Module – III & IV **LASERS AND OPTICAL FIBERS**

LASERS (Module IV)

A **laser** is a device that emits light through a process of optical amplification based on the stimulated emission of electromagnetic radiation. The term "laser" is an acronym for "**light amplification by stimulated emission of radiation**”. The first theoretical foundation of LASER was given by Einstein in 1917 using Plank’s law of radiation that was based on probability coefficients (Einstein coefficients) for absorption and spontaneous and stimulated emission of electromagnetic radiation.The first laser built in 1960 by **Theodore H. Maiman** at Hughes Research Laboratories was based on optical pumping of synthetic ruby crystal using a flash lamp that generated pulsed red laser radiation at 694 nm. Iranian scientists **Javan** and **Bennett** made the first gas laser using a mixture of He and Ne gases in the ratio of 1 : 10 in the 1960**. R. N. Hall** demonstrated the first diode laser made of gallium arsenide (GaAs) in 1962, which emitted radiation at 850 nm, and later in the same year *Nick Holonyak* developed the first semiconductor visible-light-emitting laser.

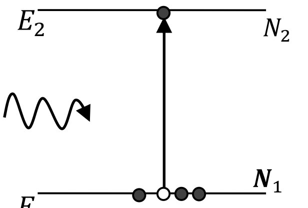
A laser differs from other sources of light in that it emits highly coherent, monochromatic, directional and intense beam of light. These properties find them to be useful in many applications. Among their many applications, lasers are used in optical disk drives, laser printers, and barcode scanners; DNA sequencing instruments, fiber-optic and free-space optical communication; laser surgery and skin treatments; cutting and welding materials; military and law enforcement devices for marking targets and measuring range and speed; and laser lighting displays in entertainment.

Depending up on the type of active medium used for lasing, the lasers are classified as solid state lasers, gas lasers, semiconductor diode lasers, dye lasers etc. in another way of classification, lasers are classified as continuous lasers and pulsed lasers. A laser beam whose output power is constant over time is called a continuous laser. In pulsed lasers the optical power appears in pulses of some duration at some repetition rate.

Expression for energy density in terms of Einstein’s coefficients:

Consider two atomic states of energies E_1 and E_2 with a population of $N_1$and respectively. Let radiation's with a spectrum of frequencies be incident upon the system. Let $U_\gamma\, d\gamma$ is the energy incident/unit volume of the system. According to Albert Einstein, radiations may interact with matter in three different ways namely induced absorption, spontaneous emission and stimulated emission.

(i). <u>Induced absorption:</u> An atom in the ground state may absorb energy from the incident radiation and get excited in to one of the excited state. This phenomenon is called induced absorption. Absorption of energy from the incident radiation is probabilistic in nature. The rate of induced absorption is proportional to the number of atoms in the ground state(N_1) and energy density of incident radiation $[\rho(\nu)]$. The phenomenon can be represented mathematically as



Induced absorption

$$\boldsymbol{A + h\nu \rightarrow A^*}$$

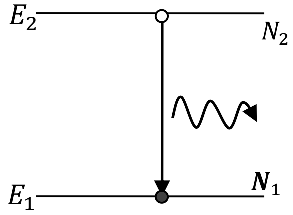
This phenomenon is probabilistic in nature. The energy absorbed by the atom from the incident photon $h\nu = E_2 - E_1 = \Delta E$

The rate of induced absorption $R_{IA} \propto N_1\rho(\nu)$

Or $\boldsymbol{R_{IA} = B_{12}\, N_1 \rho(\nu)}$ -------------- (1)

Where $\mathbf{B_{12}}$ is called Einstein’s probability coefficient for induced absorption.

(ii). <u>Spontaneous emission:</u> The atom in the excited state makes a downward transition by itself, by emitting a photon, soon after the completion of its life time there in the excited state. This phenomenon is called spontaneous emission.



Spontaneous emission

$$\boldsymbol{A^* \rightarrow A + h\nu}$$

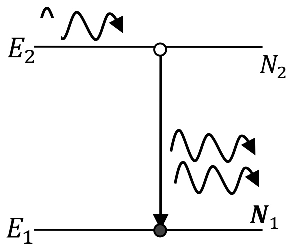
Spontaneous emission is non-probabilistic in nature. The energy of emitted photon is $h\nu = E_2 - E_1$. The rate of spontaneous emission solely depend up on the number of atoms (N_2) in the excited state (E_2).

$R_{sp} \propto N_1\rho(\nu)$

Or $\quad R_{sp} = A_{21}\, N_2$ -------------- (2)

Where A_{21} is called Einstein's probability coefficient for Spontaneous emission.

(iii). Stimulated emission: An atom in the excited state may be forced to de-excite before the completion of its life time by the influence of an incident photon by emitting two identical photons. This phenomenon is called stimulated emission.



Stimulated emission

$$A^* + h\nu \rightarrow A + 2h\nu$$

The stimulated emission is also probabilistic in nature. The two photons emitted are identical in all respect. The energy of each photon is hν = $E_2 - E_1$. The rate of stimulated emission depends up on the number of atoms (N_2) in the excited state (E_2) as well as the energy density of incident photon.

$$R_{st} \propto N_2\rho(\nu)$$

Or $\quad R_{st} = B_{21}\, N_2\rho(\nu)$ -------------- (3)

Where B_{21} is called Einstein's probability coefficient for Spontaneous emission.

