nu = \frac{c}{\lambda}$

$$\therefore \qquad \Delta\nu = \frac{-c}{\lambda^2}\Delta\lambda$$

$$\text{or} \qquad \frac{1}{\tau_C} = \frac{C}{\lambda^2}\Delta\lambda \qquad \text{(ignoring negative sign)}$$

$$\text{or} \qquad \tau_C = \frac{\lambda^2}{C\Delta\lambda}$$

$$\therefore \qquad l_C = C\tau_C = \frac{\lambda^2}{\Delta\lambda} \qquad ...(18)$$

We define $\frac{\lambda}{\Delta\lambda} = Q$ as Quality factor of each wave train. In terms of Quality factor, coherence length can be written as

$$l_C = \lambda Q \qquad ...(19)$$

(*b*) **Spatial Coherence.** Consider a beam of parallel waves as shown in fig. (6). Draw a line perpendicular to the direction of propagation of the beam. Let P and Q are two points on this normal line. Let $\phi_P$ & $\phi_Q$ are the phases of these points at any time. The phase difference between these points is given by $\Delta\phi' = \phi_P - \phi_Q$

If $\Delta\phi'$ is independent of time then beam of parallel waves is said to exhibit spatial coherence.

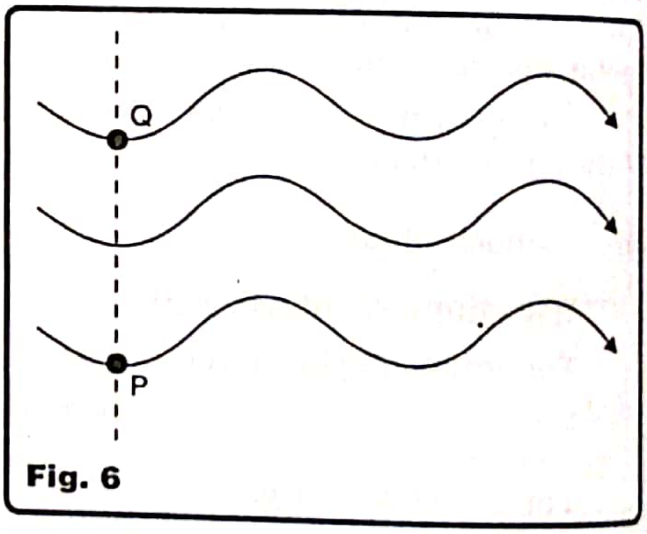


**Fig. 6**

Consider a point source at a distance D from two slits $S_1$ & $S_2$ as shown in fig. (7). Let $d$ is distance between slits $S_1$ & $S_2$. For simplicity, we assume that the distance of screen from slits is also D.

Let O is the centre of screen. The rays of light from S reach $S_1$ & $S_2$ and then these rays reach at O and form central maximum at O because the two rays cover equal path length in reaching from S to O through $S_1$ & $S_2$ respectively (see rays designated as 1 in figure).

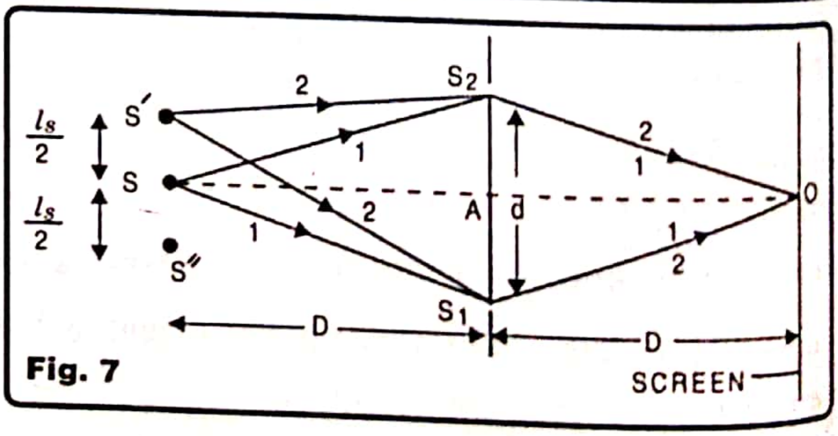


**Fig. 7**

Now consider another monoch-romatic point source S′ at a distance $\frac{l_s}{2}$ from S so that the light rays reaching at $S_1$ & $S_2$ from S′ differ in path by $\frac{\lambda}{2}$ exactly. When these rays (shown as ray no. 2) will reach at O, then they form a minimum at O. Thus maxima of S are overlapped by minima of S′ and vice versa. Due to this, we will not observe any bright and dark fringe on the screen. Similarly we can place a light source S′′ at distance $ls/2$ below S.

This explannation tells us that if we take a light source which is not a point source, but its size is less than the distance between S′ & S′′ $\left(i.e. \frac{l_s}{2}+\frac{l_s}{2}=l_s\right)$ then interference will be sustained and if size of source of light is more than $l_s$, then interference pattern will not be sustained. $l_s$ is called spatial coherence length. It gives maximum value of the size of a source of light.

From figure it is clear that

$$|S_1S'| = \left[D^2+\left(\frac{d}{2}+\frac{l_s}{2}\right)^2\right]^{\frac{1}{2}}$$

$$\approx D+\frac{1}{2D}\left(\frac{d}{2}+\frac{l_s}{2}\right)^2$$ (Expanding by binomial & neglecting higher terms)

Similarly $$|S_2\,S'| = \left[D^2+\left(\frac{d}{2}-\frac{l_s}{2}\right)^2\right]^{\frac{1}{2}} \approx D+\frac{1}{2D}\left(\frac{d}{2}-\frac{ls}{2}\right)^2$$

Thus $$|S_1S'|-|S_2\,S'| = \frac{dl_s}{2D}$$

or $$\frac{\lambda}{2}=\frac{dl_s}{2D} \qquad \left(\because |S_1\,S'|-|S_2S'|=\frac{\lambda}{2}=\text{path difference}\right)$$

or $$l_s=\frac{\lambda D}{d} \qquad \text{....(20)}$$

This equation gives expression for spatial coherence length.

Let $\theta$ is the angle substended by the source of light on the slits (see fig. (8)).

Then $$\theta=\frac{l_s}{D}$$

⇒ $$\theta=\frac{\lambda}{d} \qquad \text{...(21) (using (20))}$$

or $$d=\frac{\lambda}{\theta} \qquad \text{...(22)}$$

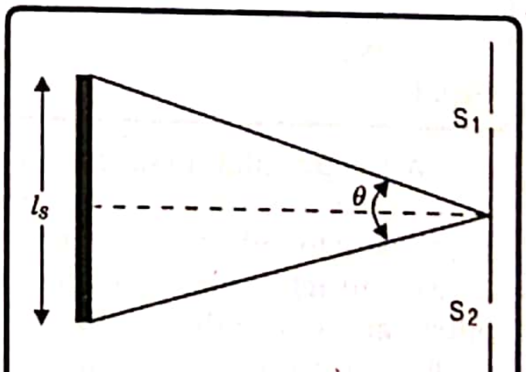


Fig. (8)

Thus an extended light source can behave as coherent light source if distance between slits $S_1$ and $S_2$ is less than $\lambda/\theta$ and as non coherent light source if $d$ is more than $\frac{\lambda}{\theta}$, where $\theta$ is angle subtended in radian by the source of light on the slits. The quantity $\frac{\lambda}{\theta}$ is called Lateral coherence width.

## (5) COMPONENTS OF A LASER

A laser essentially consists of three components :

(*i*) **Pump.** A pump is basically energy source for a laser. It gives energy to various atoms of Laser medium and excites them so heavily that population inversion is achieved as well as maintained with time. The function of pump depends upon the nature of the Laser medium. Various pumping schemes have been already discussed in article 3.

(*ii*) **Active Medium.** When energy is given to Laser medium using a pump, then only a small fraction of Laser medium shows Lasing action. This part of Laser Medium is called Active medium. The atoms/molecules of the active medium are called Active centres. For example in case of Ruby laser $Al_2O_3$ is doped with $Cr_2O_3$. The lasing action is because of doped chromium ions ($Cr^{+3}$) only. Hence these ions are active centres. Similarly in He–Ne laser, Ne-atoms are active centres.

(*iii*) **Optical Resonator.** An optical resonator is a set up, which is used to obtain amplification of stimulated photons, by oscillating them back & forth between two extreme limits. It consists of two plane or concave mirrors placed co-axially. One of the mirror is partially reflecting and other is totally reflecting. Laser output is received from partially reflecting mirror. The space between two mirrors is called cavity.

Figure (9) shows the action of optical resonator by assuming plane mirrors. Rod of active medium is placed between the two mirrors as shown in figure.

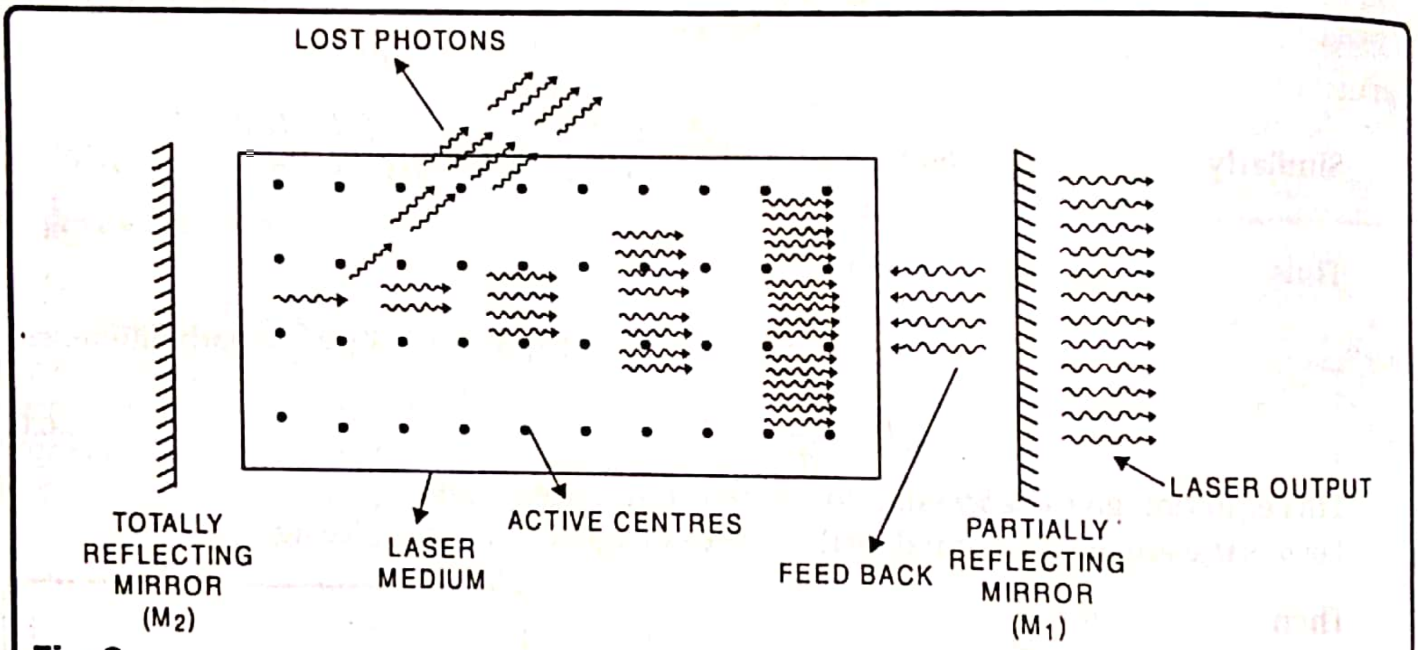



**Fig. 9**

When population inversion is achieved using pumping, then one or more atoms (active centres) may de-excite spontaneously, thereby emitting a photon of energy. This photon acts as stimulant for other active centres and as it passes through laser medium, it initiates stimulated emission in active medium. The emitted photons themselves act as stimultants for other active centres and hence the number of emitted photons go on increasing. All these photons travel parallel to the direction of initial spontaneously generated photon. If by chance this photon is travelling along the principal axis of the mirror, then this beam of parallel photons is reflected partially by the mirror $M_1$, while the transmitted part of the beam gives us Laser output. The reflected photons act as feed back for the active medium because these photons again enter in active medium and their number enhances due to further stimulated emission. This beam of photons is totally reflected back into active medium by second mirror $M_2$ and the number of photons further increases due to stimulated emission. Thus again highly intense beam of photons strikes the mirror $M_1$ which reflects them partially and transmitted beam gives us Laser output.

If the initial spontaneous photon is travelling obliquely with respect to principal axis of the mirror then the stimulated photons generated by it will also travel obliquely. However these photons are not reflected back into Laser medium by any of the mirrors $M_1$ or $M_2$. Hence such photons are lost. Thus optical resonator will multiply only those photons which travel parallel to the axis of the resonator. Hence laser beam is highly directional. However the partially reflecting mirror acts as a small aperture for the beam of photons and due to wave character of light, diffraction of beam takes place as it emerges out of partially reflecting mirror. Due to this the laser beam is not exactly directional, but it is slightly diverging. However angular divergence of Laser is very small as compared to ordinary source of light.

## Modes of optical Resonator

We have just seen that the light amplification takes place due to the action of optical resonator, which makes light photons to oscillate back and forth between two mirrors. Thus at any time light waves are moving in both directions between two mirrors of the cavity. These waves moving in opposite direction interfere with each other and form stationary wave pattern between the two mirrors. However the two waves can interfere in many different ways and standing wave pattern formed between the mirrors is stable if the electric field is zero at each mirror. "Every stable standing wave pattern between the two mirrors is called Longitudinal Mode", because they are associated with longitudinal direction of electromagnetic waves within the cavity. Each longitudinal mode has different wavelength or frequency, however the wavelength of every mode satisfies the following condition.

$$L = m\left(\frac{\lambda}{2}\right) \qquad ...(23)$$

where $m = 1, 2, 3.....$

and L = distance between mirrors

and $\lambda$ = wavelength of a longitudinal mode.

