Applied Physics for CSE stream

MODULE-1

LASER

Laser is an acronym of Light Amplification by Stimulated Emission of Radiation.

Characteristics of Laser beam

The following important properties of laser make it different from other ordinary source of light.

1) **Laser is highly monochromatic.**
   The laser beam is emitted in a very narrow frequency band.
2) **Laser light is spatially coherent.**
   The laser is highly coherent due to stimulated emission of radiation.
3) **Laser light extremely high directionality or unidirectionality.**
   The laser beam has very small divergence due to the resonant cavity. Hence light intensity does not decrease as fast with distance as it does in ordinary source of light.
4) **The laser beam is extremely bright or intense.**
   Light from laser is much brighter than other ordinary sources of light.

Interaction of radiation with matter: The three possible ways through which interaction of radiation with the matter can take place are

- Induced Absorption
- Spontaneous Emission
- Stimulated Emission

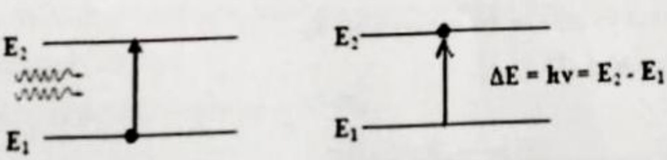
Induced Absorption:

It is a process in which an atom in the ground state undergoes transition to the higher energy state by absorbing an incident photon.

The process can be represented as

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

Where Atom* indicates an excited atom



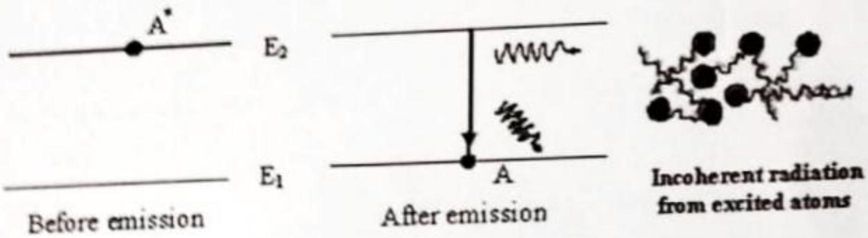
Before Absorption **After Absorption**

Spontaneous Emission:

It is a process in which an atom in the excited state undergoes transition to the ground state by emitting a photon without any aid of external agency.

As shown in the figure, consider an atom in the excited state E_2. It makes a transition to the ground state E_1 by the emission of a photon of energy **hv**. It may be represented as

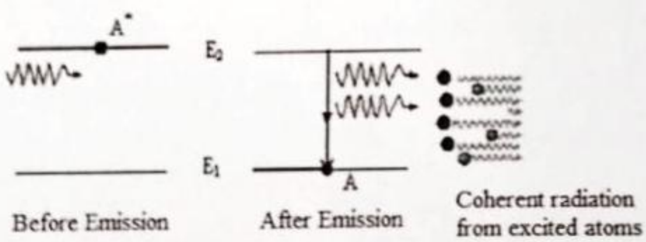
Atom* → Atom + Photon



Stimulated Emission:

It is a process in which an atom in the excited state undergoes transition to the ground state by the influence of passing photon. During this process a stimulated photon is emitted along with the incident photon and these photons are found to be coherent.

Atom * + Photon → atom + 2 Photons (Photon + Photon)



This principle is used for laser action.

Einstein's Coefficients:

(Expression for energy density of photons in terms of Einstein's Coefficients under thermal equilibrium condition)

- Consider two energy states E_1 and E_2.
- Let E_1 be the lower energy state and E_2 be the higher energy state.
- Let N_1 be the number of atoms per unit volume in the energy state E_1 and N_2 be the number of atoms per unit volume in the energy state E_2
- Let E_ν be the energy density of photons.

1. **Induced Absorption:**

In this case, an atom in the lower energy state E_1 undergoes transition to the higher energy state E_2 by absorbing a photon.

The number of such absorptions per unit time per unit volume is called Rate of induced absorption.

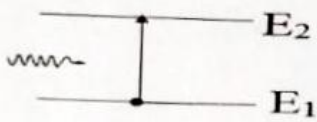
Rate of induced absorption $\propto$ $\mathbf{N_1} E_\nu$

$$= \mathbf{B_{12}\, N_1}\, E_\nu \text{ .... } \mathbf{(1)}$$

Where N_1 is number of atoms in the state E_1,

E_ν is the energy density in frequency range ν and $\nu + d\nu$ and

$\mathbf{B_{12}}$ is called Einstein coefficient of induced absorption.

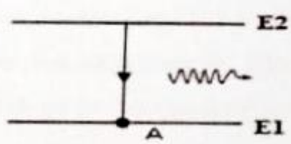


2. <u>Spontaneous Emission:</u>

In this case, an atom in the higher energy state E_2 undergoes transition to the lower energy state E_1 by emitting a photon without any aid of external agency. The number of such Spontaneous emissions per unit volume per unit time is called Rate of spontaneous emission.

Rate of spontaneous emission $\propto$ $\mathbf{N_2}$

$$= \mathbf{A_{21}\, N_2} \text{ ------- } \mathbf{(2)}$$



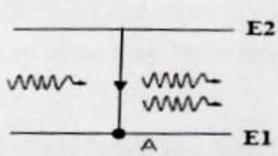
After Emission

Where, $\mathbf{A_{21}}$ is called Einstein coefficient of spontaneous emission.