At equilibrium, the rate upward transition = the rate of downward transition.

$$\therefore \quad R_{IA} = R_{sp} + R_{st}$$

$$\Rightarrow \quad B_{12}\, N_1\rho(\nu) = A_{21}\, N_2 + B_{21}\, N_2\rho(\nu)$$

$$\Rightarrow \quad \rho(\nu)\,[B_{12}\, N_1 - B_{21}\, N_2\,] = A_{21}\, N_2$$

OR $\quad \rho(\nu) = \frac{A_{21}\, N_2}{[B_{12}\, N_1 - B_{21}\, N_2\,]} = \frac{A_{21}\, N_2}{B_{21}\, N_2\left[\left(\frac{B_{12}}{B_{21}}\right)\left(\frac{N_1}{N_2}\right) - 1\right]}$ --------------------- (4)

We know that the relative population of level E_2 wrt E_1, $\left(\frac{N_2}{N_1}\right) = e^{-\left(\frac{E_2 - E_1}{KT}\right)} = e^{-\left(\frac{h\nu}{KT}\right)}$

$$\Rightarrow \left(\frac{N_1}{N_2}\right) = e^{\left(\frac{h\nu}{KT}\right)} \text{ ------------- (5)}$$

$$\therefore \rho(\nu) = \frac{A_{21}}{B_{21}\left[\left(\frac{B_{12}}{B_{21}}\right)e^{\left(\frac{h\nu}{KT}\right)} - 1\right]} \text{ --------------------- (4)}$$

The plank's law of blackbody radiation gives the energy density of emitted radiation in the frequency interval ν and ν+dν as

$$E(\nu)d\nu = \frac{8\pi h\nu^3}{C^3}\frac{1}{e^{\left(\frac{h\nu}{KT}\right)} - 1}\, d\nu$$

Or $\quad E(\nu) = \frac{8\pi h\nu^3}{C^3}\frac{1}{e^{\left(\frac{h\nu}{KT}\right)} - 1}$ -------- **(5)**

The LHS of both eqn. (4) & (5) represents the same quantity and hence one can compare the RHS of the two eqns.

By comparing the constants on RHS, we get $\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{C^3}$

And by comparing the coefficient of the exponential term $\left(\frac{B_{12}}{B_{21}}\right) = 1$ ———— (6)

The result $B_{12} = B_{21}$ implies that the induced absorption and stimulated emission are equally probable. And hence the subscripts can be neglected. $\therefore \frac{A}{B} = \frac{8\pi h\nu^3}{C^3}$

The expression for energy density in terms of Einstein's coefficients can be written as

$$\rho(\nu) = \frac{A}{B\left[e^{\left(\frac{h\nu}{KT}\right)} - 1\right]} \text{ ----------- (7)}$$

This is the expression for energy densty of radiation in terms of Einstein's coefficients

Note: The plank's law of blackbody radiation can be written in terms of Einstein's A & B coefficients as

$$E(\nu)d\nu = \frac{A}{B\left[e^{\left(\frac{h\nu}{KT}\right)} - 1\right]}\, d\nu$$

Terminologies used in lasers:

Population: The number of atoms at a particular energy level is called the population of that state. The relative population at a level E_2 with population N_2 is given by Boltzmann's factor

$\left(\frac{N_2}{N_1}\right) = e^{-\left(\frac{E_2 - E_1}{KT}\right)} = e^{-\left(\frac{h\nu}{KT}\right)}$, where N_1 is the population at the level E_1.

Lasing: The phenomenon of emission of stimulated photon after establishing population inversion is called Lasing.

Population Inversion: The state of a system in which the population of the higher energy state is greater than that of the lower energy state is called population inversion (inverted state of normal population)

Pumping: The process of lifting the atoms in the ground state to the higher energy states by supplying external energy is called pumping.

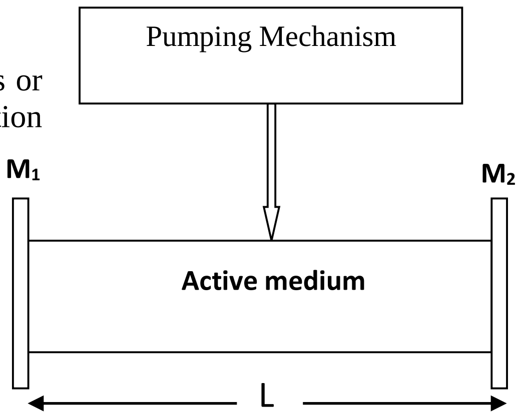
Metastable state: The allowed energy level with relatively longer life time, of the order of 10^{-3} seconds, is called metastable state.

Condition for lasing:

(i) To achieve population inversion: To have proper lasing action, the downward transition should dominate over upward transition. This is possible if the higher energy state is more populated. This state of the medium where the higher energy state is more populated than the ground state is called population inversion.

(ii) Existence of Metastable state: To have proper lasing action, the stimulated emission should dominated over spontaneous emission. This is possible id the atoms in the excited state stay there for relatively longer time, till they get stimulated. Such energy levels with life time of the order of a few milliseconds are called metastable states.

Requisites of a laser system:



(i) **Active medium:** An active medium is a system of atoms or molecules, between whose quantized energy levels the lasing action takes place.

(ii) **Pumping mechanism:** The process of lifting the atoms in the ground state to the higher energy states by supplying external energy is called pumping. The pumping mechanism may be the optical pumping, electrical pumping, or of any other mechanism, depending on the situation.

(iii) **Laser cavity (optical resonator or resonant cavity):**

Two mirrors having slightly difference in their reflectivity and facing each other, placed on either side of the active medium forms a laser cavity. The stimulatively emitted photons are directed again and again in to the active medium by these mirrors and hence the multiplication of photons takes place. All such coherent photons moving to and fro in the resonant cavity interfere together to form a standing wave pattern. As a result of such interference, the amplitude and hence the intensity, of light increases keeping the wavelength (energy) constant.

The sustained interference is achieved if the condition

$$2L=n\lambda$$

is satisfied, where L is the separation between the two mirrors.