Let V is speed of light in active medium

$n$ = refractive index of active medium

C = speed of light

$\nu$ = frequency of mode

then $$V = \frac{C}{n} \quad \text{and} \quad \lambda = \frac{V}{\nu} = \frac{C}{n\nu}$$

Hence equation (23) can also be written as

$$L = m\left(\frac{C}{2n\nu}\right)$$

or $$\nu = m\frac{C}{2nL} \qquad ...(24)$$

Thus the frequencies of allowed modes are discrete. The minimum frequency is obtained for $m = 1$.

*i.e.* $$\nu_{min} = \frac{C}{2nL}$$

This frequency is called fundamental frequency and other frequencies are integral multiple of fundamental frequency.

The frequency difference between adjacent longitudinal modes is given by

$$\Delta\nu = (m+1)\frac{C}{2nL} - \frac{mC}{2nL} = \frac{C}{2nL}$$

It should be noted that for a practical optical resonator, $m$ (number of modes) is very large number.

*e.g.* if we take Length of Cavity as 0.8 $m$ and $n = 1$ (assuming gas laser) and $\nu = 5 \times 10^{14}$ Hz for red colour, then

$$m = \frac{5 \times 10^{14} \times 0.80 \times 1 \times 3}{3 \times 10^{8}} = 4 \times 10^{6}$$

In addition to longitudinal modes, transverse modes also exist in the resonant cavity. If mirrors have finite transverse dimensions, then only that portion of the waves, which strikes the mirror, will be reflected and the portion outside the transverse dimension of the mirror will be lost. Thus the wave which oscillates in between the mirrors has finite transverse dimension, which depends on the size of the mirrors. Let $d$ is the size of a mirror and L is length of cavity. Then angle substended by one mirror on the other is given as $\frac{d}{L}$. Also we know that angular divergence for first minima due to diffraction is given approximately as $\frac{\lambda}{d}$. Thus Fresnel distance for optical resonator is given by

$$Z_F = \frac{d^2}{\lambda} \quad \text{...(24) (Standard Result, proved in lower classes)}$$

When light beam comes out of the cavity, then due to finite transverse dimensions of the mirror, the diffraction takes place, which results in loss of optical power. The loss of optical power will be less if diffraction is less. For that the length of resonator must be less than the Fresnel distance

*i.e.* $$L \leq Z_F$$

or $$L \leq \frac{d^2}{\lambda} \quad \text{...(25)}$$

Thus the length of resonator decides longitudinal mode selection and transverse size ($d$) of mirror decides transverse mode selection of an optical resonator.

## (6) ENERGY LEVEL DIAGRAM OF AN IDEAL LASER

An ideal laser medium essentially consists of four distinct energy levels for the outer most valence electron of each atom of active medium (*i.e.* active centres). These energy levels are designated as G, LL, UL, E. Let the energy values (averaged) are $E_1$, $E_2$, $E_3$, $E_4$ respectively.

The lowest energy state G is called ground state and its life time is unlimited *i.e.* an atom in this state will never leave it by itself. The highest energy state E is called excited state and its life time is very small roughly of the order of $10^{-10}s$ i.e. an atom excited to this state will de-excite to lower state within this time and in the process it will release energy either by emitting a spontaneous photon or by giving this heat to the rest portion of laser medium (*i.e.* non radiative transition), which acts as a supportive medium only. The atom may de-excite from E to ground level G as well as to intermediate energy level UL (called upper lasing level). However due to continuous pumping provided externally, the atoms de-excited to ground level G are again excited to level E. However the intermediate energy level UL has relatively much longer life time ($\approx 10^{-3}s$). This state is called metastable state. Thus within small time a lot of atoms de-excite spontaneously or non radiatively to UL and population inversion is achieved between levels UL and LL (called Lower Lasing Level). Now an atom in state UL can

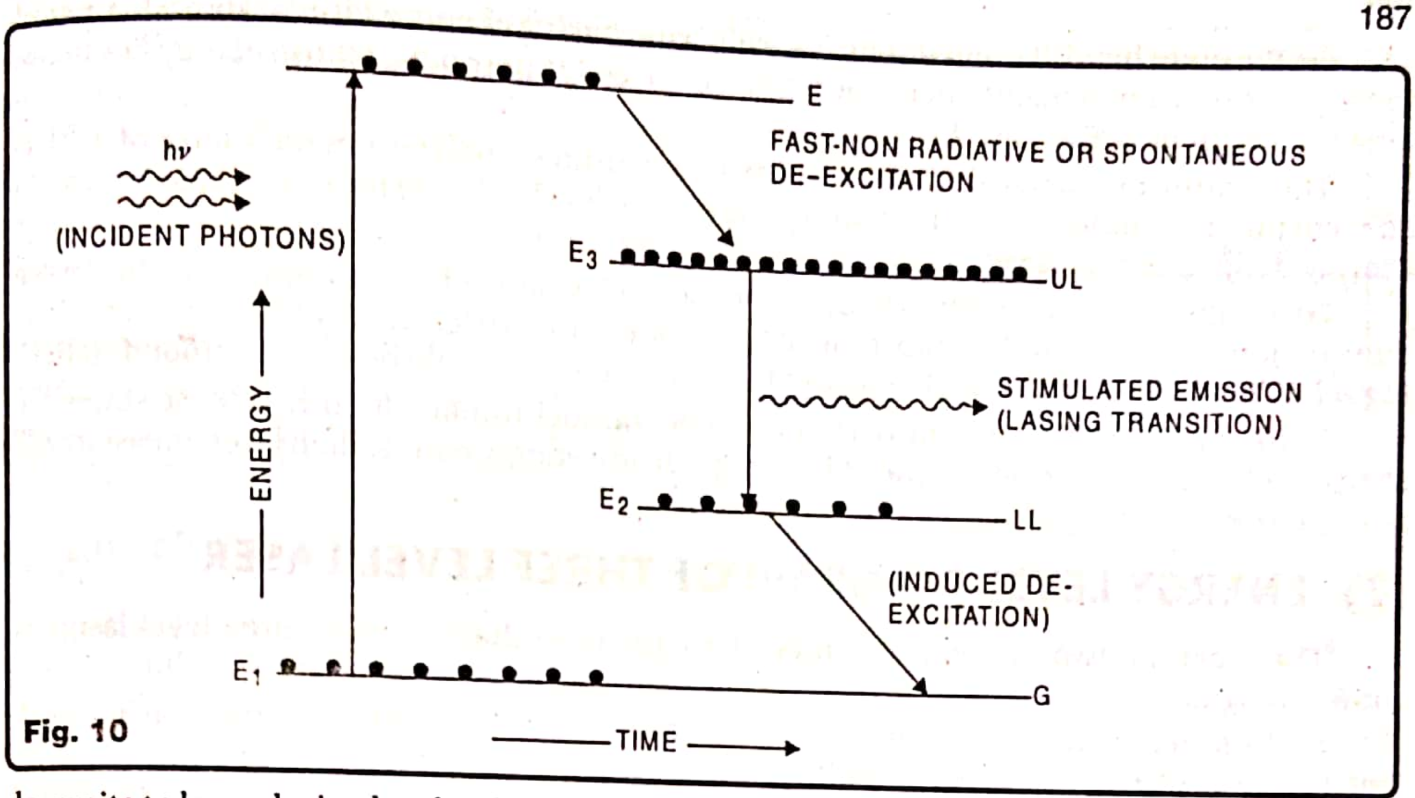



**Fig. 10**

de-excite to lower lasing level LL by emitting a spontaneous photon. This spontaneous photon will act as a stimulating photon for other atoms which are still in the metastable state UL and by the action of optical resonator, we will get highly intense beam of stimulated photons. Note that the lower lasing level is close to ground state G. Hence life time of LL is also large. So atoms will spend longer time in LL before coming to level G. Due to this, the population inversion may cease to exist between UL and LL. To overcome this, it is necessary, that atoms in state LL are simultaneously de-excited to Ground level externally. This is called induced emission *e.g.* in case of gas Lasers, induced emission is achieved by taking diameter of discharge tube very small so that atoms in state LL suffer frequent collisions with the walls of tube. Due to this these atoms will lose their excitation energy and come back to ground state G, and thus these are again ready to be pumped to excited level E. This is how a laser works.

(*i*) **Quantum Efficiency.** The energy given to the laser medium by the pump per excitation is given as

Input Energy = $E_i = E_4 - E_1$ = difference in energy of excited and ground state.

While energy given out by the laser per one lasing de-excitation is output energy $E_f = E_3 - E_2$ = difference in energy of upper & lower Lasing level.

The quantum efficiency of a laser is defined as the ratio of output energy per laser emission to input energy per excitation

$$\eta = \frac{E_3 - E_2}{E_4 - E_1} \qquad \text{...(26)}$$

(*ii*) **Properties of Various Energy Levels.** We have seen that four energy levels are involved for working of a laser. We know that a photon of energy $h\nu$ can excite an atom from level $E_1$ to level $E_4$ if the energy of photon is exactly equal to $E_4 - E_1$.

*i.e.* $$h\nu = E_4 - E_1 \qquad \text{...(27)}$$

Thus if the excited energy state E is a sharp energy level then the pumping will be very difficult as from the beam of incident photons only those photons will be absorbed for exciting atoms, which satisfy equation (27).

On the other hand, if excited state is a wide band having energy width $\Delta E$ above $E_4$ then all those photons from incident energy beam can be used for pumping, whose energy lies in the range $E_4 - E_1 \leq h\nu \leq E_4 + \Delta E - E_1$.

This feature of excited level allows us to use an ordinary polychromatic source of light as efficient pump. Thus for efficient pumping, the excited level E should be a wide band instead of sharply defined energy level.

Let us now turn our attention to upper and lower lasing levels. From equation (26), we see that quantum efficiency will be maximum if $E_4$ & $E_3$ are close to each other while $E_2$ & $E_1$ are close to each other. Thus UL must be close to excited state E and LL should be close to ground state G.

Further laser emission from UL to LL will be monochromatic if both of these states are sharply defined energy levels. If one or both of them are energy bands, then laser emission will not be monochromatic at all.

## (7) ENERGY LEVEL DIAGRAM OF THREE LEVEL LASER

There can be two possible schemes of energy level diagram of a three level laser, as shown in figure (11).

In the scheme (*a*), we see that ground level is simultaneously acting as lower lasing level. Since life time of ground level is unlimited thus atoms de-exciting from UL to G will not prefer to leave this state easily and in order to pump them again to level E so as to maintain population inversion, we require rigorous pumping.

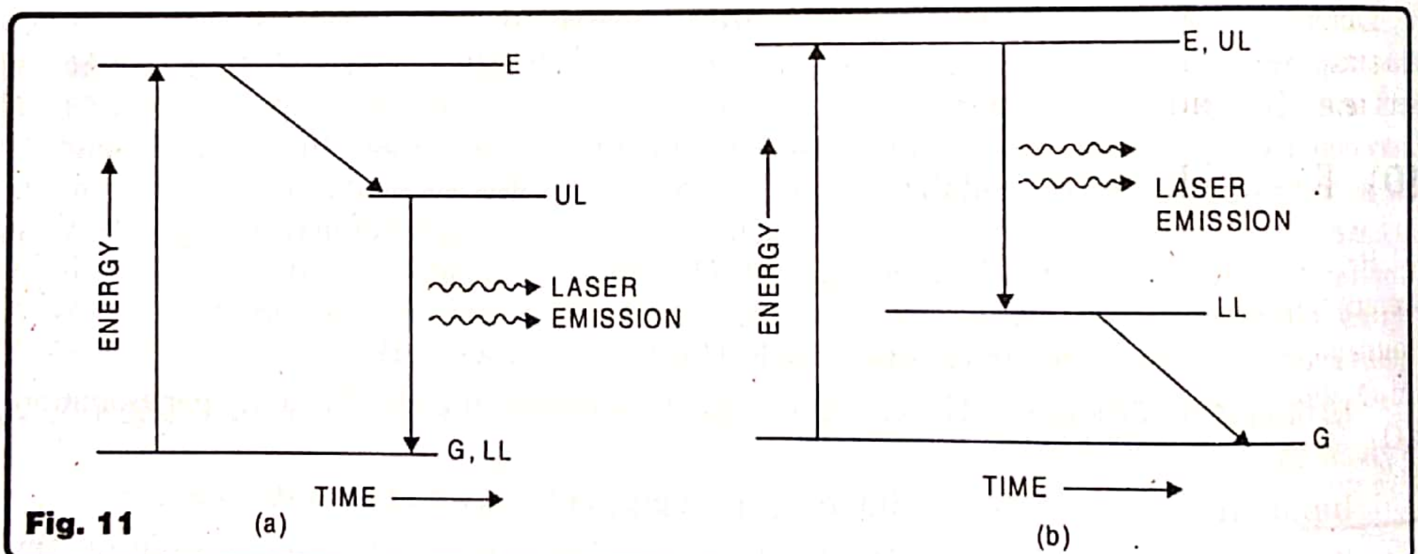



**Fig. 11**

In scheme (*b*) we see that excited level is simultaneously acting as upper lasing level. But we know that the states E & UL have totally contradicting properties & one energy level can have either of these two properties. For example if level E is a sharply defined, than laser emission from E to LL is more monochromatic, but the pumping from G to E will be almost inefficient. On the other hand if level E is band, then the pumping from G to E is easier however laser emission will be less monochromatic.

It is clear from both schemes (*a*) & (*b*) that the quantum efficiency of a three level laser is more than corresponding four level laser. However, the quality of laser beam is expected to be poor as compared to corresponding four level laser.

