Lasers

Introduction:

Laser:

- Laser is one of the outstanding inventions of the 20th century.
- A laser is a ***photonic device*** that emits light(electromagnetic radiation)through a process o optical amplification based on the ***Stimulated Emission of Radiation.***
- The term "laser" originated as an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.
- In 1960 An American Scientist T.H .Maiman was first invented solid state laser (Ruby LASER) .
- In 1961 ,A.Javan and associates developed the first gas laser (He-Ne gas LASER).Further many lasers was invented based on their applications.
- In now a days, laser is a important tool in a wide variety of fields such as optical communication systems, metal working , entertaintment, surgery and weapon guidance in wars.

Characteristics of Lasers:

Laser has certain unique properties when compared to ordinary sources of light. They are

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

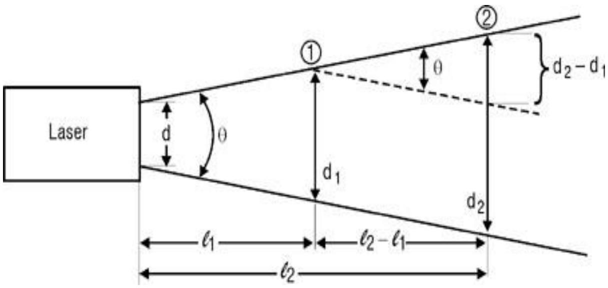
1. Monochromaticity:

- Monochromatic light means a light containing a single color or wavelength. The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors. Hence, ordinary light sources emit polychromatic light.
- On the other hand, the photons emitted from laser light sources have same energies, frequencies, wavelengths, or colors. Hence, laser emits a single wavelength or color light.

2. Directionality:

- Directional means that the beam is well collimated (very parallel) and travels over long distances with very little spread.

- In conventional light sources (lamp, sodium lamp and torchlight), photons will travel in random direction. Therefore, these light sources emit light in all directions and is highly divergent.
- On the other hand, in laser, all photons will travel in same direction. Therefore, laser emits light only in one direction. This is called directionality of laser light.
- The width of a laser beam is extremely narrow. Hence, a laser beam can travel to long distances without spreading.
- If an ordinary light travels a distance of 2 km, it spreads to about 2 km in diameter.
- On the other hand, if a laser light travels a distance of 2 km, it spreads to a diameter less than 2 cm.
- Therefore, the divergence or angular spread of a laser is very small and high directional.



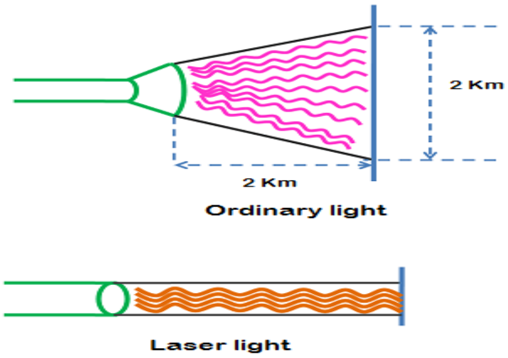


Fig: Measurement of beam divergence.

The angular spread or divergence (θ) = $\frac{d_2-d_1}{l_2-l_1}$degrees

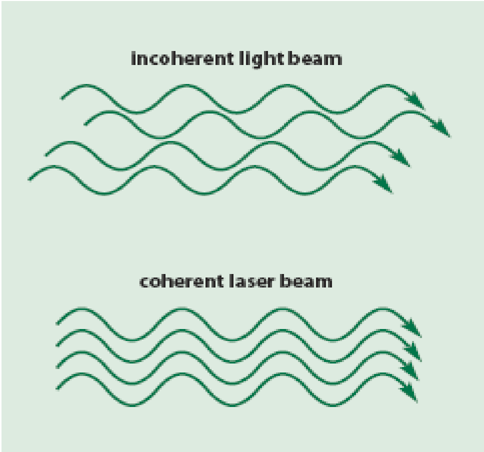
Where: d_1 = Beam diameter at point 1.
d_2 = Beam diameter at point 2.
l_1 = Distance from laser to point 1.
l_2 = Distance from laser to point 2.

3. Intensity:

- The intensity of a light is defined as the energy or light per unit time flowing through a unit normal area.
- In an ordinary light spreads in all directions; the intensity reaching the target is very less. But in the case of laser, due to high directionality many beams of light incident in small area, therefore the intensity of light high.

4. Coherence:

- The photons emitted from ordinary light sources have different energies, frequencies, wavelengths, or colors and are out of phase. Therefore, ordinary light sources produce incoherent light.
- The photons emitted from laser light sources have same energies, frequencies, wavelengths, or colors and are in phase. Therefore, a laser light source produces coherent light. To produce coherent light in a laser, a new technique used called stimulated emission of radiation.



<u>Interaction of radiation with matter:</u>
<u>Introduction</u>:
When the incident radiation (Photon) interacts with atoms in the energy levels then three three distinct processes can takes place.

- Absorption of radiation
- Spontaneous emission of radiation
- Stimulated emission of radiation

1. **<u>Absorption of radiation</u>:**
Suppose If an atom in the lower energy level (or) ground state energy level E_1 and absorbs the incident photon radiation of energy then it goes to the higher energy level (or) excited state E_2 as shown in fig(1). This process is called absorption of radiation.

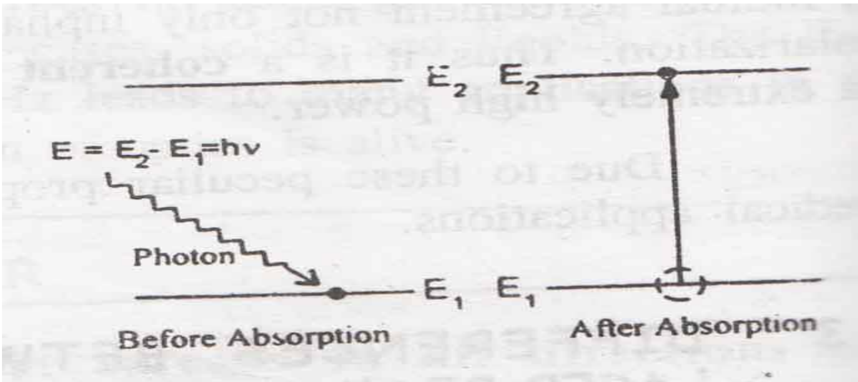


Fig: Absorption of radiation

The process may be expressed as

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

Where A=Atom in the ground state
A^*= Excited atom
$h\upsilon$ = Incident photon

- The number of absorptions depend upon the number of atoms per unit volume (N_1) in lower energy level (E_1) and the number of photons per unit volume of radiation i.e. incident radiation density ρ_υ.

The rate of absorption (R_{12}) is proportional to the following factors

i.e., $R_{12} \propto$ incident radiation density (ρ_υ)

$\propto$ No. of atoms in the ground state (N_1)

$$\therefore \boxed{R_{12} = B_{12}\,\rho_\upsilon\,N_1} \longrightarrow (1)$$

Where B_{12} is a constant and is known as Einstein's coefficient of absorption of radiation.

2.**<u>Spontaneous emission of radiation:</u>**

Normally the atom in the excited state will not stay there, for a long time i.e., it can stay up to 10^{-9} second. This called life time of atom. After the life time of the excited atom it returns to the ground state by emitting photon energy $E= E_2-E_1 = h\upsilon$, spontaneously without any external energy as shown in fig (2).

This process is known as Spontaneous emission of radiation.

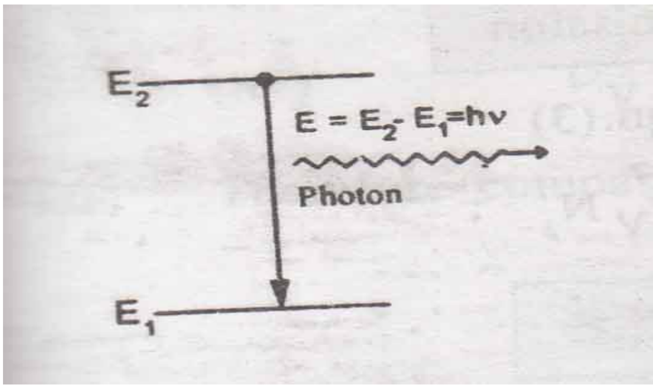


Fig: Spontaneous emission of radiation.

The process may expressed as

$$\boxed{A^* \longrightarrow A + h\upsilon}$$

Where A=Atom in the ground state

A^*= Excited atom

$h\upsilon$ = Incident photon.