Carbon dioxide Laser:

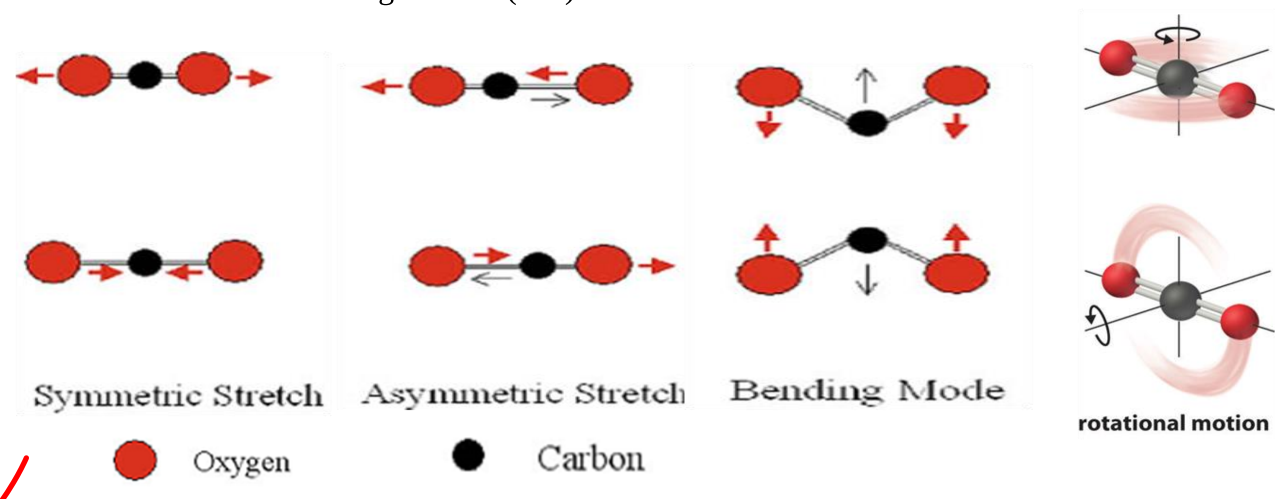
Introduction: Carbon dioxide laser is a molecular gas laser. Carbon dioxide is the most efficient molecular gas laser material that exhibits for a high power and high efficiency gas laser at infrared wavelength. It offers maximum industrial applications including cutting, drilling, welding, and so on. It is widely used in the laser pyrolysis method of nanomaterials processing.

CO_2 is a linear diatomic molecule having five degrees of freedom, three of which corresponds to vibrational motion and the remaining two corresponds to rotational motion. In other words, when CO_2 molecule absorbs energy, it executes three different modes of vibrational motion and two different modes of rotational motion. Both the rotational and vibrational energy are quantized. The rotational energy is very small compared to vibrational energy. Therefore, the rotational energy levels will be the fine structure of vibrational energy levels. However, the vibrational energy levels are discrete and each vibrational state is represented by a set of quantum numbers (m,n,q). The fundamental modes of vibration for a linear diatomic CO_2 molecule is discussed bellow

(i) Symmetric stretching: In symmetric stretching, both the oxygen atoms move simultaneously either towards or away from the carbon atom, along the axis of the molecule. This mode of vibration is designated as (100) state.

(ii) Asymmetric stretching: In asymmetric stretching, one of the oxygen atom move towards the carbon atom and the other , moves away from the carbon atom, along the axis of the molecule. This mode of vibration is designated as (001) state.

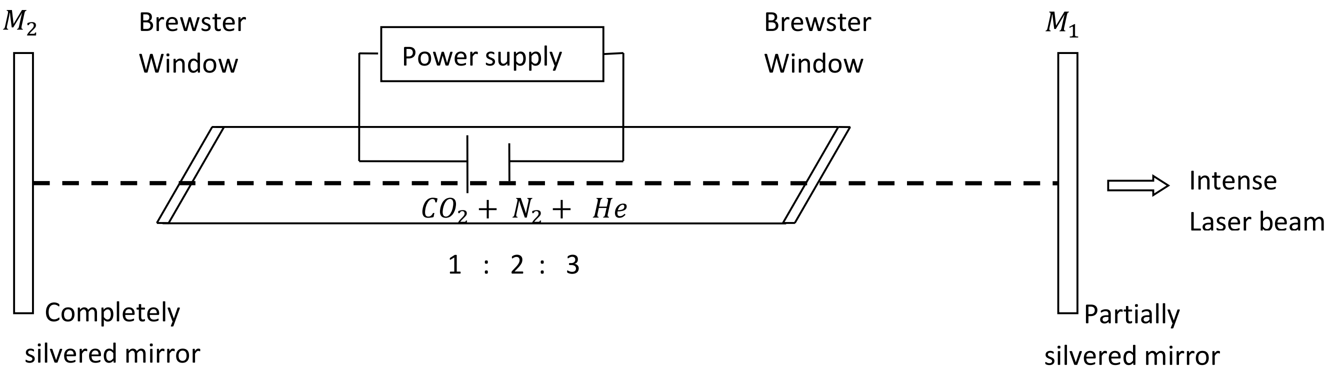
(iii) Bending mode: In bending mode all the atom move perpendicular to the axis of the molecule, but the direction of motion of the carbon atom being opposite to that of oxygen molecules. This mode of vibration is designated as (010) state.



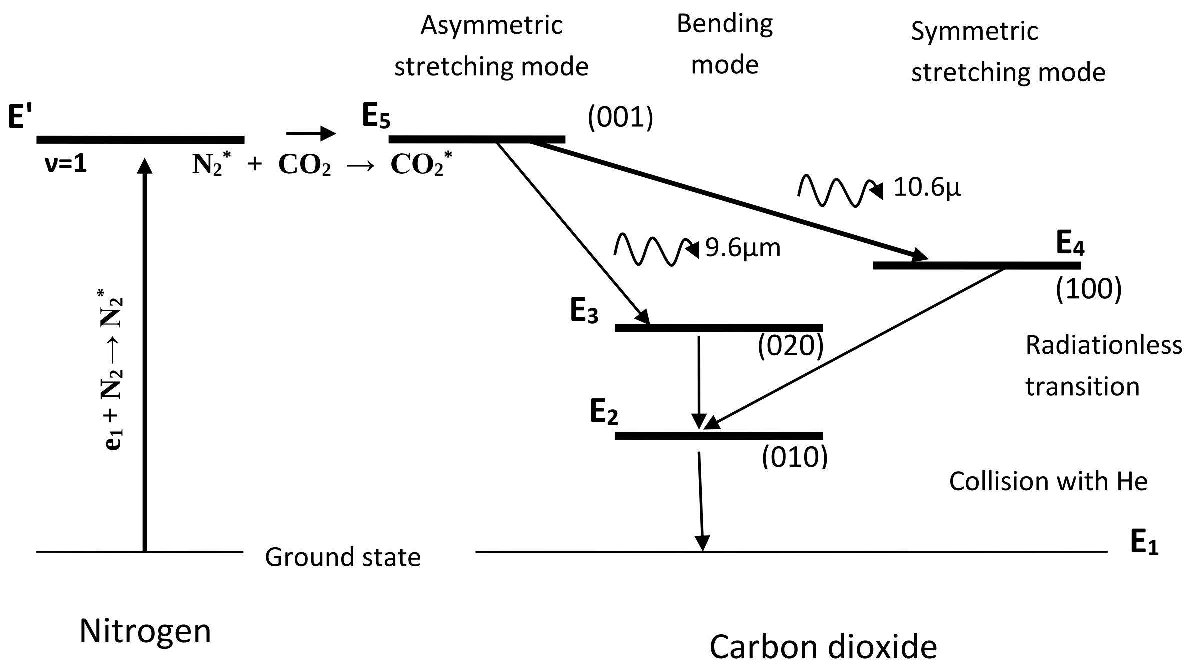
Construction:

Figure shows he construction of CO_2 laser. It consists of long discharge tube of 5cm length and 2.5 cm in diameter. The ends of the discharge tube are fitted with Brewster's window. The pressure inside the discharge tube is about 6-17 torr. The tube is filled with a mixture of CO_2, N_2 and He gases in the ratio 1:2:3. The two mirrors M_1 and M_2 placed on the either sides of the discharge tube along the axis of the tube forms the resonant cavity.

Actually the size , pressure and the ratio of the gases vary with the particular application. The high voltage power supply may be either A.C. or D.C. depending up on the usage of the laser.



Working: Though the CO_2 molecules are less in number, they are the active centres. The purpose of N_2 molecules is only to assist the population inversion. The Helium serves as good conductor of heat and prevents the population inversion at E_2.



- When power supply is switched on, the electric discharge produced excites the nitrogen molecules to the first excited state E', which is Metastable. $\mathbf{e_1 + N_2 \rightarrow N_2^*}$ ----- (1)
- The excited N_2 molecules transfer their energy to the CO_2 molecules by collision. The energy corresponding to asymmetric mode of CO_2 is very close to that of first excited state energy of N2 molecules. $\mathbf{N_2^* + CO_2 \rightarrow CO_2^*}$ ----- (2)
- Since CO_2 molecules are less in number, the population of CO_2 at the ground state decreases due to the collision with N_2 molecules and population at E_5 grows quickly. As a result population inversion is achieved at E_5 with respect to the lower levels.
- The transition from E_5 to E_4 leads to the emission of 10.6μm photon and the transition from E_5 to E_3 leads to the emission of 9.6μm photon. Any one of the spontaneously emitted photon stimulate the other CO_2 molecules at E_5.
- The co_2 molecules at E_4 and E_3 fall back to E_2 by radiation less transition. The co_2 molecules at E_2 fall back to ground state by colliding with He molecules and are available for the next cycle. The cycle repeats continuously.
- The stimulated photons get multiplied in the resonant cavity formed by the mirror M_1 and M_2 and after sufficient amplification an intense beam of laser light emerges out of the partially silvered mirror.

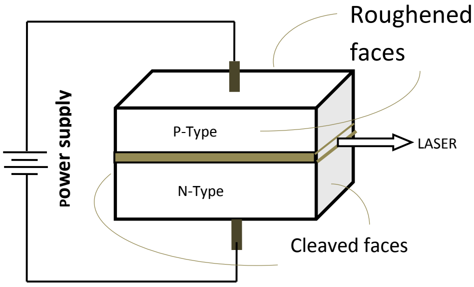
Though there are two wave length photons emitted in the process, monochromaticity can be achieved by choosing proper orientation of the Brewster window. The output is continuous wave with an efficiency about 30 -40%.

Semiconductor diode laser:

The working of semiconductor diode laser is almost similar to that of an L.E.D. The recombination of electron and the hole in the depletion region of a forward biased P-N junction emits a photon of characteristic wavelength. If a large forward current is flowing through the diode, the population inversion is established between the Fermi levels of P- type and N-type semiconductor and hence lasing can be achieved using suitable resonant cavity. In the case of L.E.D, it is the spontaneously emitted photon that gives light; where as in semiconductor diode laser, it is the stimulatively emitted photon that gives light.

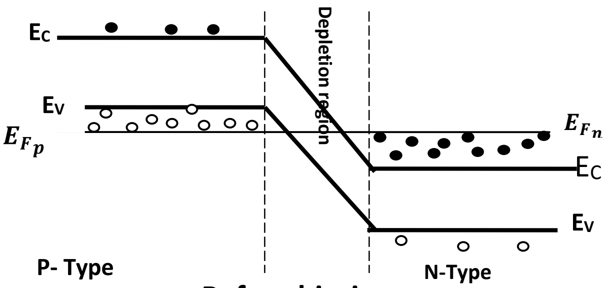
The familiar intrinsic semiconductors such as Si and Ge are indirect band gap semiconductors. The electron-hole recombination is easier in direct band gap semiconductors. The combination of III and V group elements or II and VI group elements behave as intrinsic direct band gap semiconductor. Example- single crystal grown from Ga (III group) and As (V group) is an intrinsic semiconductor.

GaAs Semiconductor diode laser:

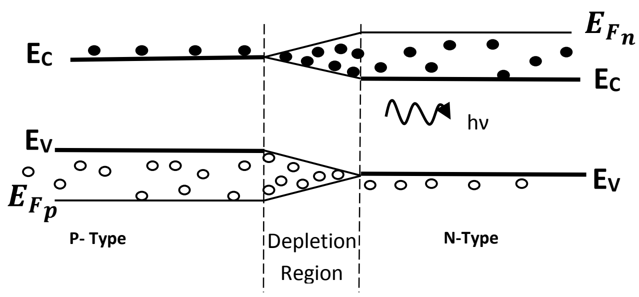


Construction: GaAs is a direct band gap intrinsic semiconductor. GaAs diode is obtained by Single crystal of GaAs (grown from suitable crystal growing technique), doped with Zinc (Zn) and Tellurium (Te) to get P-type and N-type GaAs respectively. The doping is so high that there are 10^{17} to 10^{19} atoms per cm^3. The sandwich of P-type and N-type forms a diode. The figure shows the construction of GaAs semiconductor diode laser. The two faces parallel to the junction are provided with metallic contacts to provide proper biasing. A pair of opposite faces perpendicular to the junction is well-polished and the remaining pair of opposite faces perpendicular to the junction is roughened. The refractive index of GaAs with respect to air is very high so that the cleaved (polished) faces serve as resonant cavity.