## (8) ENERGY LEVEL DIAGRAM OF A TWO LEVEL LASER

The energy level diagram of a two level laser is shown in fig. (12). Clearly excited level E is simultaneously acting as upper lasing level UL. Because of this there will be same difficulties as discussed in scheme (*b*) of three level Laser. Further ground level G will simultaneously act as lower lasing level LL. This requires rigorous pumping as discussed in scheme (*a*) of three level laser. Thus quality wise, a two level laser is of worst quality. However it is clear from the energy level diagram that quantum efficiency of a two level laser is maximum as compared to two level and three level laser corresponding to same energy difference between E and G.

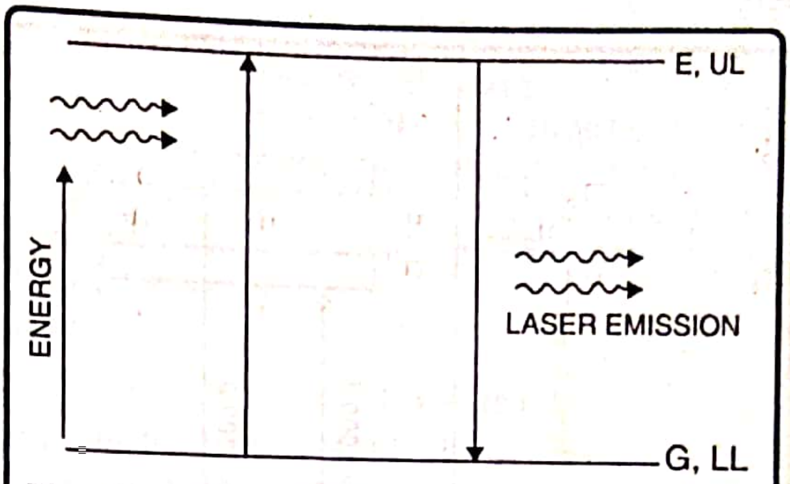


Fig. 12

## (9) LASER TYPES

Lasers can be classified on the basis of energy levels. Thus we have two level laser (*e.g.* semiconductor laser), three level laser (*e.g.* Ruby Laser ) and four level laser (*e.g.* He–Ne Laser, Nd = YAG Laser and $CO_2$ Laser)

Lasers can also be classified on the manner of pumping. Thus we have optical pumping lasers (*e.g.* Ruby laser & Nd –YAG laser), Electric discharge pumping lasers (*e.g.* $CO_2$ & He–Ne lasers) and electric pumping laser (*e.g.* semi conductor laser).

Lasers can also be classified on the basis of nature of active medium used. Thus we have solid state lasers (*e.g.* Ruby & Nd–YAG lasers), liquid state lasers (*e.g.* liquid dye lasers) and gas lasers (*e.g.* $CO_2$ and He–Ne laser).

## (10) RUBY LASER

It consists of a single rod of Ruby whose end faces are flat and one of the faces is completely silvered, which act as totally reflecting mirror, while other end is partially silvered, which act as semitransparent mirror. Thus two end faces of Ruby rod make a resonant cavity. Ruby consists of $Al_2O_3$ with roughly 0.05% of Aluminium atoms replaced by chromium atoms, by doping with $Cr_2O_3$. The energy level diagram of chromium ions $Cr^{+3}$ is shown in Fig. (14). These ions form active medium. The energy levels $E_1$ & $E_2$ are two different bands which act as excited levels.

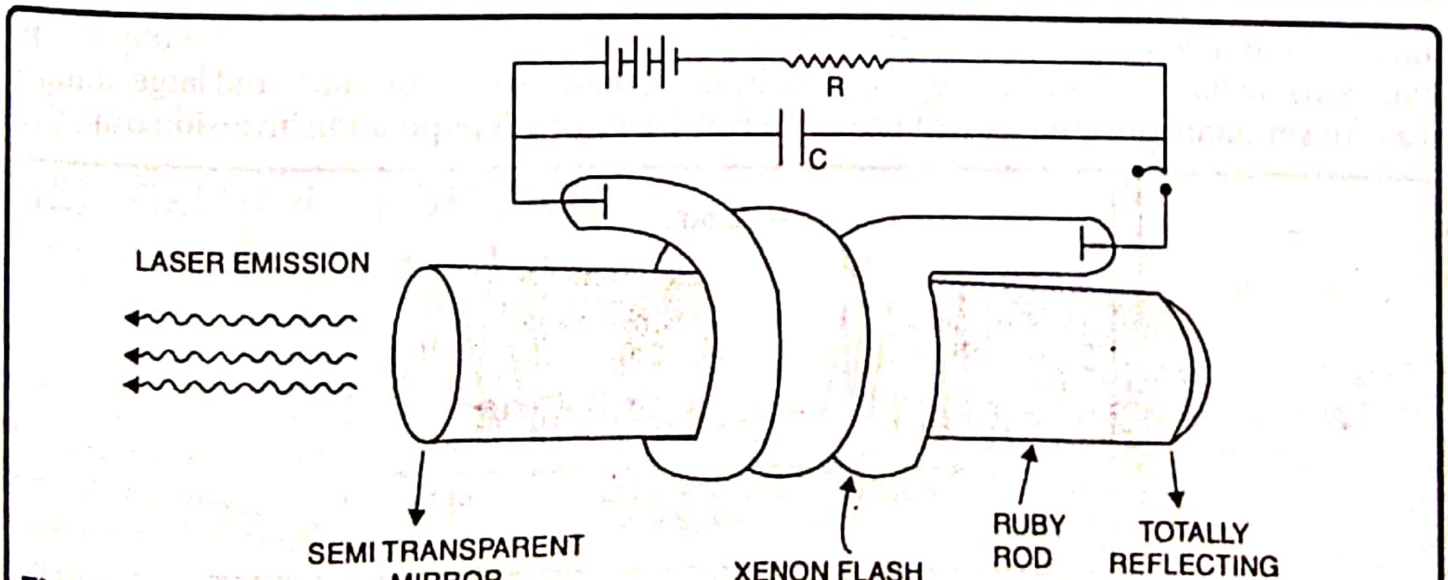


Fig. 13

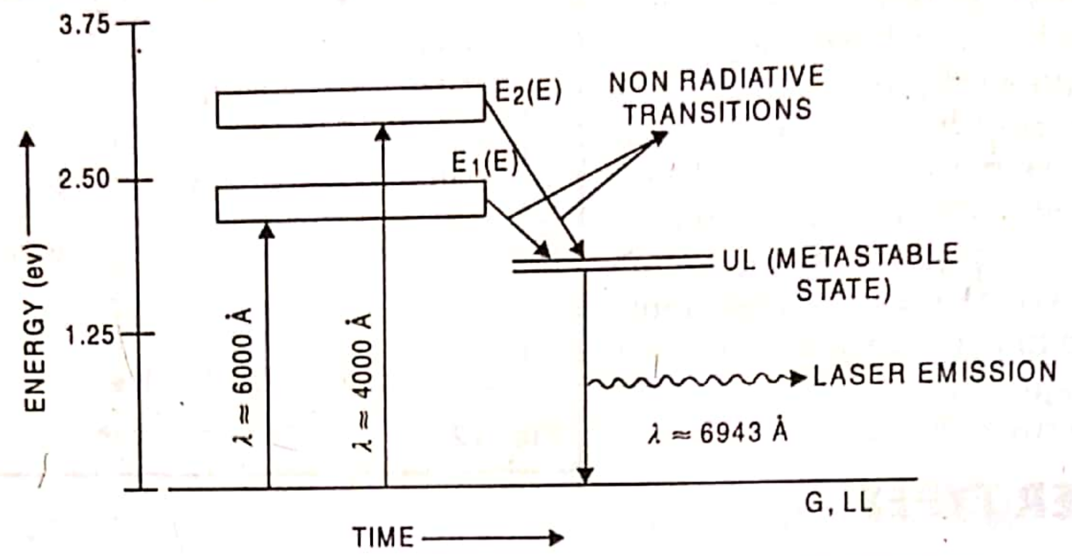


**Fig. 14**

The life time of these states is very small roughly $10^{-9}s$. The $Cr^{+3}$ ions are excited to these levels by a Xenon flash lamp, which is surrounding the Ruby Rod.

Xenon flash lamp, produces very strong pulses of polychromatic light. $Cr^{+3}$ ions may go to band $E_1$ or $E_3$ by absorbing corresponding photons from Xenon flash lamp. These ions de excite very fastly to metastable upper lasing level UL through non radiative transition. Due to long life time of the state UL, the population of chromium ions in this state goes on increasing and soon population inversion is achieved between ground level G and upper lasing level UL. Now a spontaneously emitted photon from stated UL triggers lasing action and a strong pulse of laser beam is obtained as a large number of stimulated de-excitations occur simultaneously. The wavelength of emitted light in lasing transition is ≈6943Å. Note that the laser emission is not continuous but it is pulsed *i.e.* we will get laser emission only for that time in which Xenon flash persists. The output light obtained in this time is called one pulse. When the flash stops then stimulated emission also quenches because population inversion condition ceases to exist. However there is still some emission of light energy due to spontaneous de excitation taking place from UL to G, even in the absence of Xenon flash light. Thus the graph of output optical power with respect to time is a series of pulses as shown in figure (15). Here bold line graph shows stimulated emission and dotted lines show spontaneous emission. The duration of one pulse is roughly $50\mu s$. However even during a pulse from laser, the output power is not constant and it consists of spikes. It is because of the reason that as soon as the population inversion is achieved due to energy supplied by flash, then laser action starts and large number of atoms simultaneously de-excite to ground level G. Due to this population inversion condition

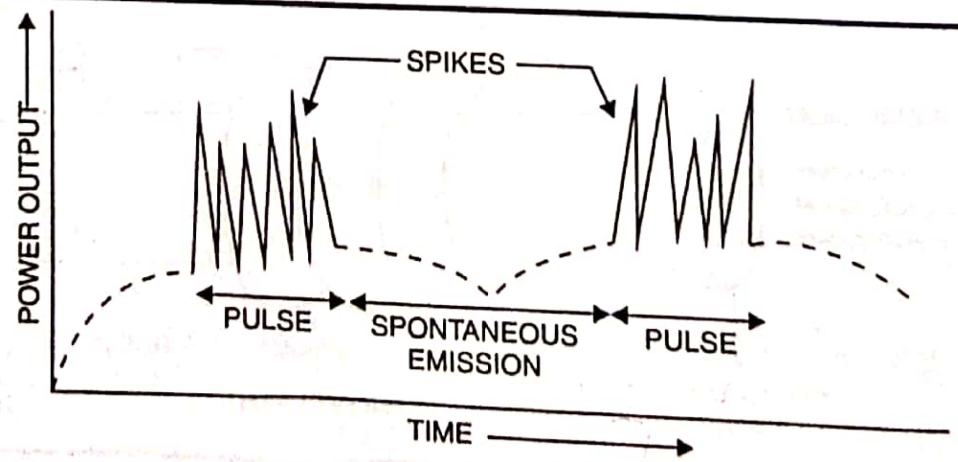


**Fig. 15**

is broken. All this happens within small time say in 5 $\mu s$. However the energy of flash is still available (because duration of one pulse $\approx 50\,\mu s$). This energy will take some time (a few micro seconds) to again produce population inversion and during that time laser action is quenched. But when population inversion in achieved, again laser action starts and again number of atoms undergo lasing transition simultaneously and laser action again stops. Thus process takes place many times in one pulse and we get spikes in each pulse.

## (11) Nd–YAG LASER

This is a four level laser and is better in quality than three level Ruby laser. The laser medium consists of Yttrium Aluminium Garnet ($Y_3Al_5O_2$) with some ions of Yttrium doped with rare earth Neodymium ion $Nd^{3+}$. The schematic laser diagram is same as shown for Ruby Laser in Fig. (13) except, Ruby rod is replaced by Nd–YAG Rod. The energy level diagram of $Nd^{3+}$ ions is shown in fig. (16).

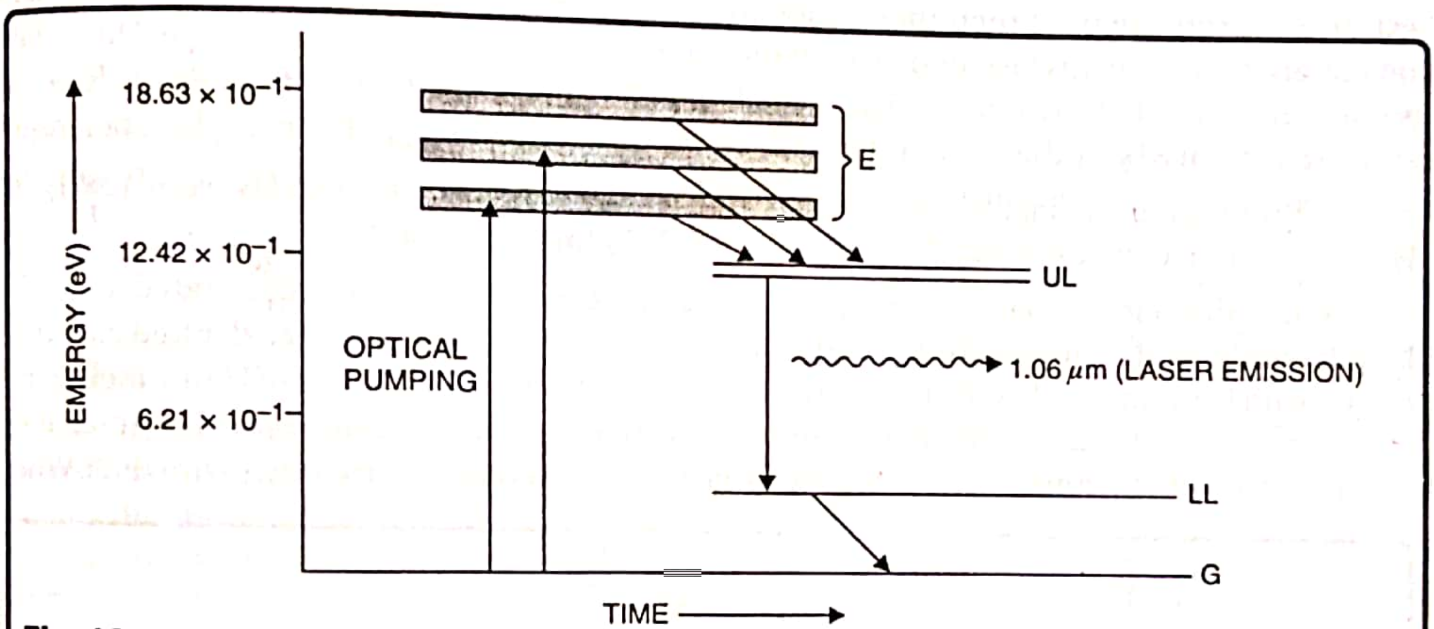


**Fig. 16**

The laser transition occurs at 1.064 $\mu m$. The excitation bands occur in blue and green colour range.