The number of spontaneous emission of radiation depends on the number of atoms per unit volume in higher energy level i.e. N_2

$\therefore$The rate of spontaneous emission is $R_{21(SP)} \propto N_2$

$$\therefore \boxed{R_{21(SP)} = A_{21}N_2} \longrightarrow (2)$$

Where A_{21} is a constant called Einstein's coefficient of spontaneous emission of radiation.

3. Stimulated emission of radiation:

Suppose if we incident some suitable form of energy on the atom in the excited state, then it can also return to the ground by emitting a photon, known as stimulated emission. In this process two photons are released. They have same frequency, wavelength and in phase difference and of same directionality as shown in fig.

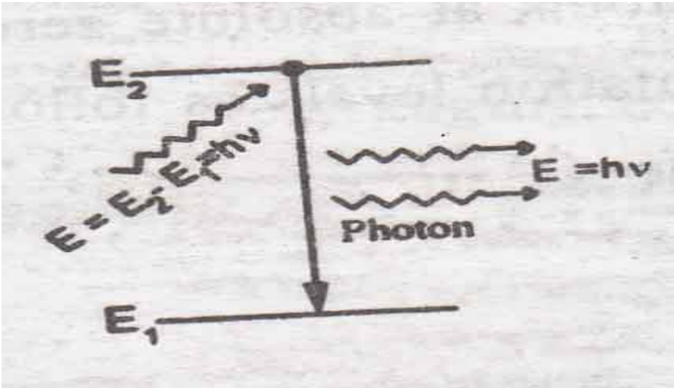


Fig: Stimulated emission of radiation.

The process may be expressed as

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

The number of stimulated emission depends on the number of atoms in the energy level (E_2) ,N_2 and the incident radiation density ρ_υ.

∴ The rate of stimulated emission R_{21} is given by

$$R_{21(St)} \propto N_2$$

$$\propto \rho_\upsilon$$

$$R_{21(St)} \propto N_2\, \rho_\upsilon$$

$$\therefore \boxed{R_{21(St)} = B_{21}\, \rho_\upsilon\, N_2} \longrightarrow (3)$$

Where B_{21} is a constant called Einstein coefficient of stimulated emission of radiation

Difference between spontaneous and stimulated emission of radiation

Spontaneous Emission of radiation	Stimulated Emission of radiation
1. This emission is postulated by Bhor	1. This emission is postulated by Einstein.
2. Emission of radiation takes place without any inducement or stimulus energy.	2. Emission of radiation takes place with help of inducement or stimulus energy.
3. The emitted photons move in all directions and are random.	3. The emitted photons move in same direction and is highly direction
4.Incoherent radiation	4.Coherent radiation
5. Low intense and less directional	5. High intense and more directional
6.Polychromatic radiation	6.Monochromatic radiation
7.It is an uncontrollable process	7.It is controllable process
8.The rate of spontaneous emission is $R_{12(SP)} = A_{21}N_2$	8. The rate of stimulated emission is $R_{21(St)} = B_{21}\ \rho_{\upsilon}\ N_2$
9. Example: Light from sodium vapor lamp and mercury vapor lamp	9. Example: Light from Ruby laser, He-Ne laser and GaAs laser etc.

Population:

The number of atoms per unit volume in an energy level is known as population of that energy level.

According to Boltzmann`s distribution law; if N is the number of atoms per unit volume in an energy state E, at temperature T , then the population of that energy level E is given by

$$\boxed{N=N_O \exp^{\frac{-E}{K_B T}}}$$

Where, N_O is the population of lower energy level and K_B is Boltzmann`s constant (1.3807 × 10− 23 J K− 1)

Einstein's coefficient's and their relations:-

In 1917 Einstein proposed a mathematical relation between absorption and emission of radiation based on Boltzmann's distribution law and Planck's theory of radiation.

Consider two energy levels of energies E_1 and E_2 ($E_2 > E_1$) .Let N_1 and N_2 be the number of atoms per unit volume of E_1 and E_2.

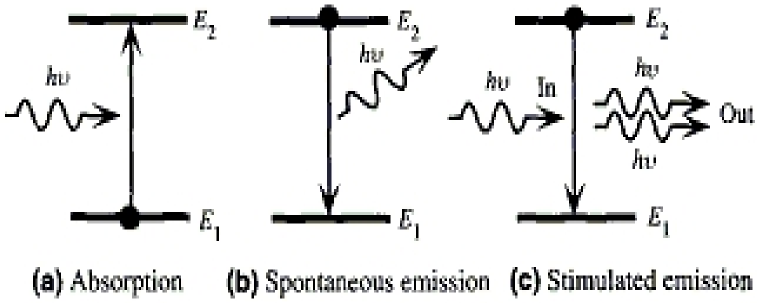


Fig: Three different processes during the interaction of light with matter.

We know that when the incident radiation (photon) interacts with atoms in the energy levels then three distinct processes takes place.

1) **Absorption :-**

   The rate of absorption (R_{12}) $= B_{12}\ \rho_\upsilon\ N_1 \quad \longrightarrow \quad (1)$

2) **Spontaneous emission :-**

   The rate of spontaneous emission is given by

   $$R_{21\,(SP)} = A_{21}N_2 \qquad \longrightarrow \quad (2)$$

3) **Stimulated Emission:-**

   The rate of stimulate emission is given by

   $$R_{21(St)} = B_{21}\ \rho_\upsilon\ N_2 \qquad \longrightarrow \quad (3)$$

Under thermal equilibrium,

The rate of absorption = The rate of emission

i.e., Eq(1) = Eq(2) +Eq(3)

$$B_{12}\ \rho_\upsilon\ N_1 = A_{21}N_2 + B_{21}\ \rho_\upsilon\ N_2$$

$$B_{12}\ \rho_\upsilon\ N_1 - B_{21}\ \rho_\upsilon\ N_2 = A_{21}N_2$$

$$\rho_\upsilon(B_{12}\ N_1 - B_{21}\ N_2) = A_{21}N_2$$

$$\rho_\upsilon = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}\ N_2}$$

$$= \frac{A_{21}N_2}{N_2(B_{12}\frac{N_1}{N_2} - B_{21})}$$

$$\rho_\upsilon = \frac{A_{21}}{B_{12}\left(\frac{N_1}{N_2}\right) - B_{21}} \rightarrow (4)$$

$$= \frac{A_{21}}{B_{12}\left[\frac{N_1}{N_2} - \frac{B_{21}}{B_{12}}\right]} \rightarrow (5)$$

We know that; Boltzmann distribution law

$$N_1 = N_0 \exp\frac{-E_1}{K_{BT}} \rightarrow (6)$$

Similarly $N_2 = N_0 \exp\frac{-E_2}{K_{BT}}$ $\rightarrow (7)$

And $\frac{N_1}{N_2} = \exp\frac{-E_1}{K_{BT}} . \exp\frac{E_2}{K_{BT}}$

i.e., $\frac{N_1}{N_2} = \exp\frac{(E_2 - E_1)}{K_{BT}}$

Since $E_2 - E_1 = h\upsilon$, we have

$$\frac{N_1}{N_2} = \exp\frac{h\upsilon}{K_{BT}} \rightarrow (8)$$

Substituting Eq (8) in Eq (5) we have

$$\rho_\upsilon = \frac{A_{21}}{B_{21}\left[\exp\frac{h\upsilon}{K_{BT}} - \frac{B_{21}}{B_{12}}\right]} \rightarrow (9)$$

According to Planck's quantum theory of radiation, the incident radiation density is given by,

$$\rho_\upsilon = \frac{8\pi h\nu^3}{C^3}\left[\frac{1}{\exp^{\frac{h\nu}{K_{BT}}} - 1}\right] \rightarrow (10)$$

Therefore comparing equations (9) and (10), we can write

$$\boxed{\frac{B_{21}}{B_{12}} = 1 \text{ or } B_{21}=B_{12}=1 \text{ and}} \rightarrow (11)$$

$$\boxed{\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}} \rightarrow (12)$$

These results were obtained by Einstein in 1917, and that is why the coefficients A_{21} B_{21} and B_{12} are called Einstein's coefficients.
From eq. (11), we conclude that the coefficient of absorption B_{12} is equal to the coefficient of stimulated emission B_{21}.
From eq. (11), we conclude that the coefficient of spontaneous versus stimulated emission is proportional to the third power of frequency of the radiation.

i.e., $\frac{A_{21}}{B_{21}} \alpha\ \nu^3$

Thus, the spontaneous emission of radiation dominates the stimulated emission of radiation at normal conditions. This is why it is difficult to achieve laser action.
The spontaneous emission produces incoherent light, while stimulated emission produces coherent light. In an ordinary conventional light source, the spontaneous emission is dominated. For, laser action stimulated emission should be predominant over spontaneous emission and absorption. To achieve this, an artificial condition is required, known as population inversion.