Working: The figure shows the enery level diagram for GaAs diode before and afeter the biasing **.** In the absence of biasing, the electrons of N-type can ot cross over the junction because of the potential barrier. When the diode is forward biased, the charge carriers are injected in to the depletion region and a large current flowes through the diode as it is hevily doped. The population inversion is achieved at the depletion region between the electron and holes . The recombination of the electon and the hole in the depletion region emits a



Before biasing



After Biasing

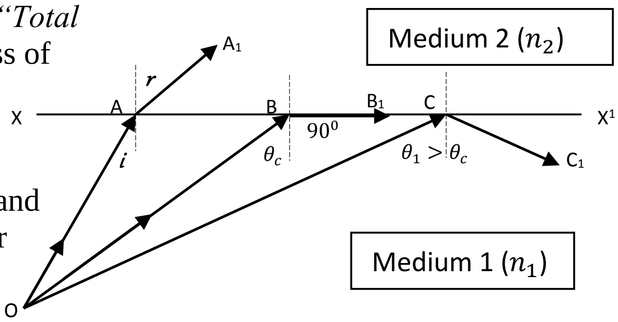
stimulatively emitted photon. This photon is reflected back in to the depletion region at the cleaved faces and stimulate the recombination. The stimulatively emitted photons are multiplied in the resonant cavity and after sufficient amplification an intense laser beam is emitted from the cleaved face having relatively low reflectance.

The energy gap for GaAs is nearly 1.4 ev. Therefore the wavelength of emitted laser light is $\lambda = \frac{h\,c}{\Delta E} = \frac{6.625 \times 10^{-34} \times 3\times10^{8}}{1.4 \times1.6\times10^{-19}}$ = 8400Å.

Optical fibers

Total Internal Reflection:

When a ray of light travels from denser to rarer medium it bends away from the normal. As the angle of incidence increases in the denser medium, the angle of refraction also increases. For a particular angle of incidence called the "*critical angle* (θ_c)", the refracted ray grazes the interface of the two media or the angle of refraction becomes equal to 90°. If the angle of incidence increases a little beyond the critical angle, the light ray is reflected back to the same medium. This is called *"Total Internal Reflection"*. In total internal reflection, there is no loss of energy. The entire incident ray is reflected back.



In the figure, XX^1 is the interface separating medium of refractive index n_1 and medium of refractive index n_2, with $n_1 > n_2$. AO and OA_1 are incident and refracted rays. ***i*** and ***r*** are angle of incidence and angle of refraction, with ***i*** > ***r***. For the ray BO, θ_c is the critical angle. OB_1 is the refracted ray which grazes the interface. The ray CO incident with an angle greater than θ_c is totally reflected back along OC_1.

For the incidence at A, From Snell's law, we have $n_1 \sin i = n_2 \sin r$

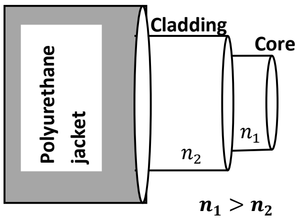
For total internal reflection, $i = \theta_c$ and r = 90° $\therefore n_1 \sin i = n_2$ (because sin90°=1)

$$\therefore \theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$$

This is the expression for critical angle.

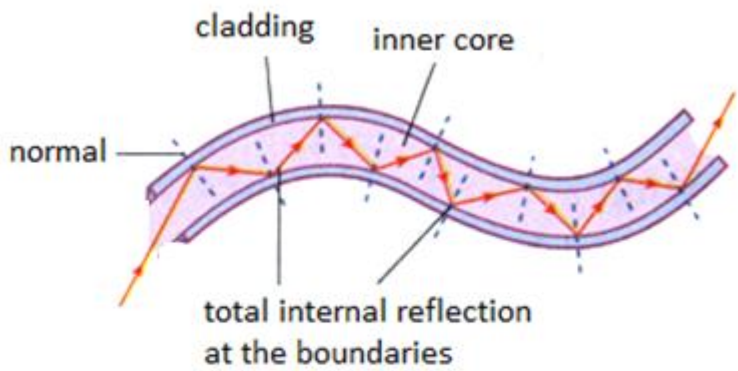
Optical Fibers* (Fabrication)*:

Optical fibers are thin rods of glass or some other transparent material of high refractive index. If light is admitted at one end of a fiber, it can travel through the fiber with very low loss, even if the fiber is curved. A fibre optic cable is made from high refractive index transparent material coated with another transparent material of relatively low refractive index. The low R.I. coat reflects 'escaping' light back into the core, resulting in the light being guided along the fibre through the phenomenon of T,I,R. The outside of the fibre is protected by cladding and may be further protected by additional layers of PVC or polyurethane jacket. Number of such fibers is grouped and moulded to form a cable. This required for protecting the fibre from mechanical deformation. They are used in optical communication. It works on the principle of Total internal reflection (TIR).