3. <u>Stimulated Emission:</u>

In this case, an atom in the higher energy state E_2 undergoes transition to the lower energy state E_1 under the influence of passing photon.

During this process a stimulated photon is emitted along with the incident photon.



After Emission

The number of such stimulated emissions per unit time per unit volume in called the Rate of stimulated emission.

Rate of stimulated emission $\propto$ $\mathbf{N_2}\, E_\nu$

$$= B_{21}\, \mathbf{N_2}\, E_\nu \text{------ } \mathbf{(3)}$$

Where, $\mathbf{B_{21}}$ is called the Einstein coefficient of stimulated emission.

At thermal equilibrium, the number of upward transitions must be equal to the number of downward transitions.

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

$$B_{12} N_1 E_v = A_{21} N_2 + B_{21} N_2 E_v$$

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

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

$$E_v = \frac{A_{21}N_2}{B_{21}N_2\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]}$$

$$E_v = \frac{A_{21}}{B_{21}\left[\frac{B_{12}N_1}{B_{21}N_2} - 1\right]} \quad \text{............(4)}$$

By Boltzmann law, we have

$$\frac{N1}{N2} = e^{\left(\frac{E2-E1}{KT}\right)} = e^{\left(\frac{hv}{KT}\right)}$$

$\therefore$ (4) becomes,

$$E_v = \frac{A_{21}}{B_{21}}\left[\frac{1}{\frac{B_{12}}{B_{21}} e^{\frac{hv}{KT}} - 1}\right] \quad \text{..............(5)}$$

According to Planck's law, the equation for energy density of radiation at given temperature, E_v is

$$E_v = \frac{8\pi h v^3}{C^3}\left[\frac{1}{e^{\frac{hv}{KT}} - 1}\right] \quad \text{..................(6)}$$

Comparing equation (5) and (6), we get

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h v^3}{c^3} \text{ and } \frac{B_{12}}{B_{21}} = 1 \text{ or } B_{12} = B_{21}$$

This means that the probability of induced absorption is equal to the probability of stimulated emission. By neglecting the subscripts, A_{21} and B_{21} can be represented as A and B respectively i.e., $A_{21} = A$ and $B_{21} = B$.

Then at thermal equilibrium, the equation for energy density is

$$\boxed{E_v = \frac{A}{B\left[e^{\frac{hv}{KT}} - 1\right]}}$$

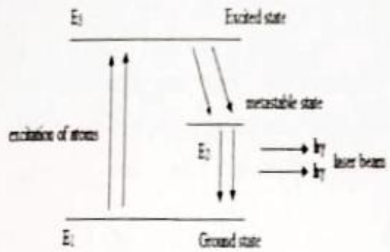
CONDITIONS FOR LASER ACTION:

There are two conditions for laser

1. **Population Inversion**
2. **Metastable State**

Population Inversion: Population inversion is the state of a system at which the population of a particular higher energy state is more than that of a specified lower energy state.

Metastable State: It is an energy state of a system in which atoms can stay for a longer Period of time that is of order 10^{-3} seconds.



To achieve population inversion a special kind of excited state called **metastable state** is used and it can be explained as follows.

Atoms in the ground state undergo transition to the higher energy state E_3 by absorbing incident photons. Since E_3 state is an ordinary excited state, atoms in the E_3 state don't stay over a long time, as a result the atoms immediately undergoes spontaneous downward transitions to the E_2 state. Since E2 is metastable state,

Atoms in the E_2 state stay over a long duration of about 10^{-2} to 10^{-3} seconds. Because of this, population of E_2 state increases and at a particular stage population inversion takes place. Once population inversion takes place the stimulated photons are emitted which gives laser beam. Hence the condition for laser action is achieved by means of **population inversion.**

REQUISITES OF A LASER SYSTEM:

There are three requisites of laser systems.

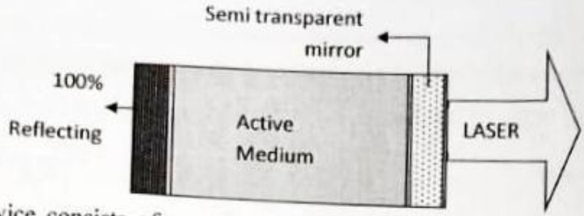
1. An Excitation source for pumping.
2. An Active medium to achieve population Inversion
3. An Optical resonant cavity or laser cavity

1. **An Excitation source for pumping action**: The process of supplying energy to the medium to excite an atom from lower energy state to a higher energy state is called pumping.

Energy can be supplied to atoms in different forms so there exists Optical pumping, Electrical pumping and Chemical Pumping.

2. **An active medium:** It may be solid, liquid or gaseous medium in which population inversion can be achieved and thereby is obtained is called an active medium.