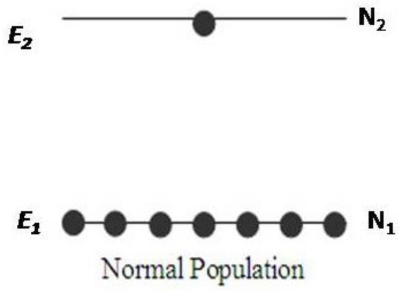
Population Inversion:

In general, the population of lower energy level will be greater than that of the higher energy level. To get stimulated emission of radiation, the population of higher energy level (E_2) should be greater than the population of the lower energy level (E_1).i.e., N_2>N_1.

The process of making a state in which the population of higher energy level (E_2) is greater than the population of the lower energy level (E_1) is known as population inversion.

Explanation:

- In general, a two energy level diagram is suitable for spontaneous emission of radiation the life time of higher energy level is in the order of 10^{-9}sec. But, to attain population inversion the life time of higher energy level must be longer. Hence population inversion cannot be attained in a two energy level diagram.
- To explain Population Inversion, let us Consider a there energy level system in which three energy levels E_1, E_2 and E_3 are present and populations in those energy levels are N_1, N_2 and N_3 respectively.
- In normal conditions E_1<E_2< E_3 and N_1> N_2 > N_3 obeying Boltzmann's distribution law.
- E_1 is the lower energy state with more time of an atom, E_3 is the higher energy state with less lifetime of an atom (10^{-9}sec) and E_2 is the intermediate energy state with more life time of an atom (10^{-3}sec) compare to that of E_3.
- This intermediate energy state with more life time of atoms is known as metastable state.
- This state provides necessary population inversion for the laser action.
- When suitable form of energy is supplied to the system, then the atoms excite from ground state E_1 to higher energy state E_3 and E_2.
- Graphically this has been as shown in fig.



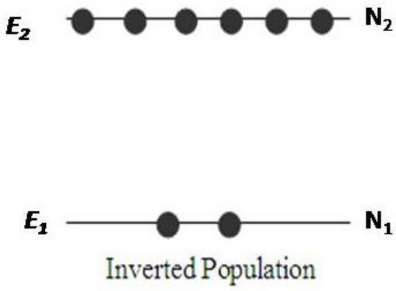
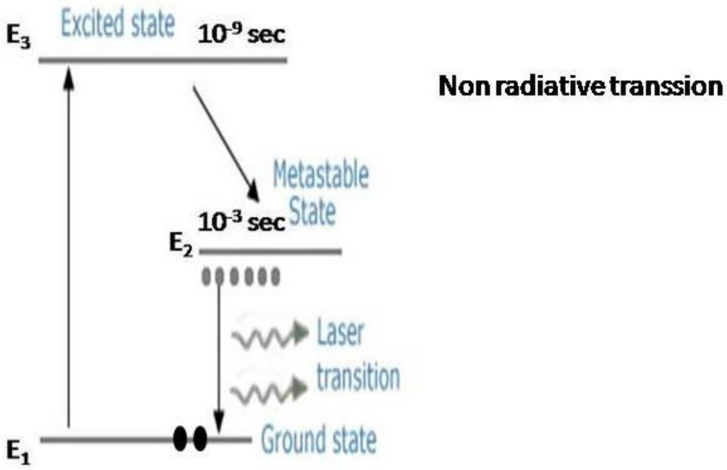


Fig: $N_1 > N_2$ **Fig: $N_2 > N_1$**



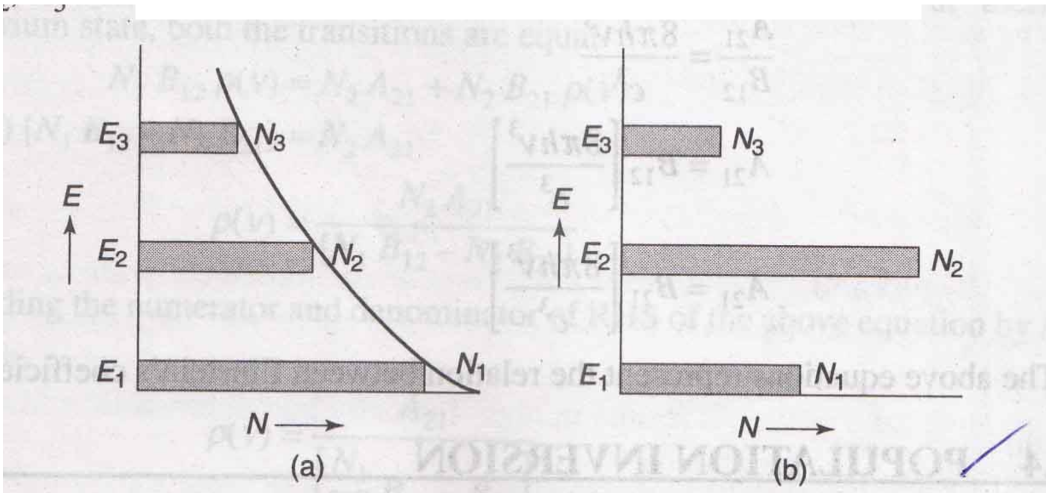


Fig: (a) Boltzmann's distribution Fig: (b) Population inversion between E_1 and E_2

- Let the atoms in the system be excited from E_1 state to E_3 state by supplying energy equal to E_3-E_1= hυ from an external source.
- The atoms in E_3 state are unstable; they can stay up to 10^{-9} s. This called life time of atoms. After the life time of the excited atoms, they can returns to the meta stable state E_2 without emission of any radiation .This process is called *non-radiative transition.*
- In E_2 state, the atoms can stay for a very long time(10^{-3}s).
- As atoms in E_1 state are continuously exciting to E_3 , so the population in E_1 energy state goes decreasing.
- A state will reach at which the population in E_2 State is greater than E_1 state (i.e.N_2>N_1). This situation is known as population inversion.

<u>Excitation mechanisms</u>:

<u>Pumping</u>:

The population inversion cannot be achieved thermally. To achieve population inversion suitable form of energy must be supplied. The process of supplying suitable form of energy to a system to achieve population inversion is called pumping. There're several methods for achieving the condition of population inversion necessary for laser action. Some of the most commonly used pumping methods are,

(i) Optical pumping method
(ii) Electrical discharge(Direct electron excitation) pumping method
(iii) Inelastic atom-atom collision pumping method
(iv) Direct conversion pumping method
(v) Chemical reactions pumping method.

<u>(i). Optical pumping method</u>:

- The process of supplying suitable form of optical energy to a system to achieve population inversion is called optical pumping.
- In this method, light source is used to supply suitable form of optical energy to excite the atoms to higher energy level to achieve population inversion.
- This type of pumping is used in solid state lasers (Ex: Ruby laser and Nd-YAG Laser).

<u>(ii). Electrical discharge (Direct electron excitation) pumping method:</u>

- In this method, a high voltage or electric field is applying to electrodes at both sides of the discharge tube containing the gas causes Electrons are ejected from the cathode, accelerated toward the anode, and collide with the gas molecules along the way.
- During the collision, the mechanical kinetic energy of the electrons is transferred to the gas molecules, and excites them. (This same method of energy transfer is used in common fluorescent lights).
- This type of pumping is used in gaseous ion lasers (Ex: He-Ne laser and co_2 Laser).

(iii). Inelastic atom-atom collision pumping method

- In this method a combination of two types of gases are used say A and B, both having same or nearly coinciding excited states A* and B* .
- In the first step ,during electric discharge , A gets excited to A* (meta stable state) due to collision with electrons .The excited atom now collide with the B atoms so that B goes to excited state B* .

$$e^- + A \longrightarrow A^*$$
$$A^* + B \longrightarrow B^* + A$$

- For example, in the helium-neon laser the electrons from the discharge collide with the helium atoms, exciting them. The excited helium atoms then collide with neon atoms, transferring energy so that Ne atoms go the excited state.

(iv).Direct conversion pumping method

- In this method, when a p-n junction diode is forward biased and then the recombination of electrons and holes across the junction emits the radiation.

$$\boxed{\text{Electron + hole} \longrightarrow \text{photon}}$$

- This method is used in semiconductor lasers.