From the excited levels E, the non radiative transitions take place to upper lasing level. A spontaneously emitted photon from UL to LL triggers laser action. The de-excitation of $Nd^{3+}$ ions from LL to G is achieved by collisions with the laser medium.

## (12) HELIUM NEON LASER

It consists of a discharge tube filled with a mixture of Helium and neon gases in the ratio 10 : 1 respectively. The pumping employed here is electric discharge pumping. Optical pumping cannot be employed for gas lasers because of the reason that in case of optical pumping, the flash tube produces a polychromatic light, which can be absorbed efficiently by solids only because they have energy bands. However in case of gases, there are no energy bands and optical pumping will be inefficient. The ends of discharge tube consists of glass windows inclined at Brewster's angle with respect to the axis of discharge tube. The optical cavity is formed by two plane mirrors placed externally to the tube. One of the mirrors is semi transparent and gives out laser emission. The disadvantage of using mirrors inside the discharge tube is that mirrors are eroded with time due to gas discharge and have to be replaced. Also when

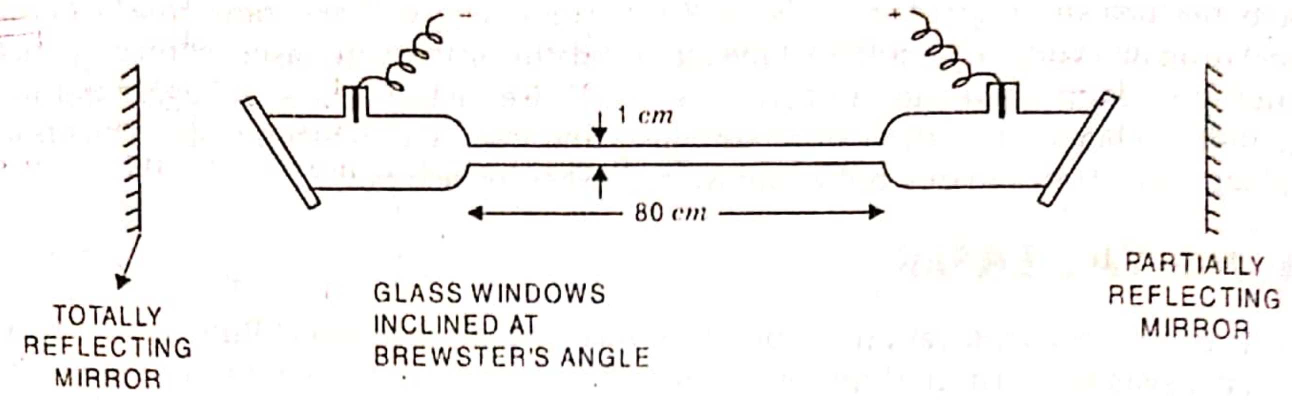


**Fig. 17**

external mirrors are used then there is loss of light at the ends of the discharge tube due to reflection. To reduce this loss, end faces of the tube are inclined at Brewster's Angle. Thus while passing through these windows, light, which is polarised in the plane of windows does not suffer reflection while other light suffers reflection. Hence output light beam is plane polarised.

The energy level diagram of He and Ne are shown in figure (18). The levels $E_2'$ and $E_3'$ of He are found to coincide almost exactly with levels $E_6$ and $E_4$ of the Ne.

When discharge is passed through gaseous mixture, electrons get accelerated along the length of tube and acquire kinetic energy on their way to Anode. These accelerated electrons collide with He atoms and excite them to level $E_2'$ or $E_3'$. These energy levels of He are metastable states having large life time. Thus before de-exciting spontaneously, He atoms can keep excitation energy with them for long time. Hence the number of excited He atoms grows with time. When

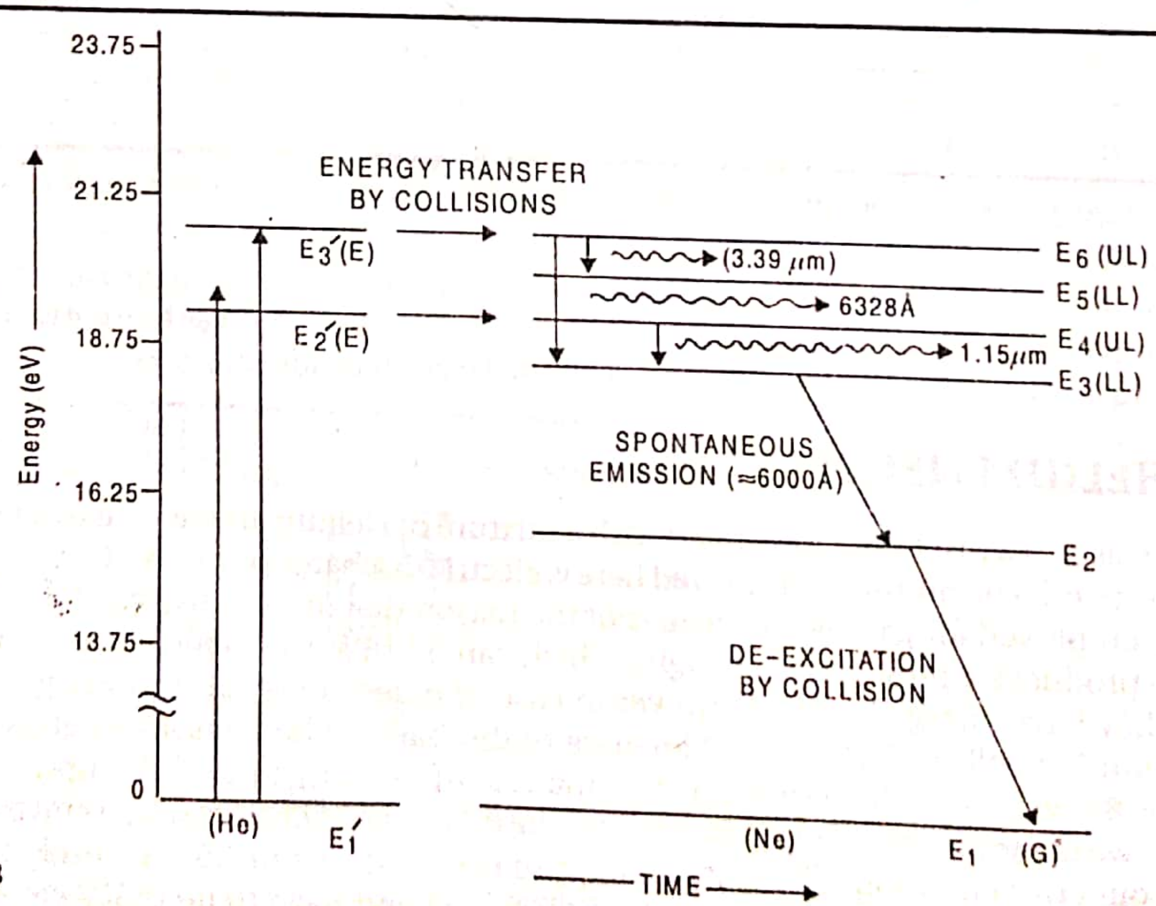


**Fig. 18**

these excited He atoms collide with Ne atoms which are in ground state G, then the excitation energy is transferred to Ne atoms, which themselves get excited to state $E_4$ or $E_6$. Thus population inversion is created between levels $E_4$ or $E_6$ and $E_5$ & $E_3$. Thus we get laser action corresponding to transitions $E_6 \longrightarrow E_5$, $E_4 \longrightarrow E_3$ & $E_6 \longrightarrow E_3$. The wavelength of emitted light corresponding to these transitions is 3.39$\mu m$, 1.15$\mu m$ and 6328Å respectively. The level $E_2$ is a metastable state in Ne. Thus there is chance of Ne atoms exciting back from $E_2$ to $E_3$ after absorbing a spontaneous photon. Due to this laser action may quench for some time. To overcome this problem, the diameter of tube is taken to be very small, so that Ne atoms in state $E_2$ collide frequently with walls of tube & get de-excited to state $E_1$ and can take part in laser action again and again.

It should be noted that the states $E_6$ & $E_4$ of Ne are excited states of very small life time. Thus if only Ne is used in discharge tube then the spontaneous emission of Ne atoms will be more than laser emission. Thus to excite a number of Ne atoms to these excited levels, the discharge tube is filled with mixture of gases. The output light from this laser is in the form of continuous waves. The colour of laser beam is red.

## (13) CARBON DIOXIDE LASER

The schematic diagram of $CO_2$ laser is same as in figure (17) except that mixture of gases contained in discharge tube is $CO_2$, $N_2$ and He gases in the proportion 1 : 2 : 3 respectively. $CO_2$ molecules act as active centres and produce lasing action.

$CO_2$ molecules is a linear molecule. When energy is given to it, it can show vibrational as well as rotational modes in addition to translationsal modes. The various vibrational and rotational modes of $CO_2$ molecule are shown in Fig. (19).

The energy level diagram of Nitrogen and $CO_2$ is shown in fig. (20). The state $E_2'$ of $N_2$ molecule is a metastable state and matches with excited state $E_5$ of $CO_2$ molecule (state $E_5$ is a vibrational energy level of $CO_2$). The $N_2$ molecules are excited by accelerated electrons and the excited $N_2$ molecules grow in number with time because of metastable nature of energy level $E_2'$. These $N_2$ molecules collide with the $CO_2$ molecules and produce population inversion between vibrational levels $E_5$ & $E_4$ or $E_5$ & $E_3$. Thus laser emission is triggered due to spontaneous

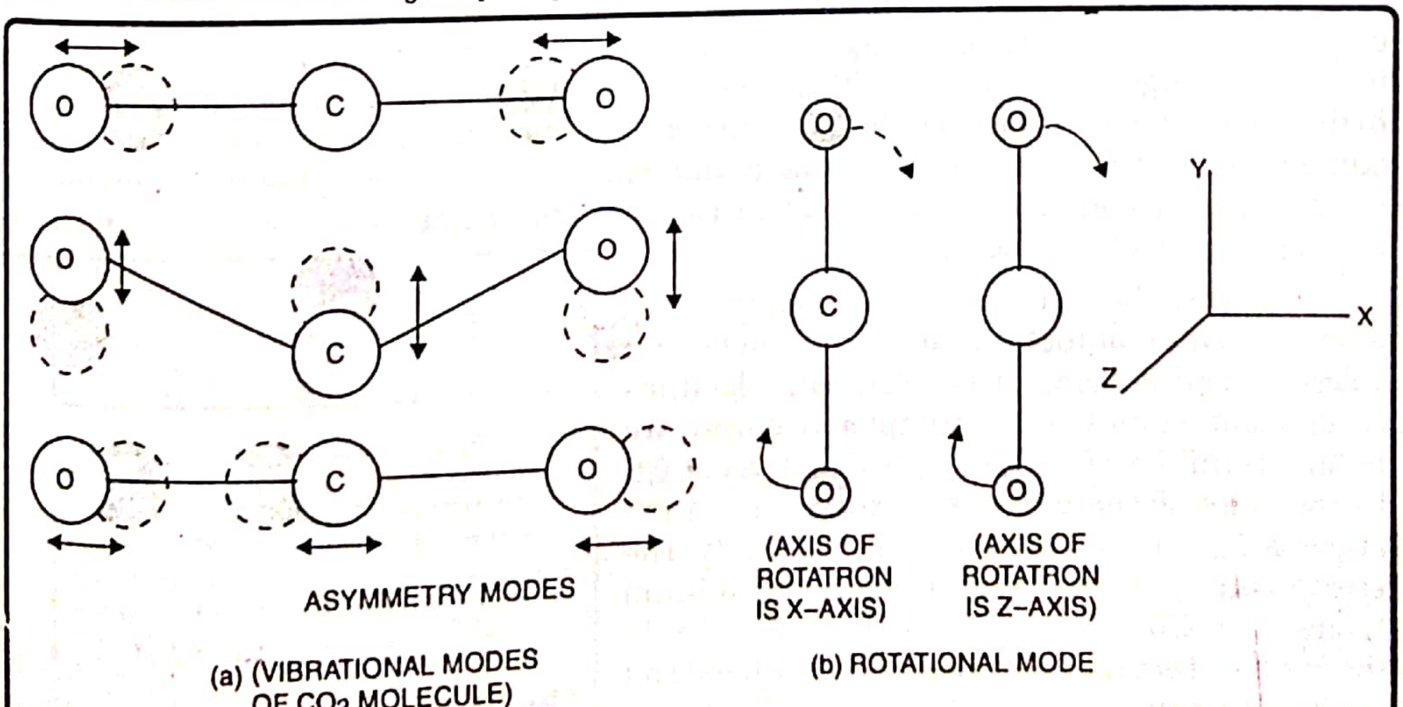



Fig. 19

transition $E_5 \longrightarrow E_4$ or $E_5 \longrightarrow E_3$. The wavelength of laser light corresponding to these transitions is $10.6\mu m$ & $9.6\mu m$ respectively, which lie in far IR region. The $CO_2$ molecules in the state $E_3$ de-excite to $E_2$ spontaneously or by colliding with other $CO_2$ molecules. The molecule in state $E_2$ is brought back to ground level $E_1$ by induced de-excitation with walls of glass tube.