3. **An Optical resonant cavity or laser cavity:**

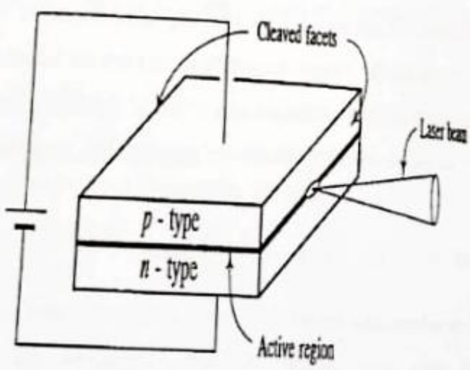


A laser device consists of an active medium bound between two mirrors. The mirrors reflect the photons to and fro through the active medium. A photon moving in a particular direction represents a light wave moving in the same direction. Thus, the two mirrors along with the active medium form a laser cavity.

SEMICONDUCTOR LASER (GALLIUM ARSENIDE LASER):

Principle: A Semiconductor diode laser is a specially fabricated p-n junction diode which emits light when it is forward biased. The 'p-n' junction is the active medium. Semiconductor lasers are continuous wave lasers.

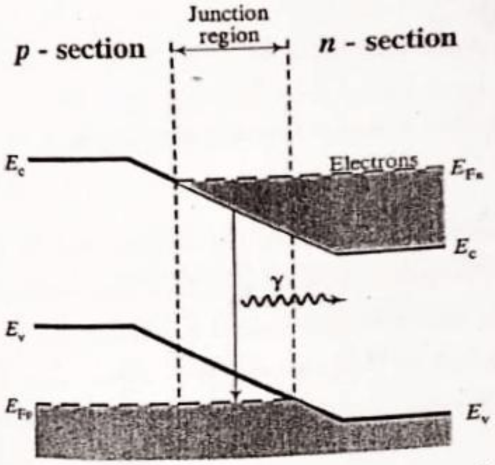
Construction:



- GaAs diode is a single crystal of Ga and As.
- Consists of heavily doped n and p sections.
- N-section is formed by doping with Tellurium and p-section with Zinc.
- Doping concentration is 10^{17} to 10^{19} dopant atoms/cm^3.
- The size of the diode is very small. The sides are 1mm and junction width is 1μm to 100μm.
- A pair of parallel planes is polished, and these play the role of reflecting mirrors. They provide sufficient reflection to sustain the lasing action.
- Other two sides are roughed surface to suppress the reflections of the photons.
- End surfaces of p-n sections parallel to the plane of junction are provided with electrodes to facilitate application of a forward bias voltage with the help of voltage source.

Working:

- Suitable forward bias voltage is applied to the diode to overcome the potential barrier. Due to forward biasing, more and more electrons are injected into the n-region. This leads to the increase in population of electrons in n-region and population of holes in the p-region. When the current crosses a certain value called threshold current, electrons from n-type come to higher energy level of the depletion region and population inversion is attained.



- Once the populations of charge carriers in the depletion region increases, the electrons are made to recombine with the holes in the lower energy level of depletion region.
- At this stage, a photon released by spontaneous emission may trigger stimulated emissions over a large no. of recombination leading to the buildup of laser radiation of high power. Thus, the current flow provides pumping in semiconductor laser.
- The energy gap of GaAs is 1.4 eV. The wavelength of emitted light is $\lambda = \frac{hc}{E_g} = \frac{6.626X10^{-34} \ X \ 3X10^{8}}{1.4X1.6X10^{-19}} = 8874$ Å.

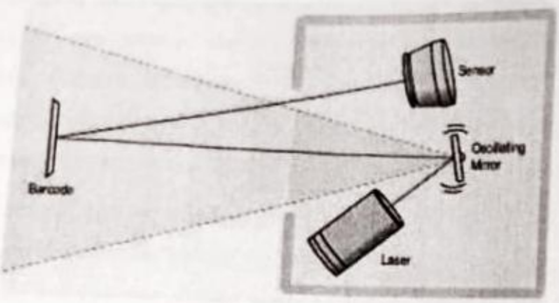
Applications of semiconductor laser:

1) Used in optical communication.
2) Used as reading devices for compact disc players.
3) Semiconductor lasers are used in laser printers.
4) Semiconductor lasers are used in medicine, interferometry, and barcode scanners.

Applications of LASER

LASER has a wide range of applications pertaining all disciplines of engineering. Here in the syllabus only three applications are discussed relevant to computing.

LASER bar code scanner

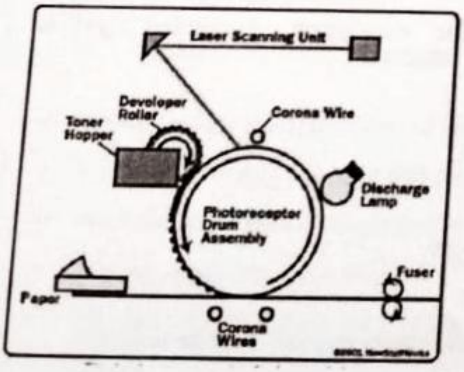


A barcode is a printed series of parallel bars or lines of varying width that is used for entering data into a computer system.

A barcode scanner/reader is a device with lights, lenses, and a sensor that decodes and captures the information contained in barcodes. Laser scanners use a laser beam as a light source and typically employ oscillating mirrors or rotating prisms to scan the laser beam back and forth across the barcode. A photodiode then measures the reflected light from the barcode. An analog signal is created from the photodiode and is then converted into a digital signal.