(v).Chemical reactions pumping method

- In this method, due to some chemical reactions, the atoms may be raised to excited state.
- For example, hydrogen fluoride chemical laser, in which hydrogen can react with fluorine to produce hydrogen fluoride liberating heat energy. This heat energy will try to excite the atoms to higher energy level.

$$H_2 + F_2 \longrightarrow 2HF + \text{Heat energy}$$

Block diagram of a laser system:

The block diagram of laser system contains three parts, they are

(i) Source of energy
(ii) Active medium and
(iii) Optical resonator .

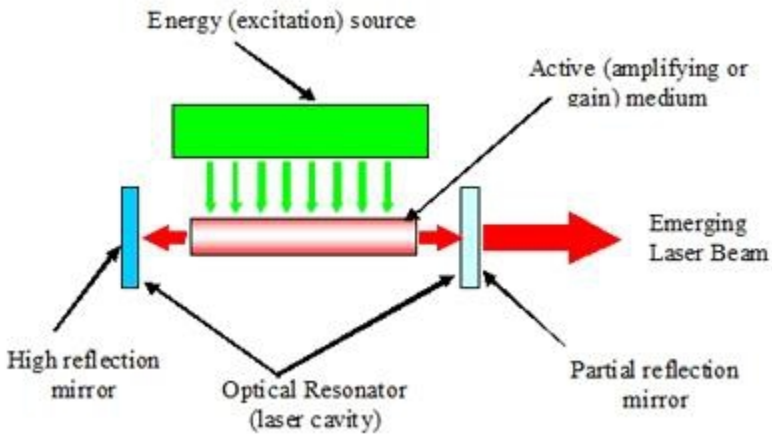


Fig: Components of LASER system.

(i) <u>Source of energy:</u>

- To achieve population inversion suitable form of energy must be supplied. It supplies suitable form of energy by using any one of the pumping methods.
- For example in ruby laser, helical xenon flash tube used as pumping source.
- In helium-neon laser, electrical discharge tube used as pumping source.

(ii) <u>Active medium</u>:

- To achieve population inversion medium is necessary**.**
- The material medium in which population inversion takes place is called as active medium. In which metastable state is present.
- In metastable state only the population inversion takes place. It can be a solid, liquid, gas or semiconductor diode junction.
- The material medium in which the atoms are raised to exited state to achieve population inversion is called as active centers.
- For example in ruby laser, the active medium is aluminum oxide (Al_2O_3) dopedwith chromium oxide (Cr_2O_3). In which chromium ions (Cr^{3+}) act as active centers.
- In helium -neon laser it is the combination of helium and neon in the ratio of 10:1 in which Ne atoms act as active centers.

(iii)<u>Optical resonator:</u>

- An optical resonator which consists of two mirrors. One mirror is fully reflective and other is partially reflective.
- An active medium is kept between in them. The light emitted due to the stimulated emission of radiation bounces back and forth between the two mirrors and hence the intensity of the light is increased enormously.
- Finally the intense, amplified beam called laser is allowed to come out through the partial mirror as shown in fig.

Types of lasers :

Nd-YAG [Neodymium-Yttrium Aluminum Garnet] laser:-

Characteristics of laser:-

Type : Solid state laser (4-level solid state laser)

Active medium : Yttrium Aluminum Garnet [$Y_3Al_5O_{12}$]

Active centre : Nd_3^+ ions

Pumping method : Optical pumping

Pumping source : Xenon flash lamp

Optical resonator : two ends of the rod polished with silver

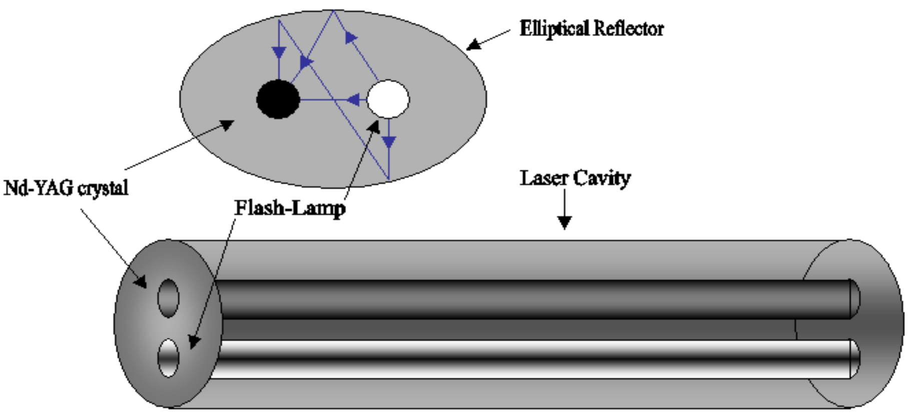
Wave length : 1.064 µm.

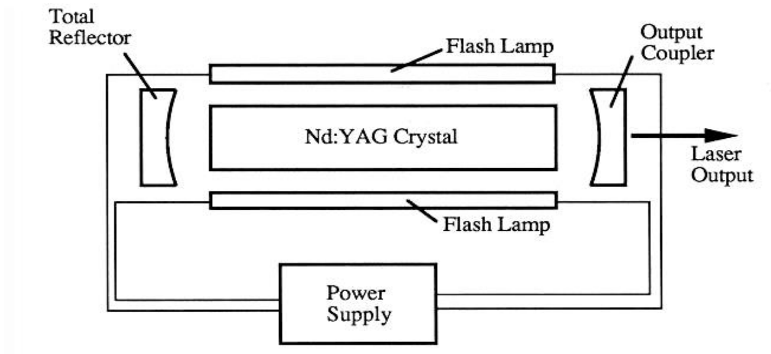
Principle:-

The neodymium ions are raised to exited states optical pumping using xenon flash lamp. Then the ions are accumulated at Meta stable state by non radiative transition. Due to stimulated emission the transition of ions takes place from Meta stable state to ground state, the laser beam of wavelength1.064 µm emitted.

Construction

- A Nd-YAG laser consists of a cylindrical Nd-YAG rod [$Y_3Al_5O_{12}$].
- In the Nd-YAG rod, Nd^{3+} ions are the active ions taking part in the laser action.
- The Nd-YAG rod will act as an active medium.
- One end of the Nd-YAG rod is fully silvered and the other end is partially silvered so that the two ends will act as optical resonator (or) cavity.
- The Nd-YAG rod surrounded by elliptical glass cavity which in turn is enclosed by xenon flash lamp filled with xenon gas s shown in fig.





Fig; Construction of Nd-YAG laser.

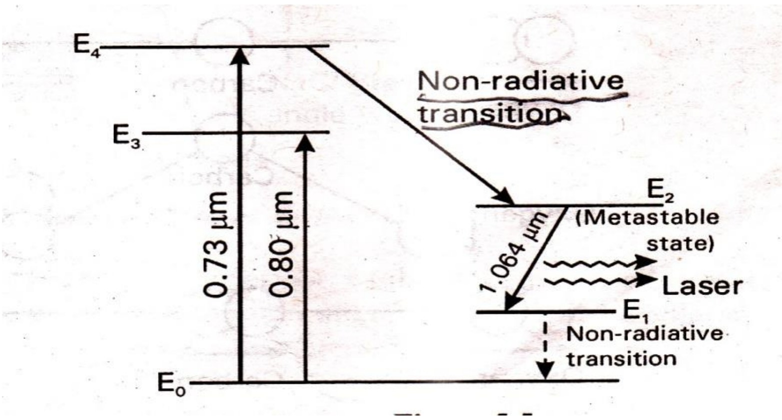


Fig: Energy level diagram of Nd-YAG laser.

Working:-

- The xenon flash lamp is switched on.
- A few thousand joules of light energy are discharged in a few milliseconds.
- A part of this light energy will be flashes on the Nd-YAG rod.
- Then the Nd^{3++} ions in the rod absorbs the particular wavelength of the incident light energy and are excited to higher energy states as shown in fig(2).
- The Nd^{3+} ions absorbs the light of photon of wavelength 0.73 µm and go to E_4 excited state and by absorbing wavelength 0.80 µm they go to E_3 excited state as shown in the energy level diagram.
- The excited Nd^{3+} ions then make a transition from these energy levels.
- The Nd^{3+} ions remain for about 10^{-9} second in these energy levels and makes non-radiative transition to the Meta stable state (E_2).
- In Meta stable state, the Nd^{3+} ions remain for longer duration of the order 10^{-3} second, so population inversion takes place between Meta stable and ground state.
- As a result, stimulated emission takes place and Nd^{3+} ions translated from Meta stable state to ground state.
- Hence, pulsed form of laser beam of wavelength 1.064 µm is emitted during transition from $E_2$to E_1.

Applications of Nd-YAG Laser

- These lasers are widely used for cutting, drilling, welding in the industrial products.
- It is used in long haul communication systems.
- It is also used in the endoscopic applications.