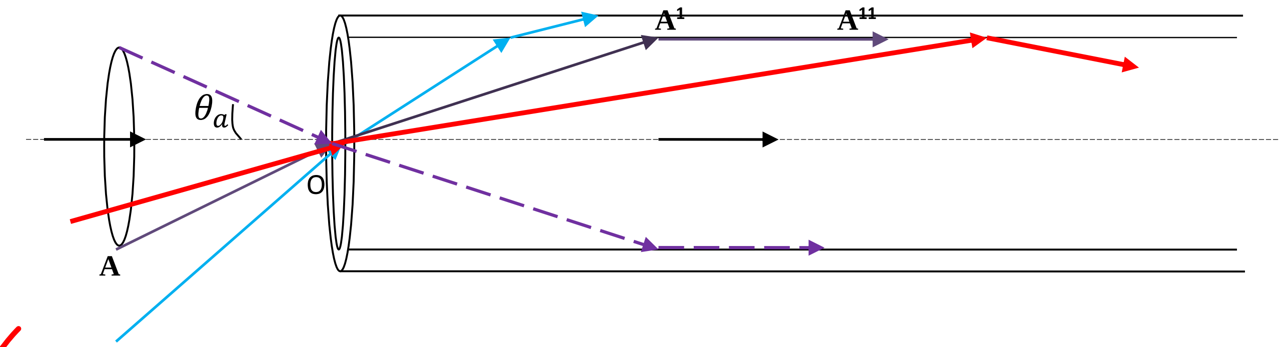
Propagation mechanism (Working Principle):

The light entering through one end of core strikes the interface of the core and cladding with angle greater than the critical angle and undergoes total internal reflection. After series of such total internal reflection, it emerges out of the core. Thus the optical fiber works as a waveguide. Care must be taken to avoid very sharp bends in the fiber because at sharp bends, the light ray fails to undergo total internal reflection.



Angle of Acceptance and Numerical Aperture:

Referring to the figure given bellow, the ray which is incident on the core surface along the axis of the fiber, pass through the core without any deviation ($\because i = 0, hence\ r = 0$). The ray incident on the core surface with smaller angle of incidence refracts with smaller angle of refraction and falls on the core-cladding interface at an angle greater than the critical angle and hence ensures TIR. The ray incident on the core surface with greater angle of incidence refracts with greater angle of refraction and falls on the core-cladding interface at an angle lesser than the critical angle and hence refracts in to cladding. There exists a particular angle of incidence, called 'θ_a' for which the refracted ray falls on the core- cladding interface at an angle equal to critical angle and it grazes the core cladding interface after refraction. This angle is called acceptance angle.



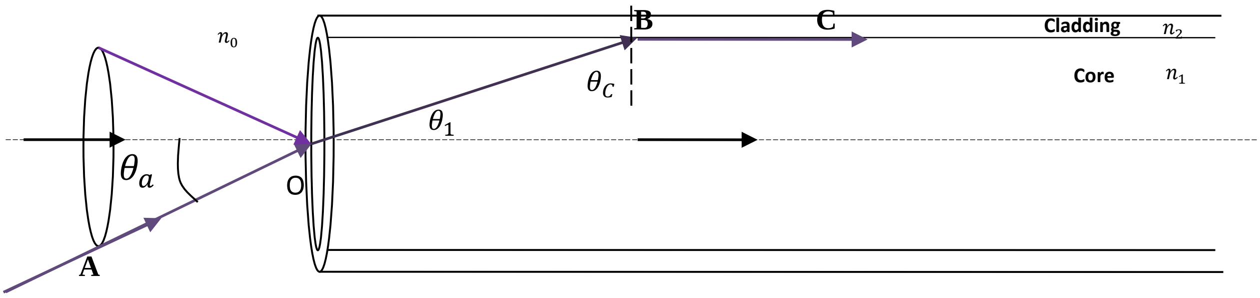
Acceptance angle: It is the maximum limit for the angle of incidence of the incident ray such that the ray refracted in to the core grazes the interface as it falls on the core-cladding interface.

Acceptance cone: The ray incident on the core surface at an angle equal to acceptance angle when rotated about the axis of the fiber forms a cone. This cone is called acceptance cone. The rays which are funnelled through the acceptance cone ensure TIR at the core cladding interface. The rays entering in to the core outside of this acceptance cone are trapped at the cladding because of the refraction at core-cladding interface.

Numerical Aperture: Numerical aperture of an optical fiber is the ability to gather incident light. It is numerically equal to the sine of the acceptance angle (θ_a).

Expression for Numerical aperture and Condition for propagation:

Consider a ray of light in a medium of RI 'n_0' entering in to a fiber having a core of RI 'n_1' and cladding of RI 'n_2' at a point "O" on the core surface. The ray OA incident at O, at an angle θ_a refracts in to the core at an angle θ_1 and falls on the core-cladding interface at an angleθ_C at B and grazes the interface along BC after refraction.



For the refraction at 'O', Snell's law can be written as $\boldsymbol{n_0 \sin\theta_a = n_1 \sin\theta_1}$

$$\therefore \sin\theta_a = \left(\frac{n_1}{n_0}\right)\sin\theta_1 \quad ....(1)$$

Similarly For the refraction at 'B', Snell's law becomes $\boldsymbol{n_1 \sin\theta_C = n_2 \sin 90°}$

But we have $\boldsymbol{\theta_C = (90° - \theta_1)}$ $\quad \therefore \boldsymbol{n_1 \sin(90° - \theta_1) = n_2}$

$$\text{Or} \quad \cos\theta_1 = \left(\frac{n_2}{n_1}\right)$$

$$\Rightarrow \quad \sin\theta_1 = \sqrt{1 - \left(\frac{n_2}{n_1}\right)^2} = = \sqrt{\frac{(n_1{}^2 - n_2{}^2)}{n_1{}^2}} \quad .... (2)$$

$\therefore$ Eqn. (1) becomes $\boldsymbol{\sin\theta_a = \left(\frac{n_1}{n_0}\right) \cdot \sqrt{\frac{(n_1{}^2 - n_2{}^2)}{n_1{}^2}}}$

$\Rightarrow$ N. A. = $\boldsymbol{\sin\theta_a = \frac{\sqrt{(n_1{}^2 - n_2{}^2)}}{n_0}}$ (This is the expression for the Numerical aperture.)