$CO_2$ laser is much more efficient than other gas lasers because the lower laser levels of $CO_2$ molecule are vibrational-rotational energy levels of the lowest electronic level. Thus states $E_3$ & $E_4$ are very close to ground state, $E_1$ so that quantum efficiency is very large.

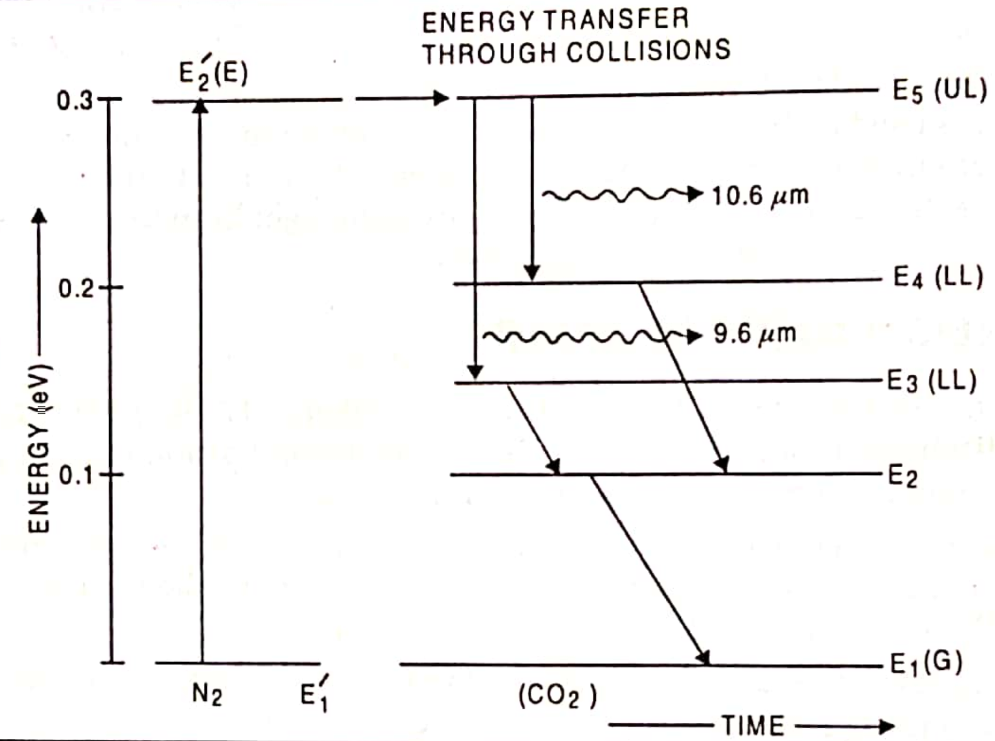



**Fig. 20**

## (14) SEMICONDUCTOR LASER

We know that in a semi conductor, there is a valence band and a conduction band. These two energy bands are separated from each other by a finite energy gap. "An Energy Band is a continuous range of allowed energy values of electron." It means an electron cannot exist inside the energy gap. It can exist either in valence band or in conduction band. The electrons in the valence band are very tightly held to the positive ion core, hence they cannot take part in conduction. On the other hand electrons in conduction band are loosely bound to ion core and can take part in conduction. Further a hole can exist only inside the valence band and it can also take part in electric conduction.

Fig. (21) shows energy level diagram of an intrinsic semi conductor at 0K. At absolute zero valence band is completely filled with electrons while conduction band is completely empty. We define 'Fermi Level' as a hypothetical level at 0K, below which all energy levels (if exist) are filled and above it all energy levels (if exist) are empty. The energy corresponding to Fermi level is called Fermi Energy ($E_F$). Obviously the Fermi level at 0K lies in the middle of energy gap between valence band and conduction band.

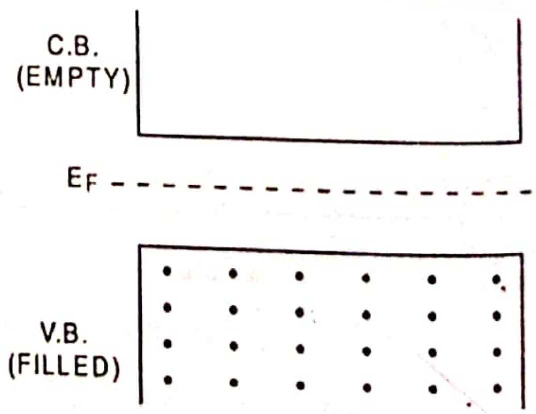



**Fig. 21**

A doped semi conductor can be *n*-type or *p*-type. In case of *n*-type semi conductor, pentavalent impurity atoms (*e.g.* phosphorus) in added to semi conductor. The fifth electron of each impurity atom is not used up in covalent bond formation. Hence it is very loosely bound to the nucleus of impurity atom. Due to this energy of this electron is large as compared to energies of electrons used in bond formation. Hence fifth electrons of all impurity atoms form a filled energy level just below the lower edge of conduction band [See fig. 22]. This energy level is called donor level. One can easily satisfy himself that Fermi level in this case lies between lower edge of conduction band and donor level. Just think over definition of Fermi Level to verify this fact.

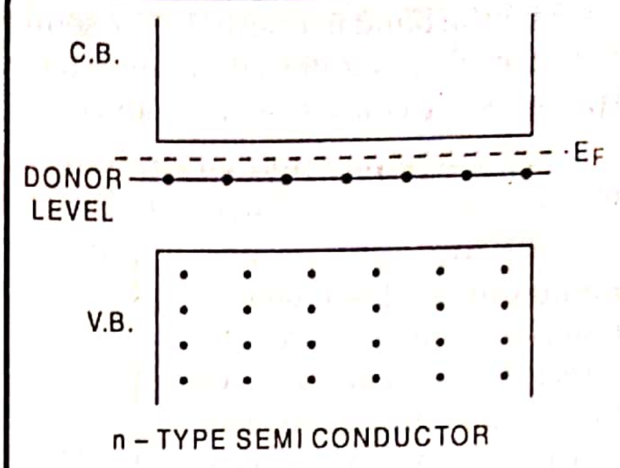


**Fig. 22**

Similarly in case of *p*-type semi conductors an empty energy level (called Accepter Level) is formed just above the valence band due to the fact that the impurity atoms added in this case are trivalent and one band between impurity atom and a semi conductor is always unsaturated due to shortage of one electron. Again we can easily convince ourselves that Fermi level in case of p-type semi conductor lies between Acceptor level and upper edge of valence band (See Fig. (23)).

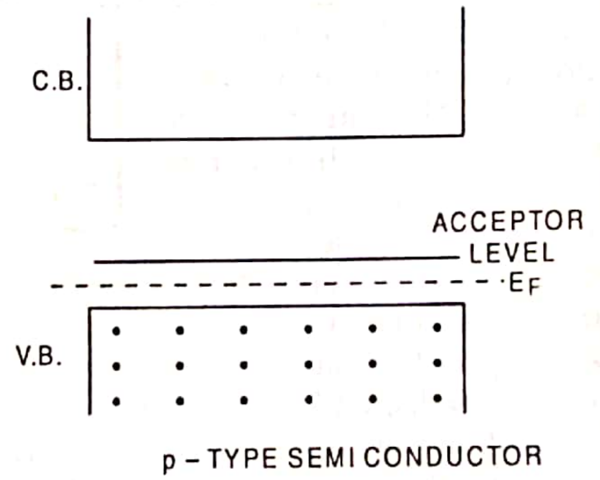


**Fig. 23**

"The Semi Conductor, in which Fermi level does not lie either inside valence band or conduction Band is called Non Degenerate semi conductor". All three types of semi conductors discussed above are examples of non degenerate semi conductor.

Let us now go on increasing impurity concentration in *n* or *p* type semi conductor. While doing so the impurity atoms come so close to each other that they start interacting just like semi conductor atoms. Due to these interactions Donor level becomes donor band and extends into the conduction band. While Acceptor level becomes Acceptor band and extends well into valence band. Hence in the case of high impurity concentration, Fermi level shifts into

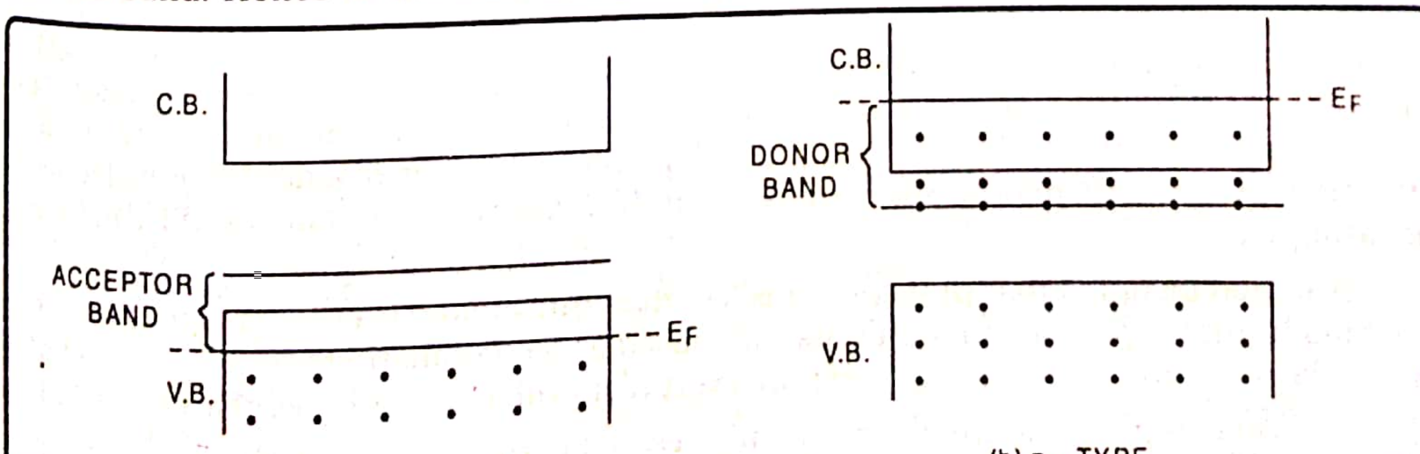


**Fig. 24** (a) p – TYPE (b) n – TYPE

conduction band in case of $n$ type semi conductor. While in case of $p$-type semi conductor, the Fermi level penetrates into valence band. This is shown in figure (24). The semiconductor now becomes Degenerate Semi conductor.

(*a*) **Homojunction Laser.** If the laser diode is made from only one $p$ type material and one $n$-type material, then it is called homojunction laser.

Figure (25) shows a homojunction laser having $pn$ junction diode of GaAs. It is a direct gap semiconductor with band gap energy of about 1.40 eV. A heavily doped $p$-type region is produced by diffusion of Zn into $n$-type GaAs. The dimensions of junction diode are very small (≈1 mm). The outer $p$ & $n$ faces of the diode, which are parallel to the junction plane are metallised, so as to make external connections. The front and rear faces are roughened, while remaining two faces, which are perpendicular to the junction plane are polished (one in partially polished and other is totally polished) and make a resonant cavity. The laser beam output is obtained through the partially polished face and is restricted to the region near junction only. The diode is given a forward bias using a battery. The energy band diagram of $pn$ junction laser diode is shown in fig. (26). When a $pn$ junction diode is formed then energy bands in $p$ & $n$ regions readjust themselves in such a way that Fermi Level is same throughout the junction diode provided no bias voltage is applied. There is small region ABC along $n$-side of diode and within the depletion region. This region is completely filled with electrons. Similarly there is a region DEF in the depletion region along $p$-side of junction and this region is of empty states only and contains no electron.

