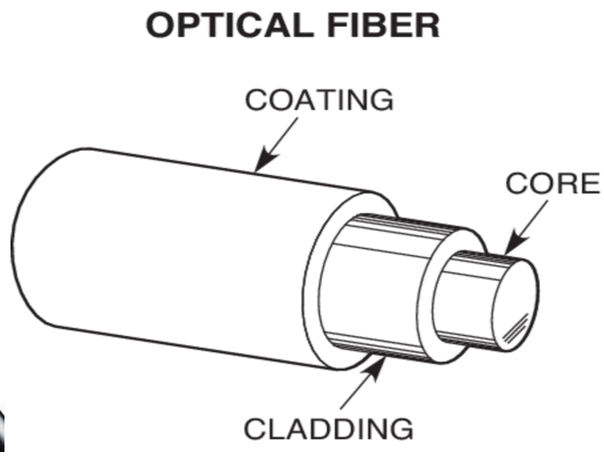
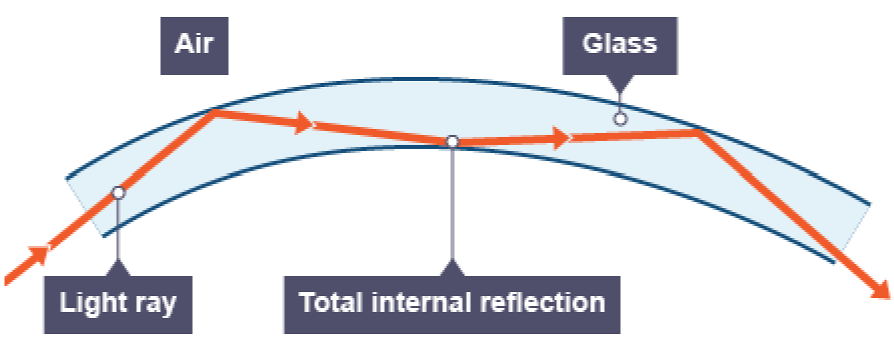
Optical Fiber

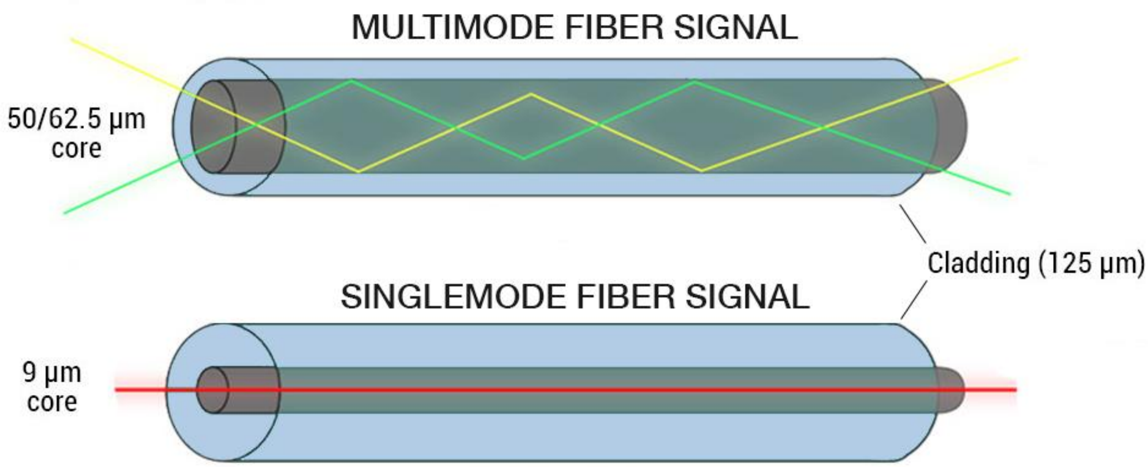


An optical fiber is a transparent cylindrical system, as thin as human hair, made up of glass or clear plastic, designed to guide light wave along its length. An optical fiber works on the principle of total internal reflection. The central part of the system is known as core and the seal outside the core is known as cladding. The refractive index of the core material is always greater than that of the cladding. The coating outside the cladding is known as buffer coating. In fact both core and cladding both are made from glass material. The optical fibers are strong wires and can be easily bent in rolls.



Types of optical fiber:-

On the basis of modes of propagation there are two types of optical fibers.



1. Single mode Optical fiber:-

In single mode optical fiber there is only one mode of propagation. It is smaller core diameter. It is step index fiber.

2. Multimode Optical fiber:-

In multimode optical fiber there are two or more than two modes of propagation, so it has larger core diameter.

On the basis of index profile, optical fibers are further classified into two groups. a) Step index fiber and b) graded index fiber.

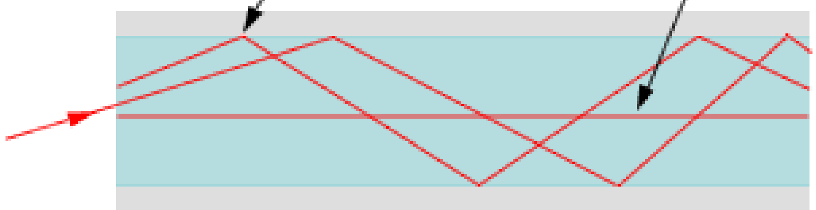
The single mode fiber is usually of step index type but the multimode optical fiber is of both step index and graded index type.

1. **Single mode step index Fiber:-**

   In single mode fiber, there is only one mode of propagation. In this type of fiber, core has higher constant refractive index ($\mu_1 = 1.52$) and cladding has lower constant refractive index ($\mu_2 = 1.48$). So refractive index changes abruptly at the core cladding interface. Therefore it is called step index fiber. It has high transmission loss due to abrupt change in refractive index. It is difficult to manufacture and handle and therefore it is costly.