Helium-Neon laser:-

This laser is discovered by Ali Javan an USA Scientist.He-Ne stands for Helium-Neon. The He-Ne laser active medium consists of two gases which do not interact form a molecule. Therefore He-Ne laser is one type of atomic gas lasers.

Characteristics of laser: -

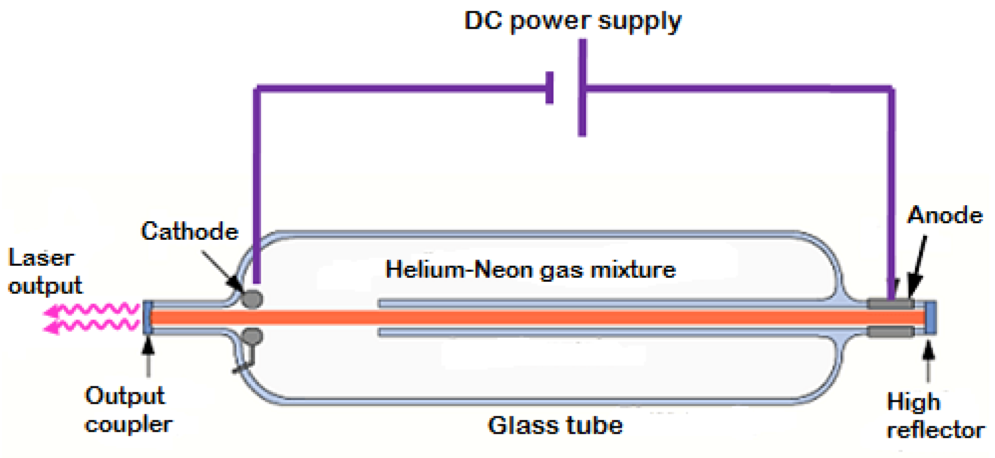
Type	: Gas laser
Active medium	: Mixture of Helium and Neon in the ratio10:1
Active centre	: Neon
Pumping method	: Electrical pumping
Optical resonator	: Pair of concave mirrors
Wavelength	: 632.8nm

Principle:-

This laser is based on principle of stimulation emission, produced in the active medium of gas. Here, the population inversion is achieved due to the interaction between two gases which have closed higher energy levels.

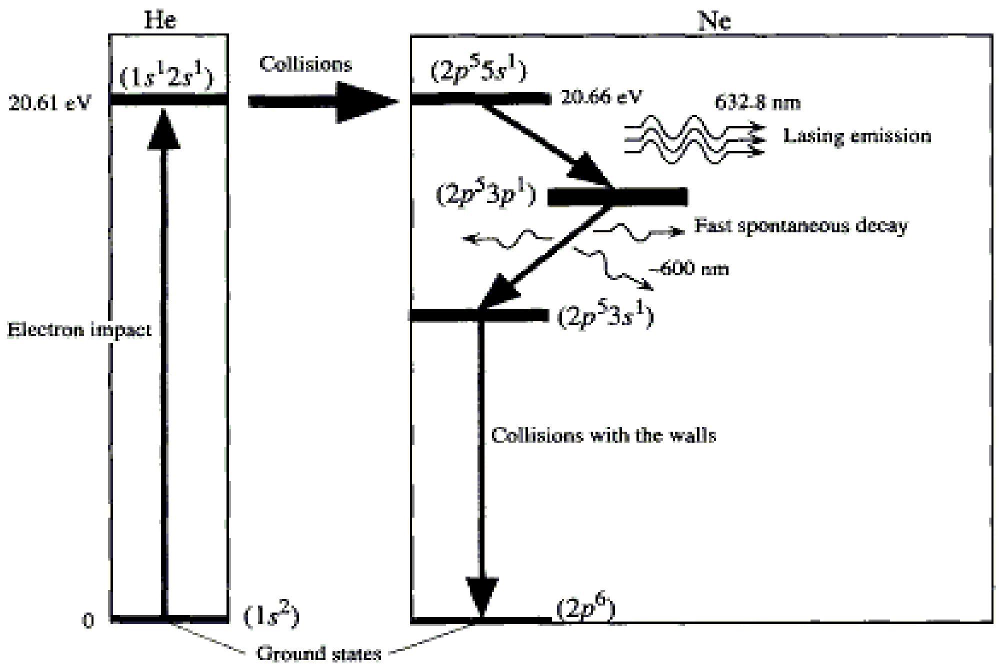
Construction: -

- It consists of a gas discharge tube, which made up of quartz and is filled with the mixture of helium under a pressure of 1mm of hg and neon under the pressure of 0.1mm of hg. The ratio of the He-Ne mixture is 10%.i.e., the number of Helium atoms is greater than the number of Ne atoms.
- The electrons at the ends of the discharge tube are connected to the radio frequency oscillator to produce electrical discharge in the He-Ne mixture as shown in fig.
- The ends faces of the discharge tube are tilted at the Brewster angle and are called as Brewster windows. It is used to produce plane polarized light by reflecting the perpendicularly polarized light .A fully reflecting and partial reflective concave mirror is placed at the left and right ends of the discharge tube respectively which acts as a resonant cavity.



Working:

- By electrical discharge in a as tube, the ground state helium atoms are excited to higher energy levels.
- The excitation occurs due to the collision of discharged electrons with helium atoms.
- The excited he atoms collide in elastically with the neon atoms which have close energy level as that of helium energy level.
- Therefore the helium atoms deliver its energy to neon atoms by the process known as resonant collision energy transfer.
- This resonant energy transfer takes place because the corresponding energy levels of Helium atoms ($2s^1$ and $2s^2$)are almost closer to the neon energy levels (2s and 3s).
- The excited states of neon are shown by energy bands.
- The first resonant energy transfer is made from $2s^1$ to 3s and stimulated emission takes place between 3s and 2p, emitting 6328A^0 wavelength of radiation.
- Stimulated emission between 3s to 3p gives 3.39μm (33912 A^0) of radiation.
- Stimulated emission between 2s to 2p gives 1.15μm (11523 A^0) of radiation.
- The transition from 1s to ground level takes place by non radiative process.
- Since the electron density in 3s and 2s levels of neon is always greater than the other levels of neon we get continuous laser output of wavelength 6328A^0 with little milli watt power.



Applications / Uses of He-Ne Laser:

The Helium-Neon gas laser is one of the most commonly used laser today because of the following applications.

- He-Ne lasers are produced in large quantities from many years.
- Many schools / colleges / universities use this type of laser in their science programs and experiments.
- He-Ne lasers also used in super market checkout counters to read bar codes and QR codes.
- The He-Ne lasers also used by newspapers for reproducing transmitted photographs.
- He-Ne lasers can be use as an alignment tool.
- It is also used in Guns for targeting.

Advantages of He-Ne Laser

- He-Ne laser has very good coherence property
- He-Ne laser can produce three wavelengths that are 1.152µm, 3.391 µm and 632.8nm, in which the 632.8nm is most common because it is visible usually in red color.
- He-Ne laser tube has very small length approximately from 10 to 100cm and best life time of 20.000 hours.
- Cost of He-Ne laser is less from most of other lasers.
- Construction of He-Ne laser is also not very complex.

Disadvantages of He-Ne Laser

The weak points of He-Ne laser are

- It is relatively low power device means its output power is low.
- He-Ne laser is low gain system/ device.
- To obtain single wavelength laser light, the other two wavelengths of laser need suppression, which is done by many techniques and devices. So it requires extra technical skill and increases the cast also.
- High voltage requirement can be considered its disadvantage.
- Escaping of gas from laser plasma tube is also its disadvantage.

GaAs semiconductor laser:-

The GaAs laser was constructed by Hall.

Characteristics:-

Type	: Semiconductor laser
Active medium	: P-N junction diode
Active centre	: Re combination of electrons and holes
Pumping method	: Direct pumping
Optical resonator	: Junction of Diodes-Polished
Wave length	: $8400A^0$ -$8600A^0$
Band gap	: 1.44 ev

Principle: - When a p-n junction is formed across a p and n-type semiconductor, then it results in the formation of depletion region across the junction. When the junction is forward biased, the width of depletion region decreases allowing more number of electrons from n-type to across the junction and recombine with holes in p-type. This, recombination of hole pairs across the junction emits the radiation.

Construction:-

- A typical GaAs laser is shown in fig.
- A rectangular block of Ga-As semiconductor is converted into p and n-type by proper doping of impurities into the block.
- The upper region acts as p-type and the lower portion as n-type .Between these two regions, we have a p-n junction to achieve population inversion p and n-regions are heavily doped with the impurities.
- The p-n junctions act as active medium. The two faces of the block, one fully polished and the other partially polished act as an optical resonator (or) cavity.