If the surrounding medium is air then N . A . =$\boldsymbol{\sin\theta_a} = \sqrt{(\boldsymbol{n_1{}^2 - n_2{}^2})}$ .... (3)

Note: (i) The condition for the effective propagation of light through the fiber is $\theta_1 \leq \theta_a$

Or $\sin\theta_1 \leq \sin\theta_a$

Or $\sin\theta_1 \leq \text{N. A.}$

(ii) **Fraction Index Changes (Δ):** The fractional index change is the ratio of the difference in the refractive index between the core and the cladding to the refractive index of core of the optical fiber.

$$\text{Therefore,} \quad \Delta = \frac{(n_1 - n_2)}{n_1}$$

(iii) **Relation between N.A. and Δ:**

From the definition of fractional index change, $\boldsymbol{(n_1 - n_2) = = n_1\Delta}$ -------- (1)

From the expression for numerical aperture N . A . = $\sqrt{(\boldsymbol{n_1{}^2 - n_2{}^2})}$ = $\sqrt{(\boldsymbol{n_1 + n_2})(\boldsymbol{n_1 - n_2})}$ ---- (2)

Since $n_1 \cong n_2$, $n_1 + n_2 = 2n_1$, **N . A . =** $\sqrt{\boldsymbol{2n_1\Delta}}$ **-------------- (3)**

This is the relation between N.A. and Δ**.** Though an increase in the value of Δ increase NA (and thus one can enhance the light gathering capacity of the fiber); we cannot increase Δ to a very large value, since it leads to what is called "intermodal dispersion" which causes signal distortion.

Modes of propagation and V-number: The number of modes of propagation refers to the number of possible paths for the rays propagating through the core. The number of modes that supports for propagation in the fibre is determined by a parameter called V − number.

$$V = \left(\frac{\pi d}{\lambda}\right)\left[\frac{\sqrt{(n_1^2 - n_2^2)}}{n_0}\right]$$

where λ is the wavelength of light propagating through the fibre and $\mathbf{n_0}$ is the RI of surrounding medium, d is core diameter; n_1 and n_2 are the RI of the core and cladding respectively.

If the surrounding medium is air, then the V −numberis given by

$$V = \left(\frac{\pi d}{\lambda}\right)\sqrt{(n_1^2 - n_2^2)} = \left(\frac{\pi d}{\lambda}\right)\text{N.A.}$$

For $V \gg 1$, the number of modes supported by the fibre is approximately $N = \frac{V^2}{2}$

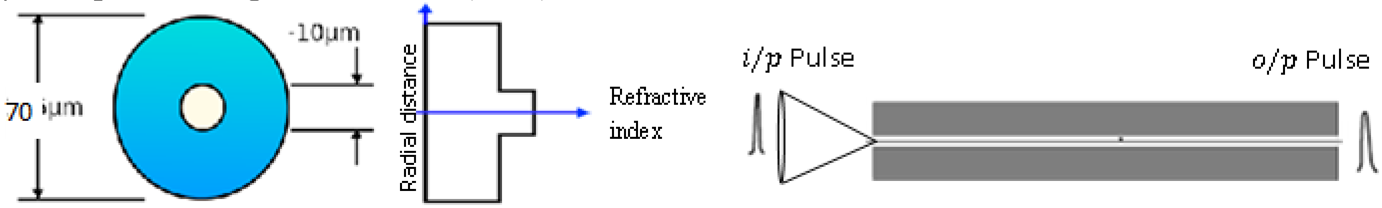
Optical Fibers

- **Depending up on the type material used for core**
  - Glass fibers
  - Plastic fibers
- **Depending up on the RI profile**
  - Step Index fiber
  - Graded index fiber
- **Depending up on the type material used for core**
  - Single mode fibers
  - Multimode fibers

Classification of Optical fibers:

The figure shows the different ways of classification of optical fibers. However from the point of view of application, they are classified as Step index Single mode fibers (SMF), Step index multimode fibers(SMMF) and Graded index multimode (GRIN) fibers.

(a) Step index Single mode fibers (SMF):

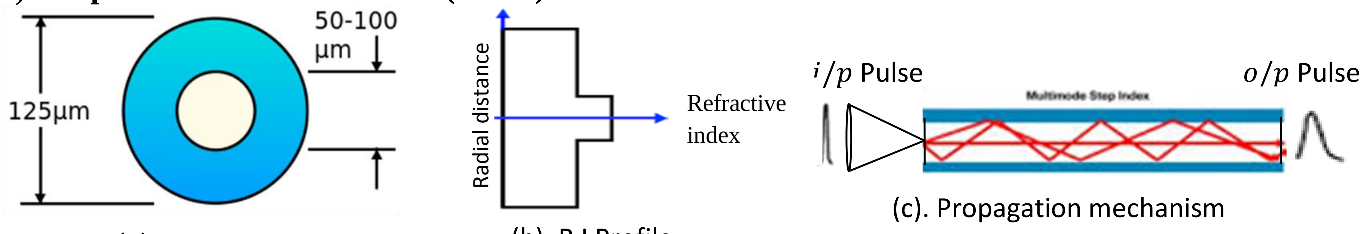


(a). Geometry (b). R I Profile (c). Propagation mechanism

- Step index single mode fibers have a thin core of diameter 8 – 10µm with a thick cladding of diameter 60 - 70µm.
- All the Single mode fibers are step index only. The RI of the core and cladding remain constant with a small percentage of fractional index change (Δ).
- These fibers support the transmission by single mode ie. V number < 2.4.
- Since the core diameter is small, the NA is small (NA < 0.3).

- The attenuation is relatively low. Since they transmit the signals in single mode, the transmission is free from intermodal dispersion. Therefore the o/p signal is almost identical to that of input pulse. ie. There is no pulse stretching.
- Because of their low NA these fiber require laser as light source and are used in long distance communications. Eg. In submarine cables.
- They are cheaper compared to other fibers. Almost 80% of the fibers manufactured are SMF. But because of their low core diameter, **splicing** is difficult.