Laser Printer

Laser printers were invented at XEROX in 1969 by researcher Gray Starkweather. Laser printers are digital printing devices that are used to create high quality text and graphics on a plain printer. A Diode Laser is used in the process of printing in LASER printer.



Working Principle

1. A laser beam projects an image of the page to be printed onto an electrically charged rotating photo sensitive drum coated with selenium.
2. Photo conductivity allows charge to leak away from the areas which are exposed to light and the area gets positively charged.

3. Toner particles are then electrostatically picked up by the drum's charged areas, which have been exposed to light.
4. The drum then prints the image onto paper by direct contact and heat, which fuses the ink to the paper.

Advantages

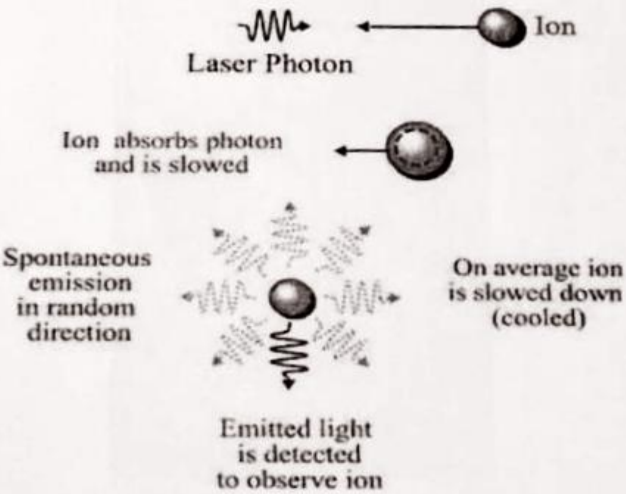
1. Laser printers can produce high quality output on ordinary papers.
2. The cost per page of toner cartridges is lower than other printers.

Disadvantages

1. The initial cost of laser printers can be high.
2. Laser printers are more expensive than dot-matrix printers and ink-jet printers.

Laser Cooling

Principle of LASER cooling: Laser cooling is the use of dissipative light forces for reducing the random motion and thus the temperature of small particles, typically atoms or ions. Depending on the mechanism used, the temperature achieved can be in the milli kelvin, micro kelvin, or even nano kelvin regime.



If an atom is travelling toward a laser beam and absorbs a photon from the laser, it will be slowed by the fact that the photon has momentum $p=\frac{E}{c}=\frac{h}{\lambda}$. It would take many such absorptions to cool the sodium atoms to near 0K. The following are the types of lasers cooling.

•Doppler cooling

•Sisyphous cooling

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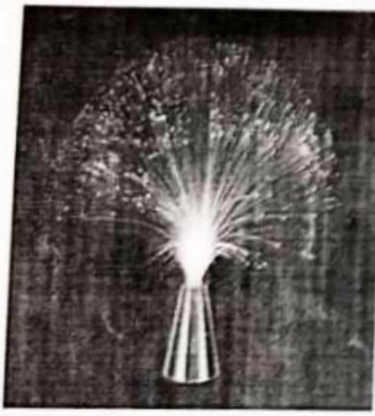
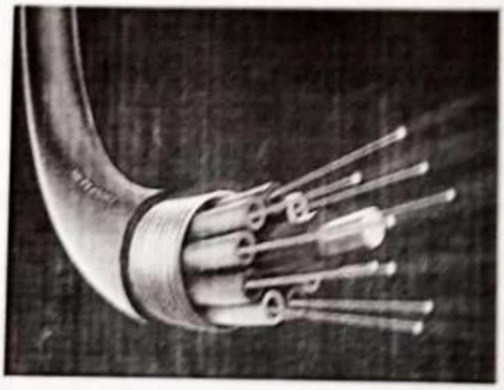
MODULE-1

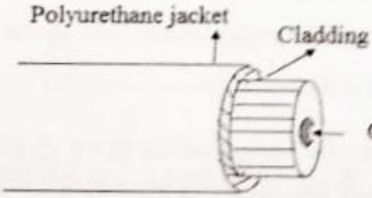
OPTICAL FIBERS

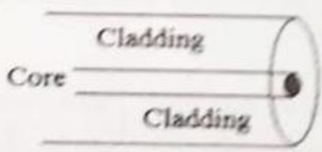
- Optical fiber is device used to transmit light through bundle of thin fibers of transparent materials from one end to other end covering a very long distance.
- These are essentially light guides used in optical communications as waveguides.
- The principle behind the transmission of light waves in an optical fiber is TIR (Total internal Reflection).





CONSTRUCTION OF OPTICAL FIBER:

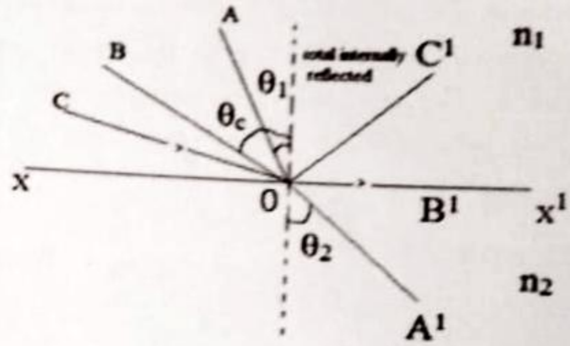




- An optical fiber is cylindrical in shape
- It has two parts a) inner part and b) outer part.
- The inner part is made of glass or plastic and its cylindrical in shape, it is called core. Core is having high refractive index.
- Outer part is a concentric cylinder surrounding the core, and is called cladding. Cladding is also made of same material with little lesser refractive index.
- The polyurethane jacket is used to enclose cladding which safeguards the fiber against chemical reaction with surroundings and also crushing.
- Many fibers which are protected by individual jackets are grouped to form a cable. A cable may consist of one to several hundred such fibers.