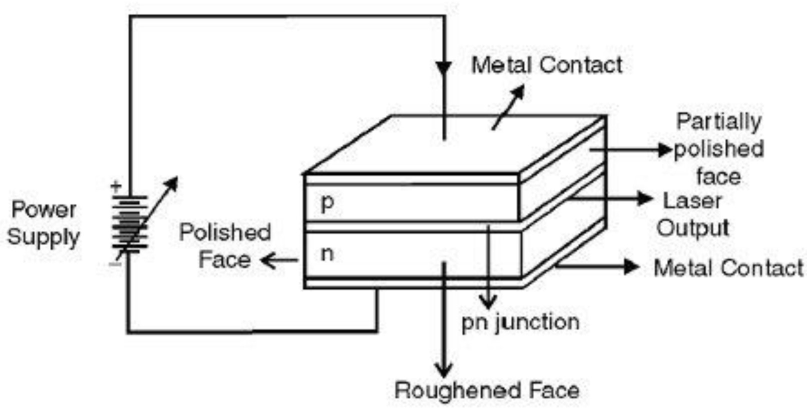


Fig: Construction of GaAs laser

Working:

- When the p-type is connected to the positive terminal of the battery and the n-type is connected to the negative terminal then the p-n junction will be in forward biased condition.
- The recombination of electron-hole pairs takes place across the junction's .Thus, laser radiation will be emitted through the p-n junction.

Calculation of wavelength:

Band gap of GaAs =1.44ev (1ev=1.6$\times$ 10^{-9} J)

$E_g = h\upsilon = h\frac{c}{\lambda}$ (c= $\upsilon\,\lambda$ and $\upsilon = \frac{c}{\lambda}$)

$$\lambda = \frac{hc}{E_g} = \frac{6.625\times10^{-34}\times3\times10^{8}}{1.44\times1.6\times10^{-19}}$$

$$\lambda = 8626A^0$$

The wavelength is near IR region.

Advantages:-

- It is easy to manufacture
- The cost is low.
- The efficiency of GaAs laser is high.

Disadvantages:

- It produces low power output.
- The beam has large divergence.

Applications of lasers: - Lasers find applications in various fields of science technology. They are described below.

Medical applications:-

- Lasers are used in eye surgery.
- Lasers are used for treatments such as plastic surgery, skin injuries and to remove moles and tumours developed in skin tissue.
- Lasers are used in cancer diagnosis and therapy.

Scientific field:-

- Lasers are used in counting of isotopes separation and to separate isotopes of uranium.
- Lasers are used to estimate size and shape of biological cells such as erythrocytes.
- Lasers are used to create plasma.
- Lasers are used to produce chemical reaction
- Lasers are used in recording and reconstruction of a hologram.

3) Industry applications:-

- Lasers are used to cut glass and quartz.
- Lasers are used to drill holes in ceramics.
- Lasers are used to drill aerosol nozzles.
- Lasers are used for heat treatment in the tooling and automotive industry.

OPTICAL FIBER

Fiber optics

Introduction

In 1870 John Tyndall demonstrated that light follows the curve of a stream of water pouring from a container; it was this simple principle that led to the study and development of application of the fiber optics. The transmission of information over fibers has much lower losses than compared to that of cables. The optical fibers are most commonly used in telecommunication, medicine, military, automotive and in the area of industry. In fibers, the information is transmitted in the form of light from one end of the fiber to the other end with min.losses.

Advantages of optical fibers

1. Higher information carrying capacity.

2. Light in weight and small in size.

3. No possibility of internal noise and cross talk generation.

4. No hazards of short circuits as in case of metals.

5. Can be used safely in explosive environment.

6. Low cost of cable per unit length compared to copper or G.I cables.

7. No need of additional equipment to protect against grounding and voltage problems.

8. Nominal installation cost.

9. Using a pair of copper wires only 48 independent speech signals can be sent simultaneously whereas using an optical fiber 15000 independent speeches can be sent simultaneously.

Basic principle of Optical fiber

The mechanism of light propagation along fibers can be understood using the principle of geometrical optics. The transmission of light in optical fiber is based on the phenomenon of total internal reflection.

Let n_1 and n_2 be the refractive indices of core and cladding respectively such that $n_1>n_2$. Let a light ray traveling from the medium of refractive index n_1 to the refractive index n_2 be incident with an angle of incidence "i" and the angle of refraction "r". By Snell's law

$$N_1 \sin i = n_2 \sin r \ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

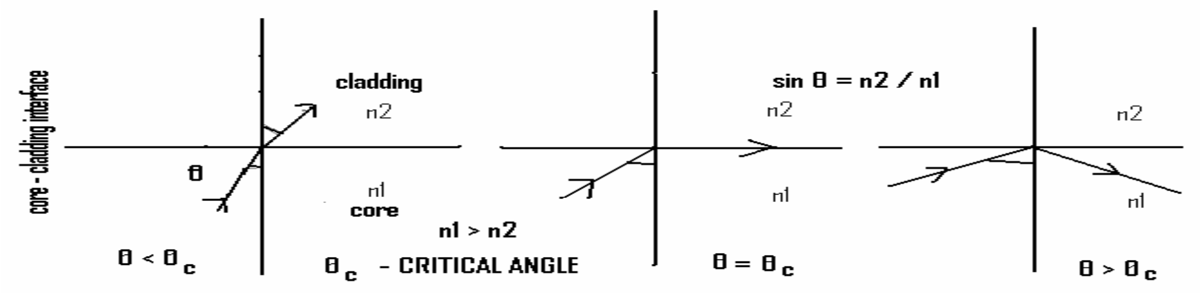
The refractive ray bends towards the normal as the ray travels from rarer medium to denser medium .On the other hand ,the refracted ray bends away from normal as it travel from denser medium to rarer medium. In the later case, there is a possibility to occur total internal reflection provided, the angle of incidence is greater than critical angle (θ_C).

This can be understood as follows.

1. When $i < \theta_C$ then the ray refracted is into the second medium as shown in below fig1.

2. When $i = \theta_C$ then the ray travels along the interface of two media as shown in fig2.

3. When $i > \theta_C$ then the ray totally reflects back into the same medium as shown in fig3.



Suppose if $i = \theta_C$ then $r = 90^0$, hence

$$n_1 \sin \theta_C = n_2 \sin 90^0$$

$$\sin \theta_C = n_2 / n_1 \text{ (since } \sin 90^0 = 1)$$

$$\theta_C = \sin^{-1} \frac{n_2}{n_1} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

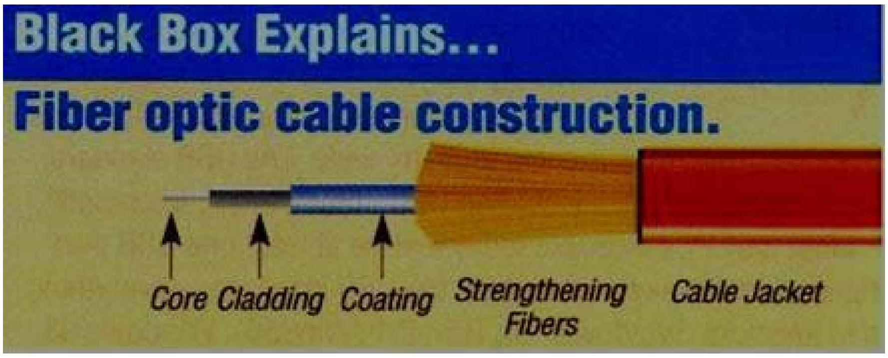
Thus any ray whose angle of incidence is greater than the critical angle ,total internal reflection occurs ,when a ray is traveling from a medium of high refractive index to low refractive index.

Construction of optical fiber

The optical fiber mainly consists of the following parts.

i. Core
ii. Cladding
iii. Silicon coating
iv. Buffer jacket
v. Strength material
vi. Outer jacket

- ❖ A typical glass fiber consists of a central core of thickness 50μm surrounded by cladding.
- ❖ Cladding is made up of glass of slightly lower refractive index than core's refractive index, whose over all diameter is 125μm to 200μm.
- ❖ Of course both core and cladding are made of same glass and to put refractive index of cladding lower than the refractive index of core, some impurities like Boron, Phosphorous or Germanium are doped.
- ❖ Silicon coating is provided between buffer jacket and cladding in order to improve the quality of transmission of light.
- ❖ Buffer jacket over the optical fiber is made of plastic and it protects the fiber from moisture and abrasion.
- ❖ In order to provide necessary toughness and tensile strength, a layer of strength material is arranged surrounding the buffer jacket.
- ❖ Finally the fiber cable is covered by black polyurethane outer jacket. Because of this arrangement fiber cable will not be damaged during hard pulling, bending, stretching or rolling, though the fiber is of brittle glass.