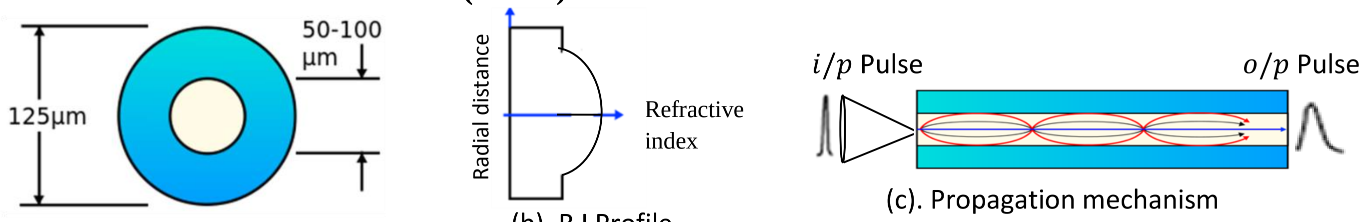
(b) **Step index Multimode fibers (MMF):**



(a). Geometry (b). R I Profile (c). Propagation mechanism

- Step index Multimode fibers have a core of diameter of about50 – 100µm with a cladding of diameter 100 - 250µm.
- The RI of the core and cladding remain constant with a small percentage of fractional index change (Δ).
- These fibers support the transmission by multimode ie. V number >2.4.
- Since the core diameter is large, the NA is small (NA > 0.3).
- The attenuation increases with the increase in core diameter. Pulse stretching arises as a result of intermodal dispersion.
- Since NA is better, LED can be used as light source and are used in short distance communications. Eg. In LAN network cables, and CCTV and CATV(**C**ommunity **A**ntenna **T**ele**v**ision eg.Cable TV network)
- Connectors are Cheaper because of large core diameter. Hence **splicing** is easy.

Graded index Multimode fibers (GRIN):



(a). Geometry (b). R I Profile (c). Propagation mechanism

- GRIN fibers have a core of diameter of about50 – 100µm with a cladding of diameter 100 - 250µm.
- The RI of the core is maximum at the axis and falls gradually away from the axis of the fiber, however cladding remains constant.
- All the GRIN fibers are multimode fibers only ie. V number > 2.4.
- NA is a function of RI of core and fractional index change. The refractive index of the core vary with the radial distance according to the relation $\boldsymbol{n(r) = n_1\sqrt{2\Delta\left[1-\left(\frac{r}{a}\right)^2\right]}}$
- The attenuation is relatively high and pulse stretching arises as a result of intermodal dispersion.
- Either LED or a laser can be used as light source.
- They are the costliest among all the fibers.
- Connectors are costlier because of the variation in the RI of the core along the radial distance. Hence **splicing** is difficult.
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Attenuation in Optical fibers:

"Loss of power suffered by the signal as it propagate along the length of the fiber is called attenuation." Attenuation in optical fibers may be due to either absorption or scattering or radiation.

Expression for the attenuation coefficient:

The attenuation of light signal in the optical fiber takes place according to Lambert's Law. The law states that the loss in the power of light signal as it propagate along the length of the fiber is proportional to its initial intensity. **ie** $\frac{-dP}{dL} \propto P$

Or $-\frac{dP}{dL} = \alpha P$

Where, the proportionality constant α is called the attenuation coefficient.

On re arranging the above equation, we have $-\frac{dP}{P} = \alpha\, dL$

Integrating on both sides $\int_{P_{in}}^{P_{out}} \frac{dP}{P} = -\alpha \int_0^L dL$

$\therefore$ $$\log\left(\frac{P_{out}}{P_{in}}\right) = -\alpha L$$

Or $$\alpha = -\frac{1}{L}\log\left(\frac{P_{out}}{P_{in}}\right)$$ **Bell/Km**

Bell / Km is a lrge unit to express attenuation. Since attenuation shold be very small for the efficient transmission of signals, it is expressed in decibel per Kilometer

$\therefore$ $$\alpha = -\frac{10}{L}\log\left(\frac{P_{out}}{P_{in}}\right)$$ **dB/Km**

This is the expression for attenuation coefficient.

Note: (i) The length of the fiber is always measured in Km.

(ii) The logarithm is in base 10.

Mechanism of attenuation (factors contributing to Attenuation)

1. Absorption losses:-

- Any homogeneous transparent medium have a tendency to absorb photons from the incident radiation. Such an absorption by a homogeneous medium which is free from all the impurities is called **intrinsic absorption**.
- Absorption of photons by impurities like metal ions such as iron, chromium, cobalt and copper in the silica glass, of which the fiber is made of,is called **absorption due to impurities.**

During signal processing photons interact with electrons of impurity atoms and excite the atoms. During the d de-excitation, the photons may be emitted either spontaneously or stimulatively. Such spontaneously emitted photons interfere destructively. Hence it is a loss of energy.

The other impurity such as hydroxyl ions (OH) causes significant absorption loss.

2. Scattering losses:

- When the wavelength of the photon is comparable to the size of the particle then the Rayleigh scattering takes place.(whose cross-section is inversely proportional to λ^4.)
- Because of the non-uniformity in manufacturing, sharp variations in the refractive index leads to scattering.

- Scattering of photons also takes place due to trapped gas bubbles, some unreacted starting materials and any impurity such as iron, chromium, cobalt and copper present in the core.

3. Radiation losses: Radiation losses occur due to macroscopic bends and microscopic bends.

- **Macroscopic bending:** All optical fibers are having critical radius of curvature provided by the manufacturer. Such macroscopic bending arises due to wrapping of the fiber over a spool, turning the fiber around the corners. If the fiber is bent below that critical radius of curvature, the light ray incident on the core cladding interface may not satisfy the condition of TIR and hence enter in to cladding. This causes loss of optical power.
- **Microscopic bending:** Optical power loss in optical fibers is due to non-uniformity of the axis of the optical fibers when they are laid. Non uniformity arises due to manufacturing defects or mechanical strain or lateral pressure built up on the fiber. Light rays falling on such non linear core cladding interface may not satisfy the condition of TIR and hence may get trapped in the cladding. The non-uniformity of the core cladding interface due to mechanical injuries can be overcome by introducing optical fiber inside a polyurethane jacket.

Block diagram of point to point fiber optic communication system:

- The microphone in the telephone receiver converts voice in to equivalent analog electrical signals.
- The analog signals are converted in to digital signals using a coder.
- A transmitter is a semiconductor diode laser which emits light according to the digital binary input. The light emitted from the laser source is launched on the optical fiber.
- The information in the form of light can be transmitted over large distances. If necessary, repeaters can be used. A repeater receives the signal and amplifies it and transmit again.
- At the receiving end the photodiode convert the received light in to equivalent binary electrical signals.
- The decoder converts binary electrical signal in to analog electrical signals.
- The loud speaker in the handset produces sound waves to convey the voice information.