TIR (TOTAL INTERNAL REFLECTION):

It is the principle behind the transmission of light waves in an optical fiber which is a well-known optical phenomenon in physics.



A ray AO, travelling in a medium of refractive index n_1 is separated by the boundary XX^1, from another medium of lower refractive index n_2. So $n_1 > n_2$.

The incident ray AO makes an angle θ_1 with the normal in the medium of refractive index n_1. The same AO ray undergoes refraction into the medium of refractive index n_2 and it bends away from the normal, since $n_1 > n_2$. θ_2 is the angle made by the refracted ray with the normal.

If we increase θ_1 for certain value of $\theta_1 = \theta_c$ called critical angle, $\theta_2 = 90$, for such a case, the refracted ray grazes along the boundary of separation along OB^1 while incident ray is along BO.

If $\theta_1 > \theta_C$, incident ray CO always gets reflected back into the same medium in which it is incident on the boundary. These takes place as per the law of reflection.

For refraction, we have from Snell's law

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

For $\theta_1 = \theta_C$ and $\theta_2 = 90^0$

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

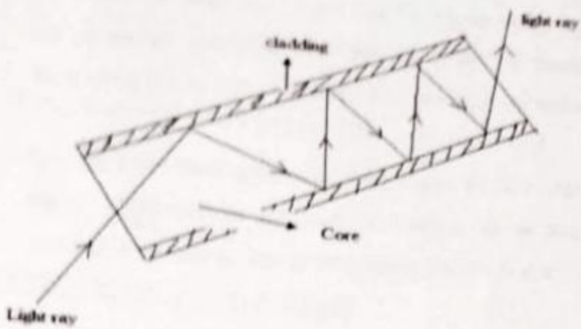
$n_1 \sin \theta_C = n_2$ $\quad (\sin 90^0 = 1)$

or

$$\boxed{\theta_C = \sin^{-1} \left[\frac{n_2}{n_1}\right]}$$

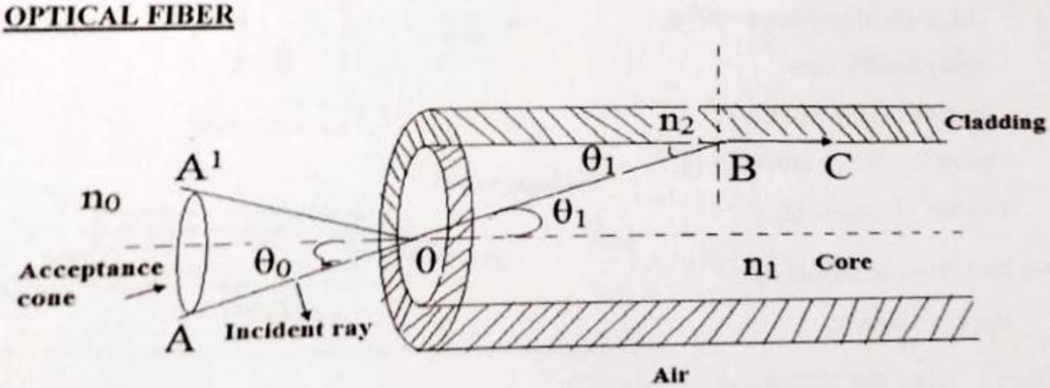
PROPAGATION MECHANISM:

"Optical fibers are the devices used to transmit light effectively along any desired path."



- Optical fibers work on the principle of total internal reflection (TIR)
- For total internal reflection there are two essential conditions, they are
  1) The light ray must pass from denser to rarer medium.
  2) The angle of incidence must be greater than the critical angle $i > c$.
- A waveguide is a tubular structure through which energy of some sort could be guided in the form of waves. Since light waves can be guided through a fiber, it is called fiber waveguide or fiber light guide.
- An optical fiber consists of a core and cladding.
- In any optical fiber the refractive index (RI) of cladding is always lesser than that of its core to achieve TIR, i.e. RI cladding < RI of core.
- When a light is incident at one end of the fiber, it undergoes total internal reflection and finally emerges at the other end of the fiber. It is found that intensity of emergent light is almost same as that of incident light. In this way optical fibers transmit light effectively along any desired path.

NUMERICAL APERTURE AND CONDITION FOR RAY PROPAGATION IN AN OPTICAL FIBER



- Consider a ray AO entering into the core at an angle θ_0 to the fiber axis. Then it is refracted along OB at an angle θ_1 in the core and further falls at critical angle of incidence (equal to 90 - θ_1) at B on the interface between core and cladding. Since the incidence is critical angle of incidence, the ray is refracted at 90^0 to the normal drawn to the interface i.e. grazes along BC.