Acceptance angle and Numerical aperture of optical fiber

When the light beam is launched into a fiber, the entire light may not pass through the core and propagate. Only the rays which make the angle of incidence greater than critical angle at the core –cladding interface undergoes total internal reflection. The other rays are refracted to the cladding and are lost. Hence the angle we have to launch the beam at its end is essential to enable the entire light to pass through the core .This maximum angle of launch is called acceptance angle.

Consider an optical fiber of cross sectional view as shown in figure n_0, n_1 and n_2 are refractive indices of air ,core and cladding respectively such that $n_1>n_2>n_0$. Let light ray is incidenting on interface of air and core medium with an angle of incidence α .This particular ray enters the core at the axis point A and proceeds after refraction at an angle α_r from the axis .It then undergoes total internal reflection at B on core at an internal incidence angle θ.

To find α at A:-

In triangle ABC, $\alpha_r = 90- \theta$ ………… (1)

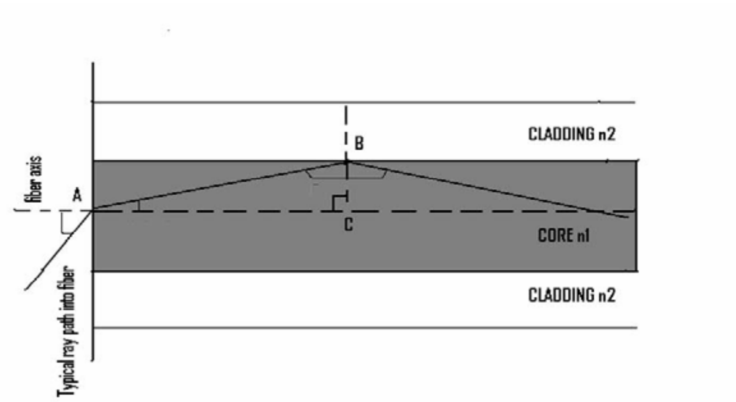
From Snell's law,

$n_0 \sin \alpha = n_1 \sin\alpha_r$ ……………(2)

$\sin \alpha= (n_1/n_0) \sin \alpha_r$ ……………….(3)

From equations 1, 3

$\sin \alpha = n_1/n_0 \sin(90- \theta) \Rightarrow \sin \alpha= n_1/n_0 \cos \theta$………(4)



If $\theta < \theta_C$, the ray will be the lost by refraction. Therefore limiting value for the beam to be inside the core, by total internal reflection is θ_C. Let α (max) be the maximum possible angle of incident at the fiber end face at A for which $\theta= \theta_C$. If for a ray α exceeds α (max), then $\theta< \theta_C$ and hence at B the ray will be refracted.

Hence equation 4 can be written as

$\sin \alpha(max)= n_1/n_0 \cos \theta_C$…………………..(5)

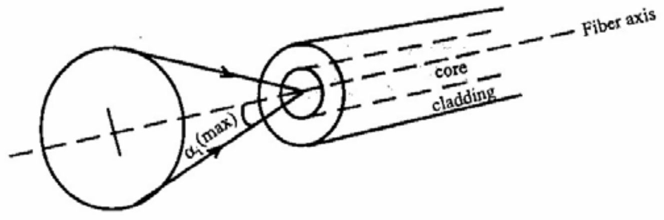
We know that $\cos \theta_C = \sqrt{(1-\sin^2 \theta_C)} = \sqrt{(1- n_2^2/n_1^2)}$

$=\sqrt{(n_1^2 - n_2^2)}/ n_1$……………………(6)

Therefore

$\sin \alpha(max) =\sqrt{(n_1^2- n_2^2)}/n_0$

$\alpha(max)= \sin^{-1}\sqrt{(n_1^2- n_2^2)}/n_0$



Acceptance cone obtained by rotating the acceptance angle about the fiber axis

This maximum angle is called acceptance angle or acceptance cone angle. Rotating the acceptance angle about the fiber axis gives the acceptance cone of the fiber. Light launched at the fiber end within this acceptance cone alone will be accepted and propagated to the other end of the fiber by total internal reflection. Larger acceptance angles make launching easier.

Numerical aperture

Light collecting capacity of the fiber is expressed in terms of acceptance angle using numerical aperture. Sine of the maximum acceptance angle is called the numerical aperture of the fiber.

Numerical aperture =NA = Sin α (max) =$\sqrt{(n_1^2 - n_2^2)}/n_0$…………….(7)

Let $\Delta = (n_1^2 - n_2^2)/2n_1^2$…………… (8)

For most fiber $n_1 = n_2$

Hence $\Delta = (n_1 + n_2)(n_1 - n_2)/2n_1^2 = 2n_1(n_1 - n_2)/2n_1^2$

$\Delta = (n_1 - n_2)/n_1$ (fractional difference in refractive indices)……………(9)

From equation (8) $n_1^2 - n_2^2 = \Delta\, 2n_1^2$

Taking under root on both sides

Hence $=\sqrt{(n_1^2 - n_2^2)} = \sqrt{2\Delta}\, n_1$

Substituting this in equation (7) we get

NA ≈ $\sqrt{2\Delta}\, n_1/n_0$ ………(10)

For air $n_0 = 1$, then the above equation can changed as

NA ≈ $\sqrt{2\Delta}\, n_1$

Numerical aperture of the fiber is dependent only on refractive indices of the core and cladding materials and is not a function of fiber dimensions.

Types or classification of optical fibers

Optical fibers are classified as follows:

Depending upon the refractive index profile of the core, optical fibers are classified into two categories

1) Step index
2) Graded index

Depending upon the number of modes of propagation, optical fibers are classified into two categories, they are

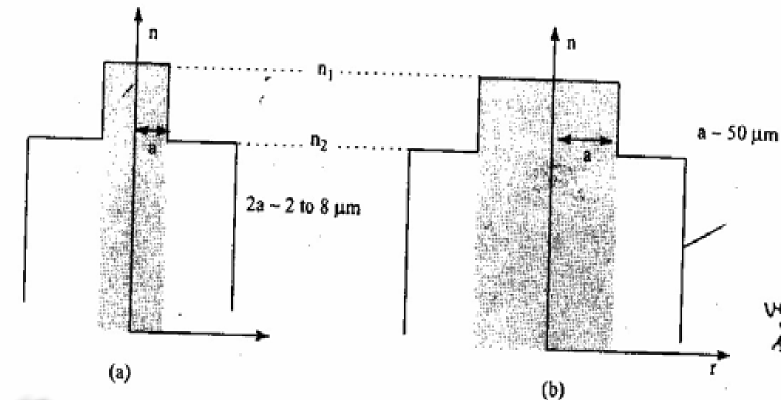
1) Single mode
2) Multi mode

Based on the nature of the material used, optical fibers are classified into four categories.

1) Glass fiber
2) Plastic fiber
3) Glass Core with plastic cladding
4) PCS Fibers(Polymer-Clad Silica fiber)

Step index fibers

In step index fibers the refractive index of the core is uniform throughout the medium and undergoes an abrupt change at the interface of core and cladding. The diameter of the core is about 50-200μm and in case of multi mode fiber. And 10μm in the case of single mode fiber. The transmitted optical signals travel through core medium in the form of meridonal rays, which will cross the fiber axis during every reflection at the core-cladding interface. The shape of the propagation appears in a zig-zac manner.