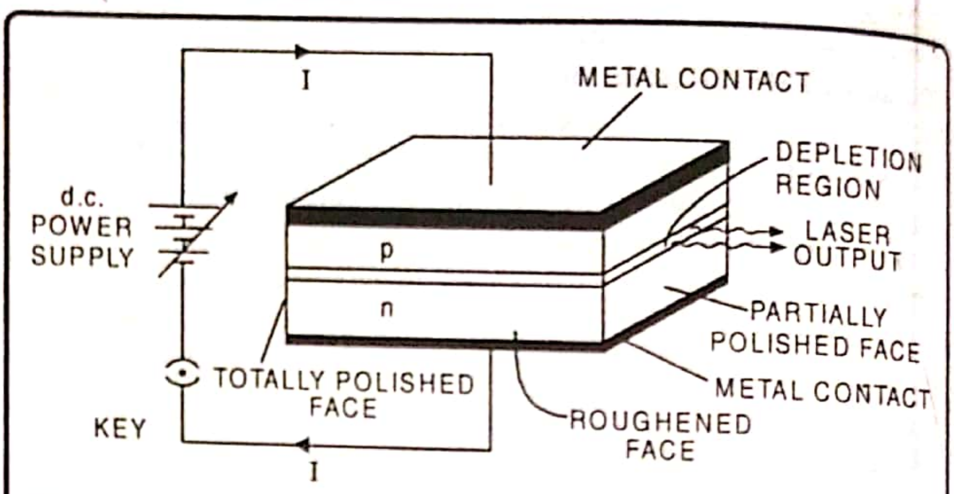
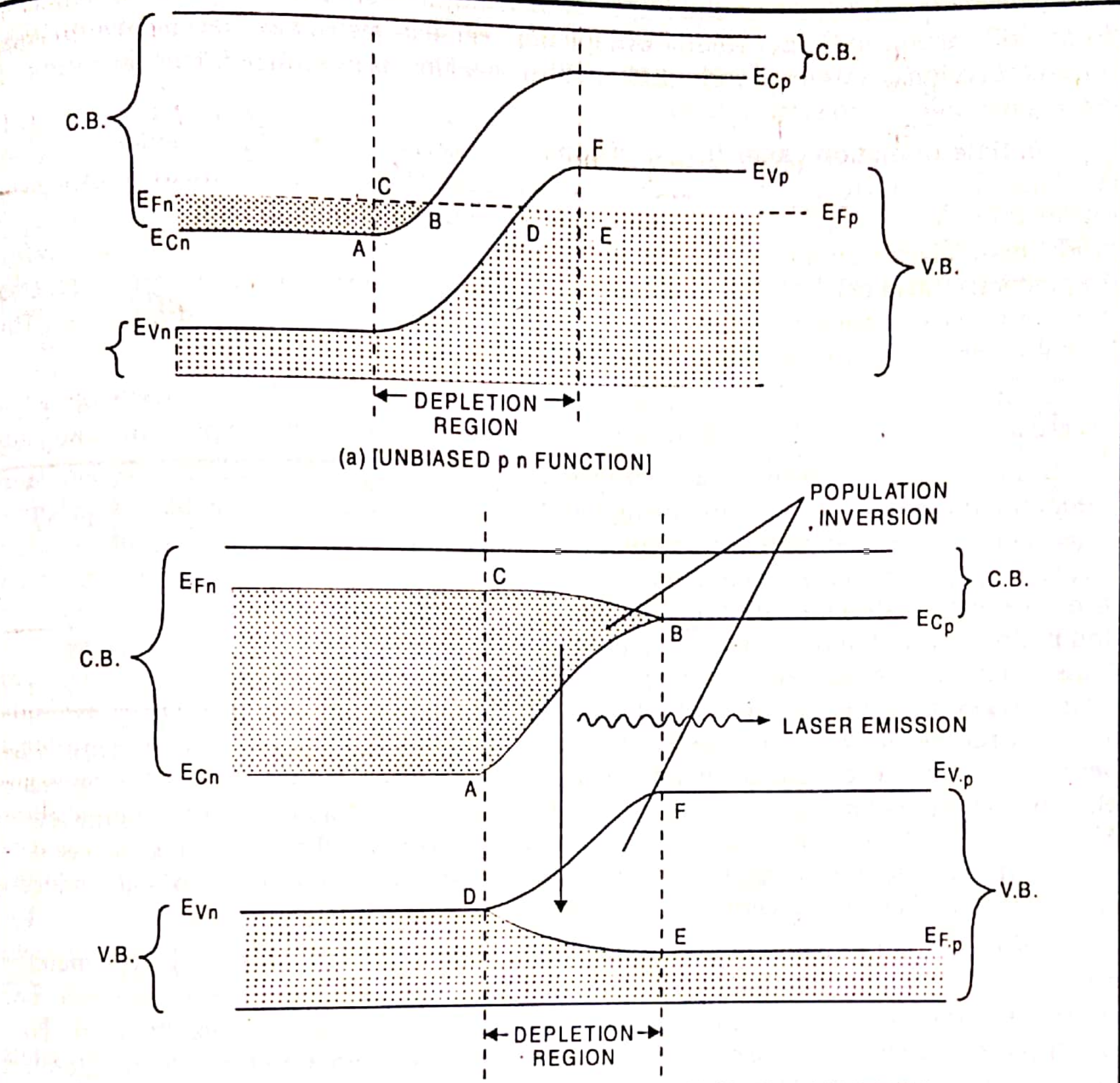



**Fig. 25**

When forward bias (greater than barrier voltage) is given to diode then electrons are injected by battery in the $n$-side and removed off from $p$-side of diode. Thus no. of filled states go on increasing along $n$-side and no. of empty states go on decreasing in $p$-side if forward bias is increased continuously. Due to this Fermi level gets broken down within the diode. Since it is highest filled energy level, thus it rises along $n$-side of junction and falls down along $p$-side of junction due to forward bias, hence the region ABC and region DEF start growing. A stage in reached when empty states of region DEF in $p$-side lie exactly below filled states of region ABC in $n$-side. At this stage current passing through diode is called 'Threshold Current' and population inversion is achieved within the depletion region near junction only. Hence a spontaneously emitted photon due to transition from states of ABC to states of DEF can trigger off lasing action.

If should be noted that (*i*) If current is less than threshold current then light is emitted from diode due to spontaneous de-excitation caused by recombination of electrons and holes across the junction. The light is emitted from every region of diode and goes of in all directions.

(*ii*) When applied current is more than threshold current, then population inversion is achieved only in a small region within the depletion region of size ≈ 1 $\mu$m. Thus laser light




(a) [UNBIASED p n FUNCTION]

(b) [FORWARD BASED (MORE THAN THRESHOLD) pn FUNCTION]

**Fig. 26**

comes out only through this narrow region. Further the size of this region is comparable to wave length of visible light. Hence this region behaves like a narrow aperture and causes diffraction effects to light waves. Due to this light beam from diode laser shows maximum divergence amongst all lasers.

(*iii*) This laser is a two level laser and each of these two levels comprises of a large number of closely spaced energy states (*i.e.* energy band). Further laser transition is form one band (region ABC) to other band (region DEF). As a result the wavelength of emitted radiation is not unique but extends over a range 600 nm to 700 nm.

(*iv*) Quantum efficiency of this laser is very large because electric energy is directly converted into light energy.

(*v*) The threshold current for these homojunction diodes is very high. If the area of cross-section of junction region is very large then volume of junction region (depletion region) will be large and hence on passing large current through such current there will be very large amount of heat produced due to ohmic resistance of the junction. Thus there is need to minimise the area of junction and hence volume of depletion region in such a way that effective excitation within the region is preserved and simultaneously heat loss is minimized. This can be done by making heterojunction lasers.

(*b*) **Heterojunction Laser.** In case of homojunction laser the width of depletion region is very large compared to the width required to make laser. Thus when current flows through this region, then excessive amount of heat is produced. Further current density is high enough to produce sufficient excitation for laser action only near the junction and it is too low away from the junction (and hence less than threshold value). The means in the region away from junction, there is no laser action but there is only energy wastage due to heat production. Thus homojunction lasers can work only at low temperatures.

In order to make a room temperature lasers, it was necessary to develop a heterojunction. In case of heterojunction lasers there are more than one type of $p$ or $n$ type semiconductors.

Figure (27) shows a simple heterojunction laser (in which there are two different types of $p$-materials and one type of $n$-material and vice versa). It contains upper layer of $p$ type material made from Al GaAs and middle layer of another $p$-type material GaAs and then a substrate of $n$ type GaAs. The $p$ type GaAs layer has thickness of 0.1 – 0.2 $\mu$m. which acts as active region or active medium. This is the only region where current can flow because the energy of conduction band of AlGaAs is inceased and it acts as barrier for conduction electrons and prevents current from flowing in the $p$ type AlGaAs region ($\because$ energy level of AlGaAs is above fermi level). Thus we see that charge carriers in the heterojunction lasers are confined to a much smaller region than heterojunction lasers as a result of which heat production is very small and current is very high so that laser action is achieved.

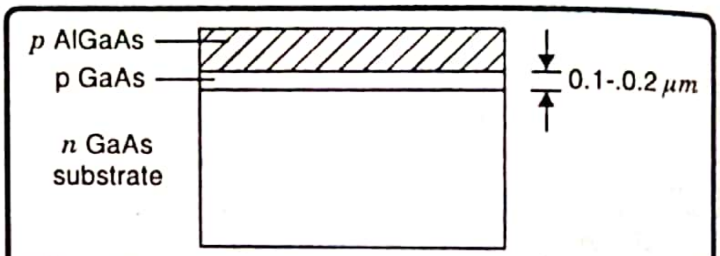


**Fig. 27**

Figure (28) shows a double heterojunction laser (in which there are two $p$-type materials and two $n$-type materials). Due to two types of $p$ and two types of $n$ materials, we have more control over the size of active region and over the variation of refractive index. The control over width allows to reduce heat loss and makes laser suitable to be operated at room temperature. While control over refractive index helps to change wave guiding properties of active region when heterojunction is used as a laser. In order to further reduce the size of active region, the side walls of active region are narrowed by lithographic techniques. With this the value of threshold current can be decreased further.

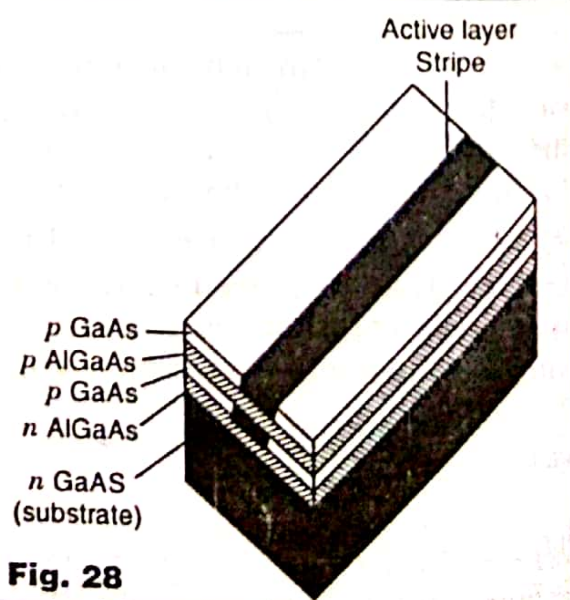


**Fig. 28**

## (15) APPLICATIONS OF LASERS

(*a*) **Applications in Industry.** Material processing is most important and fundamental technique in mechanical industry. It consists of drilling, cutting, welding, heat treatment etc. These applications are discussed briefly below :

**1. Drilling.** Drilling holes by a laser beam is based on intense evaporation of material using light pulses of very short duration ($\approx 10^{-4}s$). The energy supplied should be such that rapid evaporation rate is more than the rate at which heat is distributed laterally in the workpiece. Thus using short duration pulses we can reduce the lateral distribution of heat and hence control the size and shape of hole. While drilling using a laser there is no contact with the workpiece thus problems of wear and tear are minimised and the speed of process increases. Most commonly used lasers for drilling are $CO_2$ laser and Nd YAG laser. $CO_2$ laser is useful in drilling holes in metallic as well as non metallic materials, while Nd YAG is used for drilling in metals only. Laser pulses are so strong that these can be used to drill holes in diamond also which is not an easy task to perform mechanically.

**2. Cutting.** A wide range of materials can be cut using $CO_2$ lasers. These materials include paper, wood, cloth, glass, quartz, steel etc. The cutting process requires removing of material. Laser beam is focussed on the materal and strong jet of oxygen or nitrogen gas is blown at the laser spot so that surface of material is cooled and debris is blown away from the cutting zone simultaneously. Laser cutting is very precise. There is minimum mechanical distortion and thermal stress in the material being cut. There is no contamination of the material during cutting. The process is very fast thereby increasing the production rate. The power required to cut a material depends on its nature e.g. metals can be cut with 100W-500W output of $CO_2$ laser while plywood requires 8kW $CO_2$ laser.

**3. Welding.** Welding is the joining of two or more pieces of two metal plates. The two metal plates to be welded are held in content and then a focussed laser beam is made to move along the line of contact along with a jet of inert gas like He, Ar or $N_2$ so as to avoid oxidation of metal surface. The laser beam heats the two surfaces in contact above their melting points and surfaces fuse together to form a strong joint. This process is contactless process, hence no contamination occurs at the joint. Further heat affected zone is relatively small compared to mechanical welding. Power required is also less compared with mechanical welding. This technique can be employed to join two surfaces which are otherwise inaccessible when mechanical welding is employed. Most important advantage of this technique is that it can be easily automated by using computer interface. Further note that laser welding can be done in atmosphere unlike electron beam welding.

**4. Heat Treatment.** It is a process of heating metals and other materials for some time so as to harden them. Heat treatment causes surface layer to become crystalline. With this surface becomes more harder and shows less wear and tear. The commonly used laser for heat treatment is $CO_2$ laser. Moreover most of metals have high reflectance at 10.6$\mu$m, whch is wavelength of $CO_2$ laser light. Thus chances of absorption of $CO_2$ laser beam are increased by applying a coating of graphite or zinc phosphate to metal surface. Heat treatment using lasers require less power. It can be used for selective heat treatment of desired area.

(*b*) **Applications In Medicine.** Lasers are used widely in medical applications like diagnostics and surgery. A few applications are described briefly :

1. Retina is the right sensitive layer at the back of eyeball. Some times it becomes torn and gets detatched from back ball of eyeball. Once small portion of retina gets detatched, it continues to increase and can lead to total blindness. Argon laser beam is focussed on desired point in the retina. The green beam of laser is strongly absorbed by red blood cells of retina and causes thermal effects, which welds the retina back to eyeball.

2. Cataract occurs when natural lens of eye becomes cloudy and obstruct vision. If not treated at early stage, it can lead to blindness. This disease is treated by removing the natural lens and replacing it by a plastic lens. In some cases, the natural membrane behind the lens

also becomes cloudy after cataract operation and causes vision destruction again. Nd YAG laser can be used to remove clouded membrane. A series of laser pulses are focussed on small region (10–50 $\mu$m) of the membrane and it ruptures the membrane due to high electric field.

3. In case of some diabetic patients, abnormal blood vessels spread across the surface of retina. These are very fragile and release blood into clear liquid (called aqueous humour) of the eye. This process causes gradual dimming of eyesight. Laser photocoagulation is used to destroy areas of new blood vessels and thus preventing the disease.