- Any ray that enters into the core at an angle of incidence less than θ_0 will have refractive angle less than θ_1 because of which its angle of incidence 90^0-θ_1 at the interface will become greater than the critical angle of incidence and hence undergoes total internal reflection.
- On the other hand any ray that enters at an angle of incidence greater than θ_0, will have to be incident at the interface at an angle less than the critical angle, it get refracted into the cladding region. Then it travels across the cladding and emerges into the surroundings and will be lost.
- If now OA is rotated around the fiber axis keeping θ_0 same, it describes a conical surface.
- Therefore if a beam converges at a wide angle into the core, then those rays which are funneled into the fiber with in this cone will only be totally internally reflected, and thus confined within for propagation.

θ_0 is called waveguide acceptance angle or the acceptance cone half angle.

Sinθ_0 is called Numerical aperture (NA) of the fiber. The condition for ray propagation is, if θi is the angle of incidence, then the ray will propagate if $\theta i < \theta_0$

(Or) $\sin \theta_i < \sin \theta_0$

Numerical aperture: "The light gathering capacity of an optical fiber is known as numerical aperture. NA = Sinθ_0

Expression for NA

Let n_0, n_1, n_2 be the refractive indices of surrounding medium, core and cladding respectively. For refraction at the point of entry of the ray "AO" into the core, we can apply Snell's law, i.e., at point O

$$n_o \sin \theta_0 = n_1 \sin \theta_1 \quad \text{--------} (1)$$

At the point B

The angle of incidence $= 90^0 - \theta_1$

Apply Snell's Law

$$n_1 \sin (90^0 - \theta_1) = n_2 \sin 90^0$$

$$n_1 \cos \theta_1 = n_2 \qquad (\sin 90^0 = 1)$$

$$\cos \theta_1 = \frac{n_2}{n_1} \quad \text{-------} (2)$$

Equation (1) can be written as

$$\sin \theta_0 = \frac{n_1}{n_0} \sin \theta_1$$

$$= \frac{n_1}{n_o} \sqrt{(1 - \cos^2 \theta_1)}$$

$$= \frac{n_1}{n_o} \sqrt{1 - (\frac{n_2}{n_1})^2}$$

$$= \frac{n_1}{n_0}\sqrt{\frac{n_1^2 - n_2^2}{n_1^2}}$$

$$= \frac{n_1}{n_0}\frac{\sqrt{n_1^2 - n_2^2}}{n_1}$$

$$\boxed{\sin\theta_0 = \frac{1}{n_0}\sqrt{n_1^2 - n_2^2}}$$

If the medium surrounding the fiber is air then n_0=1

Therefore, $\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

i.e. $$\boxed{NA = \sqrt{n_1^2 - n_2^2}}$$

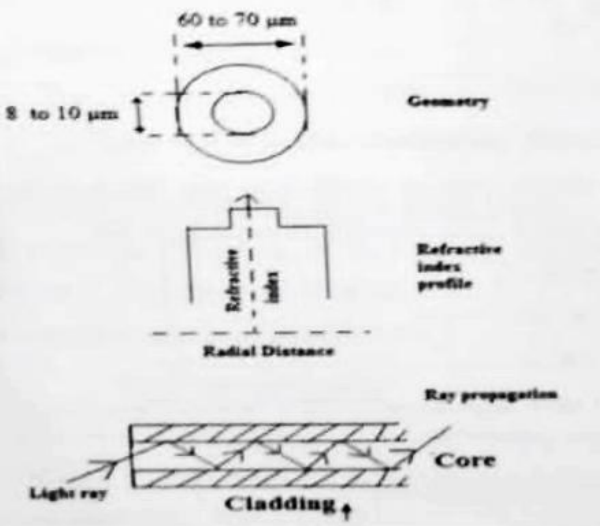
TYPES OF OPTICAL FIBERS:

- Optical fibers are classified into 3 types based on the materials used for making optical fibers, number of modes transmitted and the RI profile of the fibers.
- The curve which represents the variation of refractive index with respect to the radial distance from the axis of the fiber is called the <u>Refractive Index Profile</u>.

Optical fibers are classified into 3 types namely:

a) Step index single mode fiber
b) Step index multimode fiber
c) Graded index multimode fiber

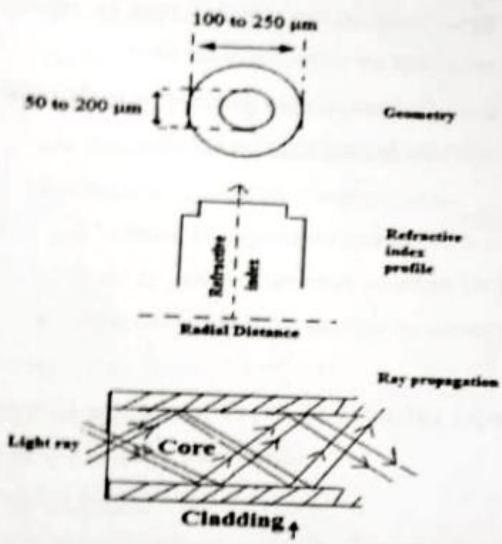
Step index single mode fiber:



- Here core material has uniform refractive index value.
- Cladding also has uniform refractive index but of little lesser value than that of core. This results in a sudden increase in the value of RI from cladding to core.
- RI profile takes the shape of a step.