Refractive index profile for (a) monomode and (b) multimode step index fi

UNIT-2: LASERS AND OPTICAL FIBER

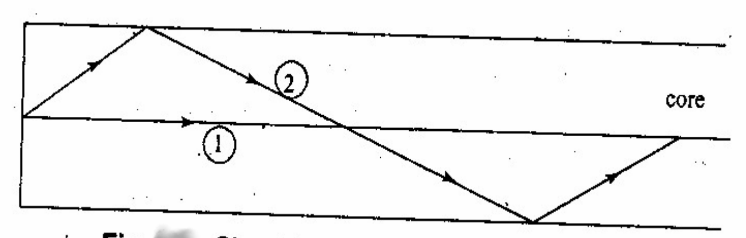
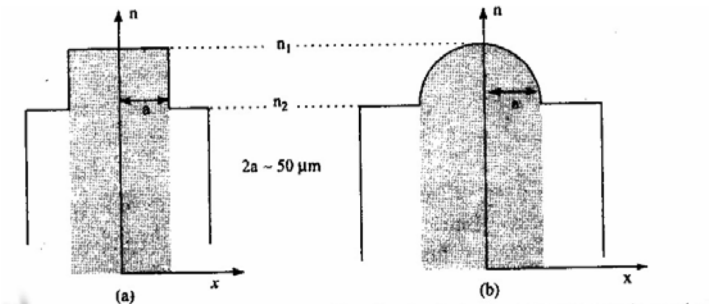


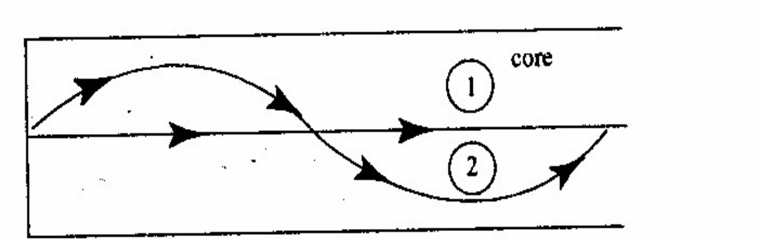
Fig. Signal transmission in step index fiber

Graded index fiber

In these fibers the refractive index of the core varies radially. As the radius increases in the core medium the refractive index decreases. The diameter of the core is about 50μm.The transmitted optical signals travel through core medium in the form of helical rays, which will not cross the fiber axis at any time.



Refractive index profile for (a) multimode step index and (b) multimode graded index fibers



Propagation of different model rays inside graded index fiber

Attenuation and losses in fibres

When the light signal propagates in the optical fibre losses arises due to different factors and these losses are referred to attenuation in optical fibre. The various factors causing attenuation in optical fibre are:

1. Material or impurity losses
2. Scattering losses
3. Absorption losses
4. Bending losses
5. Radiation losses
6. Inherent defect losses
7. Inverse sequence law losses
8. Transmission losses

9. Core and cladding losses

Losses are expressed in decibels per kilometer (dB/km). The attenuation loss is given by

$$P_{out} = P_{in}\, 10^{-\alpha L/10} \quad \text{-------------}\rightarrow (1)$$

where P_{out} = power at a distance L from the input

P_{in} = amount of power coupled in to the fibre

α = fibre attenuation in dB/km and

L = length of the optical fibre

Therefore, attenuation in the fibre is defined as the ratio of the optical power output P_{out} obtained from a fibre of length 'L' to the optical power P_{in} fed to the input of the fibre

∴ from eqn(1), we have

$$\alpha = \frac{10}{L}\log\left(\frac{P_{in}}{P_{out}}\right) \text{ dB/km}$$

Material or impurity losses

The doped impurities present in the fabrication of an optical fibre in order to vary the refractive index causes losses in the light signal propagation through the fibre.

Scattering losses

In glass fibre the glass contains many microscopic in homogeneities and material content. Due to this, a portion of light signal passing through the glass fibre gets scattered. This scattering losses vary inversely with the fourth power of the wavelength.

Absorption losses

Absorption loss is caused by the nature of core material and varies inversely to the transparency of the material. For glass fibres, ion-resonance absorption, ultraviolet absorption and infrared absorption are the three separate mechanisms which contribute to total absorption losses.

Bending losses

Whenever a fibre deviates from a straight line path, radeative losses occur. These losses are prominent for improperly installed single mode optical cable.

Radiation induced losses

When the glass molecular matrix interacts with electrons, neutrons, X-rays and gamma rays, the structure of the glass molecules is altered and the fibre darkens. This introduces additional losses which increase with amount, type, dose and exposure time of radiation.

Inherent defect losses

The inherent defect present in core and cladding cause losses of the propagating light signal through it. The surface defect in the core cause losses in the light signal. Grease, oil and other contaminates on the surface of the fibre also causes signal losses due to variation of refractive index.

Inverse sequence law losses

In all light systems, there is the possibility of losses caused by divergence of the beam. The illuminance per unit area is inversely proportional to the square of the distance ($1/_{r^2}$).

Transmission losses

These losses are caused by light which is caught in the cladding material of optical fibres. This light is either lost to the outside, or is trapped in the cladding layer and is thus not available for propagation in the core of the fibre.

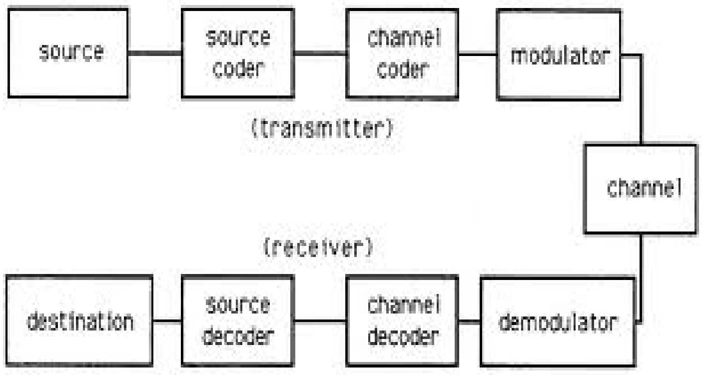
Core and cladding losses

In a fibre core and cladding have different refractive indices, as they have different compositions. So the core and the cladding have different attenuation coefficients, causing the power losses to the fibre.

Fibre optic communication system

A fundamental digital fibre optical communication system is shown in fig. Fibre optic communication system consists of three important components. They are

1) Optical transmitter
2) Fibre repeater
3) Optical receiver



Optical transmitter

An optical transmitter converts an analogue or digital signal into optical form. It consists of an encoder, light source and modulator. The input analogue signal is converted into a digital signal by means of an encoder. The converted digital signal is fed to the source. The source can be a LED or a semiconductor laser diode. The optical carrier wave from the source is modulated based on intensity, amplitude or frequency with the help of a modulator. This optical signal is coupled to the optical fibre by means of couplers. The couplers launch the optical signal into the fibre without any distortion and loss. The optical signal through fibre is properly connected to a repeater with the help of a connector.

Fibre repeater

The optical while travelling through very long optical fibers through long distances can suffer transmission losses and fibre losses like dispersion. As a result, we get a weak optical signal at the output end of the fibre. To minimise the losses, we use fibre repeaters at regular intervals between the fibres. The repeater consists of an amplifier and regenerator. The amplifier amplifies the weak optical signal, it is reconstructed to original optical signal with the help of regenerator and it is transmitted through the optical fibre. At the last stage, it is received by optical receiver.

Optical receiver

The receiver unit consists of a photodetector, amplifier, demodulator and decoder. The photodetector consists of PIN photo diode or avalanche photo diode. This works on the principle of creation of an electron-hole pair at the p-n junction by successive collisions of the incident optical signal. The released electrons output a current which is in direct relationship with the incident optical signal. This electric current is then amplified and demodulated to obtain a digital signal. This signal is then decoded and the transmitted signal is outputted.

Advantages of optical fibres in communication

1) Extremely wide band width
2) Smaller diameter, lighter weight cables
3) Lack of cross talk between parallel fibres
4) Immunity to inductive interference
5) Potential of delivering signals at low cost
6) Much safer than copper cables
7) Longer life span
8) High temperature resistance
9) Optical fibres are more reliable and easy to maintain than copper cables.

Applications of optical fibres

Medicine

1) Fibre scope in endoscopy is one of the widely used field optical technique to view the internal parts of the disease affected body.
2) This technique is widely used for diagnoses of interior of lungs, stomach and other human body parts.
3) Optical fibres are used in photodynamic therapy for cancer.
4) They are used in the treatment of lung disorders.
5) They are used in the treatment of bleeding ulcers.
6) They are used in the investigation of heart, respiratory system and pancreas.

Sensors

Optical fibres were widely used in sensors for sending and measuring of acoustic fields, magnetic fields, currents, acceleration, strain, pressure, temperature, rotation, etc. Rotation sensing can be done with the help of fibre optic gyroscope.

A fibre optic sensor consists of a light source which generates light signals. These signals passes through the optical fibre placed in the sensing fields and then passes through the light detector. The variation in the light signal is caused by the sensing field and is detected by the detector as shown in fig. The optical fibre may be of single mode or multimode type.

Communication

1) Optical fibres are extensively used in optical communication system.
2) Nearly 10,000 information carries signal can be transmitted simultaneously through the optical fibre.
3) Due to higher band widths optical fibre carries more information.
4) Without any crosstalk the information can be safely delivered.
5) During war time they are used for secret communication.

They are used for guiding weapons and submarine communication systems