4. Laser angioplasty is used in clearing the blocked arteries. An argon laser beam delivers energy to the blockage through fiber optic catheter and a disposable balloon. The inflated balloon and laser pulses assist each other in clearing the path through blockage. This technique opens even totally blocked arteries.

5. Lasers are also used to destroy kidney stones and gallstones. In this technique a narrow optical fiber is threaded through the kidney so as to face the stone. Laser pulses are now passed through fiber, which fall on stone and shatters it into small pieces/powder, that can pass through uterer without pain.

6. Laser welding of human blood vessels is more advantages than conventional suturing. Argon laser with 1 mm spot size is used for this purpose.

**(c) Other Important applications of Lasers**

1. Helium Neon Laser is used is interferometry. Laser printing, bar code reading and as pointing and directional reference beams. The 1.15 $\mu$m laser emission of He–Ne laser can be used for measurements of optical fibre transmission line, which have a minimum loss in that wavelength region.

2. Argon and Krypton Lasers are used for phtotheraphy of the eye, for pumping in dye lasers, laser printers, stereolithography etc.

3. $CO_2$ laser is used in the general field of material processing like cutting, drilling, material removal, etching, melting, welding, alloying, annealing, hardening etc.

4. Dye Lasers are used in in study of atomic physics and in photochemistry and in emission and absorption spectroscopy of solids.

5. Ruby laser finds applications in holography. These are also used in studying plasma properties like electron denstiy and temperature. These are also used to remove tatoos and also skin lesions resulting from excess melanin.

6. Nd-YAG Laser is used for drilling, spot welding, laser marking, resistor trimming, circuit mask, memory repair. These are widely used in medical applications like surgery like gall bladder surgery, membrane cutting. These lasers are also used in military applications such as range finding and target designation.

7. Semiconductor Lasers find use in long distance communication using optical fibres. These are also used in compact disc players. The semiconductor laser is the needle or probe, that reads the information from the compact disc. In addition these lasers are ued in high speed printing, free space communication and as a pump source for other solid state lasers.

## (16) HOLOGRAPHY (QUANTITATIVE IDEA)

An ordinary photograph can only record two dimensional view of a three dimensional object. It is because of the fact that photographic emulsion can store only the intensity of the radiations falling on it and cannot record phase of light waves.

"A Hologram is a recording medium, which can store in it three dimensional view of an object in the form of an interference pattern."

The first process in making a hologram is recording. In the recording process, the recording medium is exposed to two different light beams one of which is incident directly from light source on recording medium & is called reference beam, while other falls on recording medium after reflection (in fact scattering) from the object. This beam is called object beam.

Let $$y_1 = A_1 e^{i\phi_1} \qquad ...(28)$$

be a plane wave incident on recording medium directly from source of light *i.e.* $y_1$ represents reference beam. Here $A_1$ is amplitude and $\phi_1$ is phase of the light wave of reference beam.

Let object beam falling on recording medium has amplitude $A_2$ and phase $\phi_2$, then it can be represented as

$$y_2 = A_2 e^{i\phi_2} \qquad ...(29)$$

These two beams will interfere in the recording medium and net displacement of electric field at any point is given by principle of superposition as

$$y = y_1 + y_2 = A_1 e^{i\phi_1} + A_2 e^{i\phi_2} \qquad ...(30)$$

Let I is intensity at point of super position. We know that intensity is proportional to square of amplitude. Further from (28) it is clear that $A_1^2 = y_1 y_1^*$, where $y_1{}^*$ is complex conjugate of $y_1$. Thus I is also given as

$$I \propto yy^*$$

or $$I = k_1 yy^* \text{ (where } k_1 \text{ is constant of proportionality)}$$

$\Rightarrow$ $$I = k_1 (A_1 e^{i\phi_1} + A_2 e^{i\phi_2})(A_1 e^{-i\phi_1} + A_2 e^{-i\phi_2})$$

$$= k_1 (A_1^2 + A_2^2) + k_1 A_1 A_2 \left[e^{i(\phi_1 - \phi_2)} + e^{i(\phi_2 - \phi_1)}\right] \qquad ...(31)$$

It is clear from equation (31) that resultant intensity I changes according to phase relation $\phi_1 - \phi_2$ between the two beams. Hence we have indirectly stored information of phase of light wave from object in terms of intensity. This record of interference pattern is thus Hologram of the object.

The next step in Holography is to reproduce three dimensional image of the object from a recorded Hologram. This process is called Reconstruction. In this process the hologram is firstly developed to form a transparency. This transparency has different values of transmission coefficient at different points, depending on the net intensity of light that was obtained at corresponding point on the Hologram during recording process.

Let $t$ is transmittance of transparency obtained. Then it is found that $t$ is directly proportional to net intensity I on the Hologram during recording process.

*i.e.* $$t \propto I$$

or $$t = k_2 I \qquad ....(32) \text{ (Where } k_2 \text{ is constant of proportionality)}$$

Now this transparency is illuminated by the reference beam $y_1$ which is similar to that used during the recording of Hologram.

Let $y_0$ is the output wave obtained from transparency, then by definition the transmittance of the transparency is given as

$$t = \frac{\text{Output wave}}{\text{Input wave}} = \frac{y_0}{y_1}$$

or
$$y_0 = ty_1$$
$$= k_2 I y_1 \qquad \text{(Using 32)}$$
$$= k_1k_2 (A_1^2 + A_2^2) A_1 e^{i\phi_1} + k_1k_2A_1^2 A_2 e^{i(2\phi_1 - \phi_2)} + k_1k_2 A_1^2 (A_2 e^{i\phi_2}) \qquad ...(33)$$

Using (28) & (31)

From (33) we see that output beam consist of three different kinds of waves. The first term represents the reference beam itself having modulated amplitude $k_1k_2 (A_1^2 + A_2^2) A_1$. The second term is a complex wave and it forms a real image of the object. This image can be formed on the screen and can be photographed by placing a photographic film at the position where real image is formed. The third term is nothing but reproduction of object wave itself ($A_2 e^{i\phi_2}$) but having different amplitude. This wave is the three dimensional virtual image of the object and will be identical to what we shall see if direct object is placed in front of us.

## Qualitative Discussion

The schematic diagram for recording a Hologram is shown in figure (29). A laser beam is splitted into two parts using a plane mirror called beam splitter. One part of splitted beam strikes directly on the photographic plate and is called reference beam. While other part of splitted beam strikes on photographic film after suffering reflection (scattering) from various points of object and is called object beam. The two beams interfere and a hologram is recorded in the form of interference pattern.

The schematic diagram for reconstruction process is shown in figure (30). The developed hologram (transparency) is irradiated by same reference beam as was used during the recording process. The transparency acts as a diffraction grating and secondary waves from the hologram interfere constructively in certain directions and destructively in other directions. They form a real image in front of the transparency and virtual image behind the transparency at the original site of the object. An observer sees light waves diverging from the virtual image. The image is identical to what we shall see if object it self is seen at the place of virtual image. If the observer moves round this virtual image then new details of the object, which were not noticed earlier would be observed.

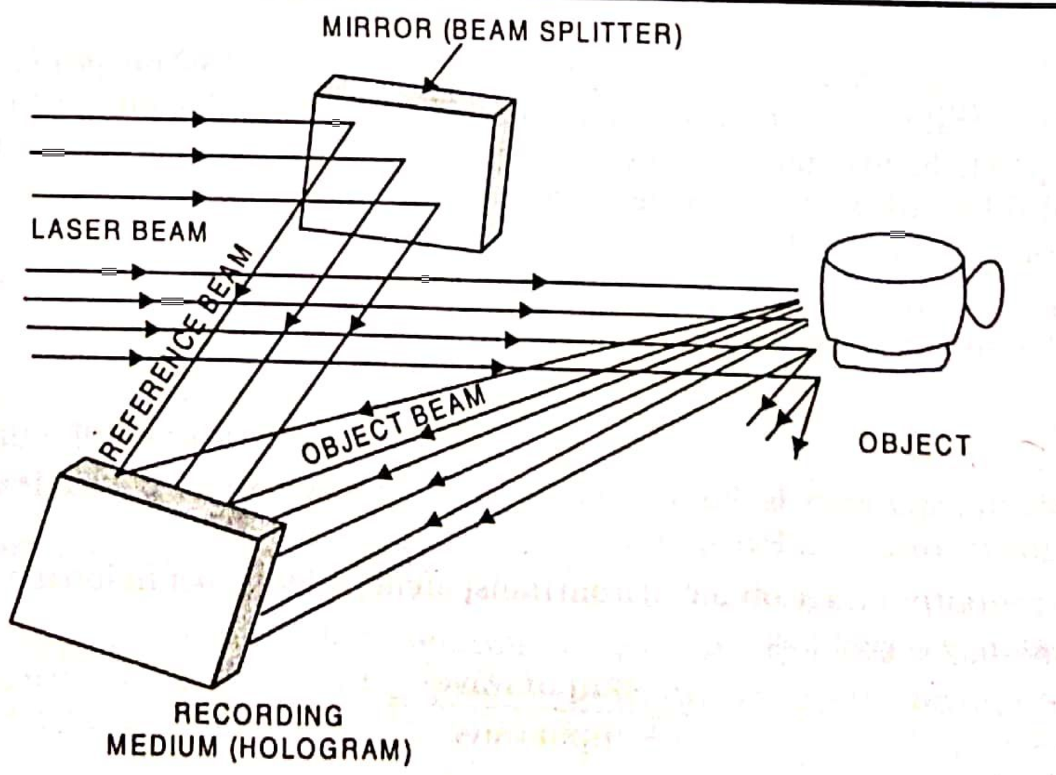



**Fig. 29**

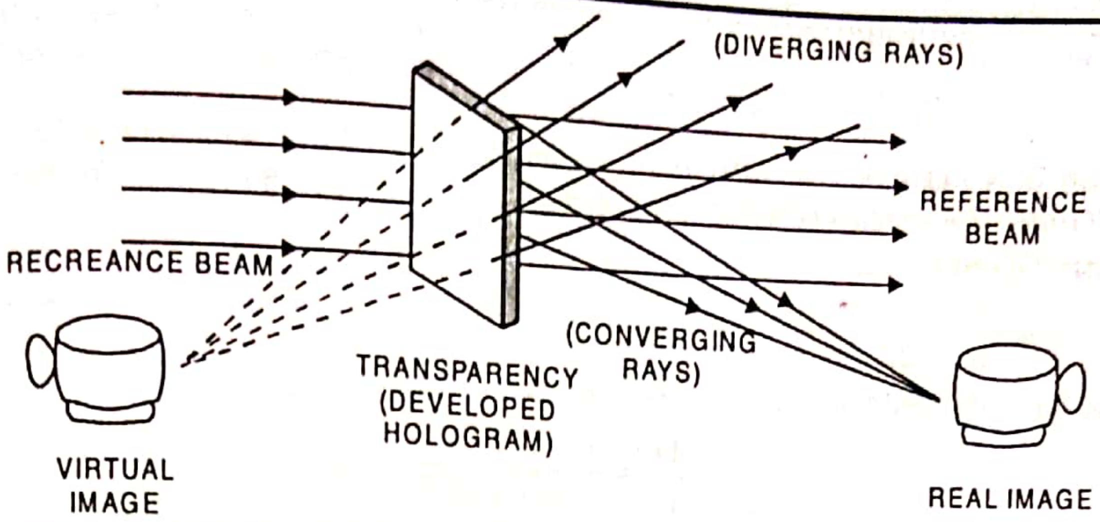



**Fig. 30**

## (17) APPLICATIONS OF HOLOGRAPHY

1. Holography is used in high capacity image storage and re-examination.

2. It is used in microscopic examination of certain kinds of specimens. If one desires to make a prolonged examination of a small specimen suspended in a medium, it is necessary to focus the microscope a number of times due to change in the position of specimen. This difficulty can be overcome by taking a short exposure hologram of the specimen. The reconstructed holographic image can be examined continuously by focusing the microscope.

3. Another important application of Holography is Holographic interferometry. This technique is used to study the distribution of strain produced in an object, when it is subjected to stress.

4. Sound waves can be easily produced as coherent beam and they can travel readily in solids. Thus we can construct three dimensional accoustical Hologram of an opaque object using sound waves. The study of accoustical hologram can give information about internal structure of object. This technique is called Accoustical Holography.

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**Example 1.** *Calculate the ratio of transition rates of spontaneous emission to the stimulated emission for light of wavelength $10^{-6}$ m and cavity temperature T = 100 K and hence determine which type of transmission will dominate?*

**Solution.** $T = 100\text{ K}$

$\lambda = 10^{-6}\text{m}$

We have
$$\frac{R_{sp}}{R_{st}} = e^{h\nu/kT} - 1 = \exp\left(\frac{hC}{\lambda kT}\right) - 1$$

$$= \exp\left(\frac{6.63\times10^{-34}\times3\times10^{8}}{10^{-6}\times1.38\times10^{-23}\times100}\right) - 1$$

$$= \exp(144.1) - 1 = 5\times10^{42}$$

Thus $\frac{R_{sp}}{R_{st}} >> 1$

Hence spontaneous emission will dominate over stimulated emission.

**Example 2.** *Calculate temporal coherence length of a mercury vapour lamp emitting in the green portion of spectrum at a wavelength of 546.1 nm with emission band width of $\Delta\nu = 6\times10^{8}$ Hz.*

**Solution.** The temporal coherence length is given by

$$l_C = C\tau_C = \frac{C}{\Delta\nu} = \frac{3\times10^8}{6\times10^8} = 0.50\ m$$

**Example 3.** *A laser beam consists of wavelength of 10 nm. The size of laser source is 100 μm. Calculate the spatial coherence length at a distance of 0.5 m from the source.*

**Solution.** Given D = 0.5 $m$

$\lambda = 10\ nm = 10 \times 10^{-9}\ m$

$d = 100\ \mu m = 100 \times 10^{-6}\ m$

The spatial coherence length is given by

$$l_s = \frac{\lambda D}{d} = \frac{10\times10^{-9}\times0.5}{100\times10^{-6}} = 5\times10^{-5} m$$

**Example 4.** *Determine what emission frequency width would be required to have a temporal cohereuce length of 10m at a source wavelength 488 nm.*

**Solution.**
$$l_C = \frac{\lambda^2}{\Delta\lambda}$$

$$\Delta\lambda = \frac{\lambda^2}{l_C} = \frac{(488\times10^{-9})}{10} = 2.38\times10^{-14}\ m$$

This gives wavelength spread around 488 $nm$

Frequency width is given by $\Delta\nu = \frac{C}{l_C} = \frac{3\times10^8}{10} = 3\times10^7$ Hz.