- Diameter of the core is 8 to 10 μm.
- Diameter of the cladding is 60- 70 μm.
- Since the core is very narrow, it can guide just a single mode. Hence it is called single mode fiber.
- These are the most extensively used ones and constituent 80% of all the fibers that are manufactured.
- They need lasers as the source of light
- It is less expensive, but very difficult to splice.
- Used in submarine cable system.

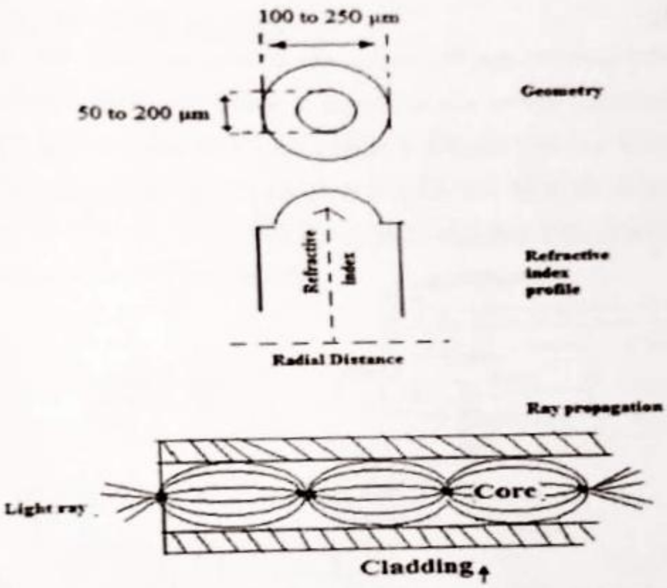
Step index multimode fiber:



- Here, the core material has uniform refractive index value.
- Cladding also has uniform refractive index but of little lesser value than that of the core. This results in a sudden increase in the value of RI from cladding to core.
- RI profile takes the shape of a step.
- Diameter of the core is 50 to 200 μm.
- Diameter of cladding is 100- 250 μm
- Here the core material has a much larger diameter, which supports propagation of large number of modes.
- RI profile is also similar to single mode optical fiber.
- Uses LED or laser as source of light.
- It is least expensive all and is used in data links which has lower band width requirements

Graded index multimode optical fiber:

- It is also denoted as GRIN.
- The geometry of GRIN is same as that of step index multimode fiber.
- The special feature of the core is that its RI value decreases in the radially outward direction from the axis, and becomes equal to that of the cladding at the interface. But the RI of the cladding remains uniform.



- Diameter of the core 50 to 200 μm.

  Diameter of cladding 100- 250 μm
- Uses LED or laser as source of light
- Application is in the telephone trunk between central offices.

ATTENUATION (POWER LOSS OR FIBER LOSS):

The power loss suffered by the signal when it propagates through the fiber is called Attenuation. It is also known as fiber loss.

The expression for attenuation coefficient is

$$\alpha = -\frac{10}{L}\log_{10}\left[\frac{P_{out}}{P_{in}}\right] \text{ dB/Km}$$

L is the length of optical fiber, P_{in} is the initial intensity with which the light is launched into the fiber and P_{out} is the intensity of the light received at output end of the fiber.

Types of attenuation or losses in fiber are:

i) Absorption loss

ii) Scattering loss

iii) Radiation loss

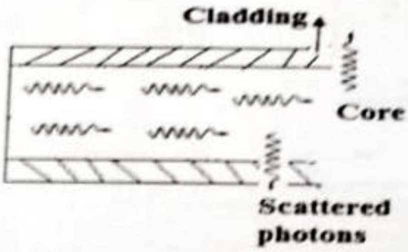
i) **Absorption loss:**

a. Absorption by impurities: Iron, Chromium, Cobalt and Copper are some of the impurities generally present in the glass fiber. When signal propagates through the fiber, a few photons associated with the signal are absorbed by the impurities present in the fiber. This results in power loss.

b. Intrinsic absorption: The absorption that takes place in the fiber material assuming that there are no impurities in it.

ii) **Scattering loss:**

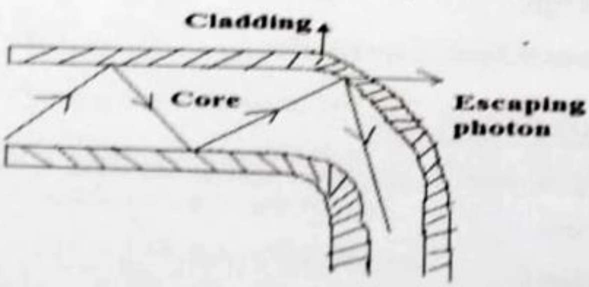
When a signal propagates through the fiber, a few photons associated with the signal are scattered by the scattering objects such as impurities present in the fiber. The dimensions of the scattering objects are very small compared to the wavelength of light. This type of scattering is similar to Rayleigh scattering. It is found that the co-efficient of scattering is inversely proportional to the wavelength of the object.