**Example 5.** *Find the intensity of a laser beam of 5 mW power having laser beam diameter as 1 cm.*

**Solution.**
$$\text{Intensity} = \frac{\text{Energy}}{\text{.time}\times\text{area}}$$

$$= \frac{\text{Power}}{\text{area}} = \frac{P}{\pi D^2/4} = \frac{4\times5\times10^{-3}\ W}{\pi\times(1\times10^{-2} m)^2} = 63.7\ W/m^2.$$

**Example 6.** *A laser beam has power of 5 mW. The size of mirror of optical resonator is 2 mm. If laser emission takes place at 6328 Å and laser beam is focused using a lens of focal length 1.5 m, calculate area spread and intensity of image.*

**Solution.** $\lambda$ = 6328 Å = 6.238 × $10^{-7}$ $m$, $d = 2\times10^{-3} m$, $f = 1.5\ m$

$$\theta = \text{Angular spread} = \frac{1.22\lambda}{d} = \frac{1.22\times6.328\times10^{-7}}{2\times10^{-3}} = 3.86\times10^{-4}\ \text{radian}$$

$$\text{Areal spread} = (\theta\times f)^2 = (3.86\times10^{-4}\times1.5)^2 = 3.35\times10^{-7}\ m^2$$

$$\text{Intensity} = \frac{\text{Power}}{\text{Area}} = \frac{5\times10^{-3}\ W}{3.35\times10^{-7}} = 1.49\times10^4\ Wm^{-2}.$$

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**Exercise 1.** When a laser diode has 2V applied to it, it draws 10 $m$A and produces 2$m$W of optical power. What is the efficiency of Lasser?

[Ans. 10%]

**Exercise 2.** For a semi conductor laser, compute the fraction of injected charges, which will produce photons, if 2$m$W optical power is radiated with a drive current of 200 $m$A at 1.3$\mu m$.

[Ans. 0.0104]

**Exercise 3.** A laser emits light of wavelength 7000Å. The diameter of aperture is 1 cm. Laser light is sent to moon whose distance from earth is $4 \times 10^8$ *m*. Calculate (*a*) angular spread of beam (*b*) Linear spread (*c*) Areal spread as it reaches the moon.

[Ans. (*a*) $8.54 \times 10^{-5}$ rad (*b*) $3.42 \times 10^4$ *m* (*c*) $11.7 \times 10^8$ $m^2$]

**Exercise 4.** A laser emits light of wavelength 6000Å at 9*m*W. The diameter of partially reflecting mirror of resonator is 2mm. If it is focussed by a lens of focal length 5 cm, calculate the area and intensity of image formed. [Ans. (*a*) $3.34 \times 10^{-10}$ $m^2$ (*b*) $2.69 \times 10^7$ W/$m^2$]

## SHORT ANSWER TYPE QUESTIONS

**Q. 1. Why laser is needed in holography ?**

**Ans.** We know that hologram records interference pattern. For recording sustained interference, the path difference between various interfering light waves should always be less than longitudinal coherence length. For ordinary light source like mercury discharge lamp the coherence length is very small ($\approx$ 3 cm). The path difference introduced between light waves reflected from different points of object can be much more than this value. Hence interference pattern cannot be recorded. While coherence length for laser source can be as high as 600 km. As a result, sustained interference pattern will be recorded on hologram. Thus hologram cannot be made without laser source.

Further if a hologram is reconstructed using ordinary light, then the reference beam, converging rays (forming real image) and diverging rays (forming virtual image), all will be in same direction. This creates a problem in observing three dimensional image, as we have to see through other two beams. Holography using ordinary light is called 'Inline Holography'. If Laser source is used instead, then the three emerging beams will be in different directions. This is called 'Off Line Holography'. It allows us to observe one kind of beam at a time.

**Q. 2. Why population inversion is essential for stimulated emission ?**

**Ans.** Because the rate of stimulated emission can be more than rate of stimulated absorption, only by achieving population inversion.

**Q. 3. What do you mean by life time of an energy state ?**

**Ans.** Life time of an energy state is defined as the time in which number of atoms in that state become $\frac{1}{e}$ times the initial number of atoms in that state. It is measure of time for which an atom remains in that state.

**Q. 4. Why optical pumping cannot be used for gas lasers ?**

**Ans.** It is because of the fact that there are no energy bands in gases. Since optical flash lamp highly intense pulses of polychromatic light, so only those radiations will be absorbed by gas molecules, whose energy is exactly equal to difference in energies of ground and excited state. Hence optical pumping cannot be used for gas lasers.

**Q. 5. In LASER, in place of 'A', it should be 'O'. Why ?**

**Ans.** In the laser, when stimulated beam of photons strikes the partially reflecting mirror, then a part of it is reflected back into the active medium. This reflected part produces another stimulated beam of photons which oscillates between two mirrors & at reflection, it is also partially transmitted and partially reflected back into active medium. This process continues. This is nothing but a positive feed back of optical power from output to input. This condition of positive feed back is a characteristic property of oscillators (also called signal generators). On the other hand in Amplifiers it is always either no feed back or negative feed back, that is employed. Thus stimulated emission is basically oscillation process than Amplification. Hence in place of 'A', there must be 'O' in the word LASER.

**Q. 6. What is the difference between an ordinary image taken by a photograph and a hologram ?**

**Ans.** An ordinary photographic image represents a two dimensional recording of a three dimensional object. It contains information about only the intensity distribution of the object wave.

If ordinary image is viewed at different angles then the character of image does not change. However a hologram records the interference pattern of the object wave with a reference beam. We can focus at different distances on a hologram, which gives us 3-dimensional sense of holographic image. Further one point on photograph contains information of one point of about only. But each part of hologram contains complete information of object

**Q. 7. Why Helium is mixed with Neon in He-Ne laser.**

**Ans.** The states $E'_2$ & $E'_3$ (See Fig. (18)) of He match almost exactly with states $E_4$ & $E_6$ of the Ne atoms. However the basic difference is that state $E_2'$ & $E_3'$ of He are metastable states and have large life time as compared to life time of states $E_4$ & $E_6$ of Ne. Due to this He atom will spend relatively long time before de-exciting to ground level spontaneously. Thus we can excite a large number of He atoms. These excited He atoms strike with a number of Ne atoms, and thus very large Ne atoms are pumped simultaneously, leading to population inversion. If alone Ne atoms are used then we will find it difficult to excite a large number of atoms at a given time due to small life of states $E_4$ & $E_6$.

**Q. 8. What is the cause of divergence of a Laser beam ?**

**Ans.** The partially transparent mirror of optical resonator acts as an aperture to the light beam. Because of small size of aperture, light waves suffer diffraction. As a result the laser beam shows divergence.

**Q. 9. No source of light including LASER, can be exactly monochromatic why ?**

**Ans.** A light beam will be monochromatic if the wavetrains produced by it have infinitely long length and constant amplitude. But $l_C = C\tau_C$. Now $l_C$ can be $\infty$ only if $t_C = \infty$ *i.e.* the atom takes $\infty$ time to de-excite from upper lasing level to lower lasing level. This infact means the atom is not de-exciting at all. Hence we can never have exactly monochromatic light source.

**Q. 10. Can sun be used as a coherent source of light by using a filter of a single wavelength?**

**Ans.** Yes, because it is not the size of source, which defines spatial coherence, but it is the angle that source would subtend at the slits. Let us say that we can filter sun light using a monochromatic filter for wavelength 5500 Å. The angle subtended by sun on earth is roughly $\theta \approx 32' = 0.01$ rad. The lateral coherence of sun is given as

$$l_W = \frac{\lambda}{\theta} = \frac{5 \times 10^{-5}}{0.01} = 0.005 \text{ cm}$$

Thus if the two slits in Young's double slit are separated by distance less than 0.005 cm, then even sun will behave as coherent source of light. However only disadvantage of using sun as light source will be the small intensity.

**Q. 11. Why the optical flash lamp tube and laser medium rod are placed in a reflector having elliptical shape ?**

**Ans.** It is because of the fect that if a ray of light is produced from one focus of an ellipse, it will always pass through the second focus, after suffering reflection from the elliptical circumference.

**Q. 12. X-rays also have wavelength ≈ 1Å, then why cannot we use optical microscope using *X-rays* to increase magnification.**

**Ans.** X-rays are having small wavelength. However they possess high penetrating power and cannot be focused using optical lenses. Thus these cannot be used for optical microscope.

**Q. 13. What is the advantage of using laser in cutting, drilling and welding processes?**

**Ans.** (*i*) There is no physical contact between tool and material. Hence damage to material and wear and tear of tool is avoided.

(*ii*) Even the hardest materials can be drilled and precision rate is very high.

(*iii*) Laser light can be used to drill those parts, which are not directly accessible.

(*iv*) Heat is produced only in a small region near the place of drilling or cutting. This decreases damage to edge due to excessive heating. Hence there is no need of subsequent finishing operation.

(*v*) With laser, dissimilar metals can be easily welded and process can be precisely controlled.

(*vi*) In case of computer controlled systems, laser can be easily used.

**Q. 14. What is advantages of using lasers in surgery?**

**Ans.** There is no direct contact between tool and organ. The surgery is almost bloodless. Laser spot can be focussed to very small size. Patient feels minimum pain during surgery and he can be discharged from hospital in a few hours.

**Q. 15. What do you mean by reflection and transmission hologram?**

**Ans.** If the recording material is arranged so that reference beam as well as object beam approach it from the same side, then hologram formed is called Transmission Hologram. The interference fringes are generally perpendicular to the surfaces of the recording material. When such a hologram is reconstructed, then reference and object beam lie on opposite sides of the hologram.

If recording material is placed such that reference beam and object beam approach it from two opposite sides, then hologram formed is called Reflection Type hologram. The interference fringes are usually parallel to the surfaces of recording medium. When such a hologram reconstructed, then reference beam and object beam lie on the same side of hologram.

**Q. 16. Why semi conductor laser is preferred for communication through optical fibres?**

**Ans.** Through optical fibres we pass modulated light waves, which carry information from one place to other. In a semi conductor laser the light output changes due to change in electric current passed through diode as in this laser, electric energy is being directly converted into optical energy. Hence optical modulation is much easier and straight forward in case of semi conductor laser. We can achieve it by changing bias current in accordance with signal. Due to this semi conductor laser is most suited for optical communication. Other reasons include low operating power, small size and small cost.

**Q. 17. What is Q-switching?**

**Ans.** The process of obtaining intense and short light pulses from laser by making very large number of active centres de-excite simultaneously is called Q-switching. In this technique Q factor of laser is decreased for some time by slightly tilting the mirrors of optical resonator. With this losses in laser increase and lasing action is prohibited even when appreciable population inversion is obtained. As a result population in UL grows up significantly. Suddenly mirrors are made parallel again. Due to this Q-factor increases and very large no. of atoms undergo lasing action simultaneously, thereby producing highly intense light pulse.

**Q. 18. What is concentric and confocal Resonator?**

**Ans.** In case of concentric resonator, there are two concave mirrors of equal radius of curvature R placed co-axially such that their centre of curvature lie at same point *i.e.* separation between two mirrors is 2R.

In case of confocal Resonator, the two concave mirrors are placed co-axially in such a way that their focus lie at same point. In this case, separation between mirrors is R.

**Q. 19. How white light reflection holograms are constructed?**

**Ans.** White light reflection holograms are also called 'Rainbow Holograms'. In this kind of holography, the object is exposed to three primary colours and their diffraction patterns are recorded in the same manner as conventional technique. This Hologram can be reconstructed using sun light. The three dimensional coloured image will be seen through light reflected from hologram. Only these colours will be reflected, which were used in the recording process and these colours will be reflected in different directions. Thus as observer changes the angle of observation, the colour of object appears to change.

## QUESTIONS

1. What is the importance of coherence in laser ?
2. What is active medium, population inversion and optical pumping ? Give their importance in study of lasers ?
3. Describe holography. What is needed for holography ?
4. What do you mean by spontaneous & stimulated emission ?
5. What do you understand by holography ? Derive the relation between Einstein's coefficients.
6. Explain the terms (*a*) Life time of an energy state (*b*) Metastable states (*c*) Optical pumping (*d*) Population inversion.
7. Explain the production of Lasers by Ruby Crystal.
8. Differentiate between a three level and four level laser system. Give the construction and working of $CO_2$ Laser. Where $CO_2$ lasers are used ?
9. What is Holography ?
10. What are important characteristics of LASER Light ?
11. Explain spontaneous emission in Laser.
12. What is Holography ? Mention its applications.
13. Describe Laser action in $CO_2$ laser with suitable energy level diagrams.
14. In LASER, in place of A, it should be 'O'. Why ?
15. Explain spontaneous and stimulated emission of radiation. Describe principle, construction & working of a three level Ruby Laser.
16. Discuss the construction & working of a Ruby Laser.
17. Explain briefly, why four level laser is better than a three level laser ?
18. Explain with suitable diagrams, the difference between spontaneous & stimulated emission. How will you achieve higher probability of stimulated emission ?
19. Describe the construction & working of a He–Ne laser.
20. Describe the construction & working of Nd–YAG laser. Write its important applications.