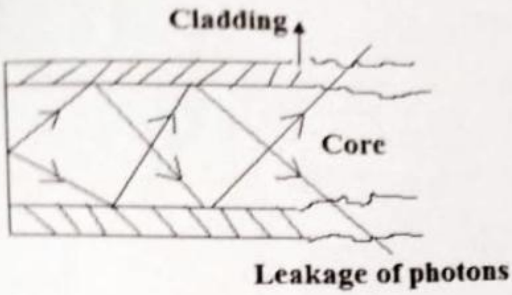
iii) **Radiation loss:**

It is due to the bending of fibers and it can be explained as follows:

a) **Macroscopic bending:** They are the bends with radii much larger compared to fiber diameter. It occurs while wrapping the fiber on a spool or turning it around a corner. If the bending is too sharp then the power loss becomes very high.



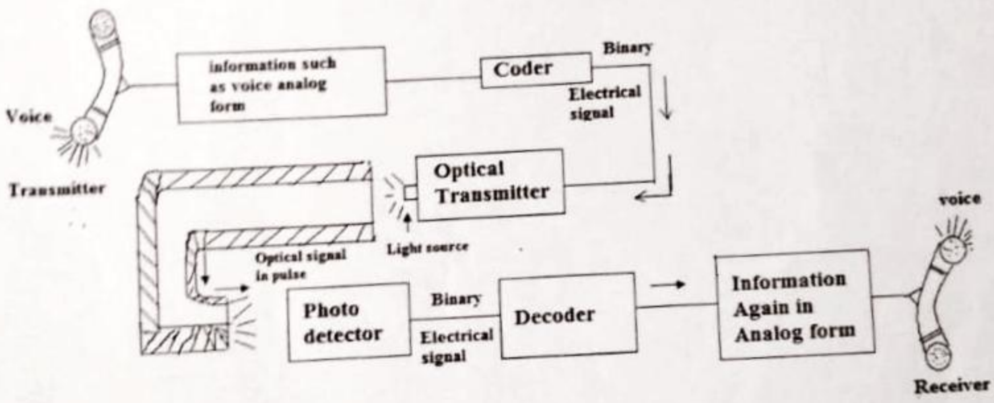
b) **Microscopic bending:** It occurs due to the non-uniformity in the fibers while manufacturing. Because of this a few modes undergo leakage which results in power loss.



APPLICATIONS OF OPTICAL FIBERS

1. Fiber Optic Communication:

Optical fiber communication is the transmission of information by propagation of optical signal through optical fibers over the required distance which involves driving optical signal from electrical signal at the transmitting end and conversion of optical signal back to electrical signal at the receiving end.



- Firstly we have analog information such as voice of a telephone user. The voice gives rise to electrical signals in analog form coming out of the transmitter section of the telephone.
- The analog signal is converted to binary data (digital) with the help of an electronic system called Coder.
- These electrical pulses are converted into optical pulses by modulating the light emitted by an optical source, in the binary form. This unit is called optical transmitter (converts electrical signals into light signals)
- This optical Signal is fed into the fiber.
- The receiver section uses Photo detector which converts the optical signal into corresponding electrical signal then electrical signal is amplified and recast in the original form by means of an electrical regenerator, which is part of receivers section.
- Lastly using the Decoder, the binary electrical signal is converted back to analog electrical signal, which will be same information such as voice, which was there at the transmitting end.

2. **Fiber Optic Networking**

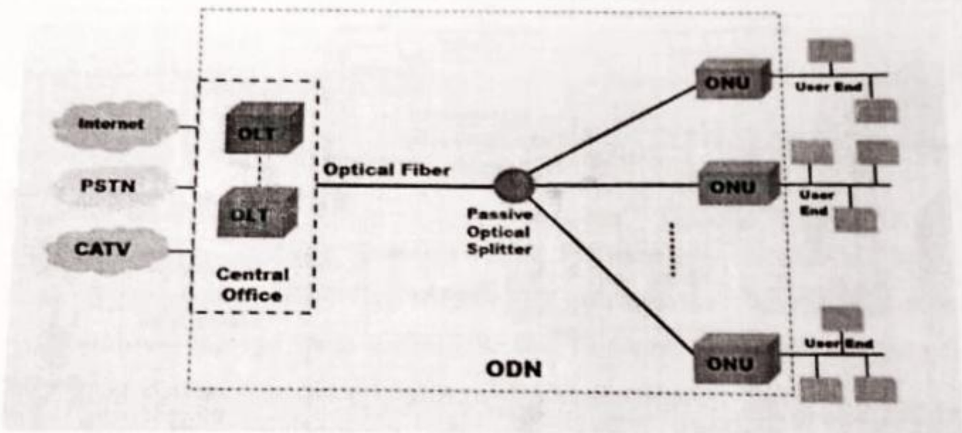
Local Area Network

A Local Area Network (LAN) is a type of computer net- work that interconnects multiple computers and computer- driven devices in a particular physical location. Traditionally copper coaxial cables are used for LAN.

Passive Optical LAN

Passive here refers to the unpowered condition of the fiber and splitting/combining components. Passive optical LANs are built entirely using Optical fiber cables. The passive optical LAN is complicated as it works on the concept of optical network terminals (ONT) and passive optical splitters. Network switches act as passive splittersand the commercial media converters act as optical net- work terminals in a real-time application of passive optical LAN.

Passive Optical Network



Advantages

1. High speeds and bandwidth
2. Longer distances are possible
3. Less chance of errors