2. **Multimode step index Fiber:-**

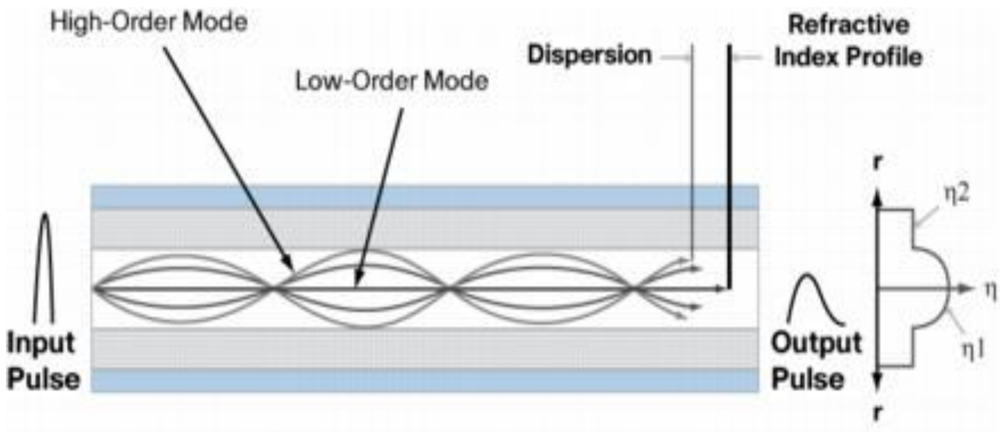
   In multimode fiber, there are multiple modes of propagation. In this type of fiber, core has higher constant refractive index ($\mu_1 = 1.52$) and cladding has lower constant refractive index ($\mu_2 = 1.42$). So refractive index changes abruptly at the core cladding interface. Therefore it is called step index fiber. It has high transmission loss due to abrupt change in refractive index. It is easy to manufacture and is less costly.



Step-Index Multimode Fiber

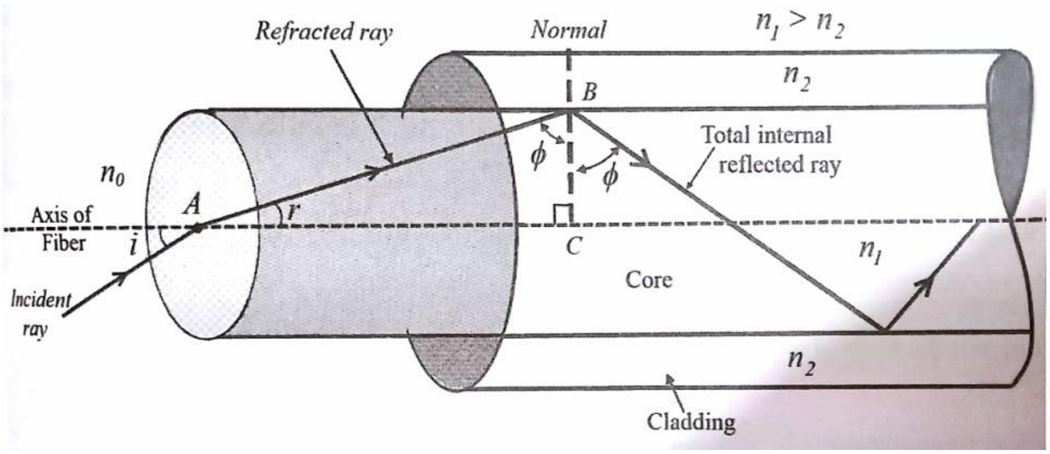
3. Multimode Graded index Fiber:-

In multimode fiber, there are multiple modes of propagation. The number of modes in graded index fiber is about half of that in multimode step index fiber. So it has lower dispersion than in multimode step index fiber. It has low transmission loss because the continuous decrease in the refractive index causes bending of light towards the centre of the core. Its manufacture is more complex than step index multimode fiber.



Multimode Graded Index

Propagation of light wave in Optical Fiber:-



Consider a ray incident on an optical fiber, making an angle 'i' with axis from outside as shown in figure. The refractive index of outside is μ_0, that of core is μ_1 and cladding is μ_2 respectively. From Snell's law, for ray from air to core is;

$$\frac{\mu_1}{\mu_0} = \frac{\sin i}{\sin r}$$

$$or, \qquad \mu_0 \sin i = \mu_1 \sin r \ldots\ldots\ldots (1)$$

$$or, \qquad \frac{\mu_0}{\mu_1} \sin i = \sin r$$

$$or, \qquad \frac{\mu_0}{\mu_1} \sin i = \sin(90 - \emptyset)$$

$$or, \qquad \frac{\mu_0}{\mu_1} \sin i = \cos \emptyset$$

$$\therefore \cos \emptyset = \frac{\mu_0}{\mu_1} \sin i \ldots\ldots\ldots (2)$$

Again, from Snell's law for ray from core to cladding.

$$\frac{\mu_2}{\mu_1} = \frac{\sin i}{\sin r}$$

Now, the angle of incidence 'i' is critical angle 'c', when angle of refraction is a right angle.

$$\mu_1 \sin c = \mu_2 \sin 90 \ldots \ldots \ldots (3)$$

From equation (2) and (3), squaring and adding we get;

$$sin^2 c + cos^2 c = 1 \quad (when\ \emptyset = c)$$

$$or, \quad \frac{\mu_2^2}{\mu_1^2} + \frac{\mu_0^2}{\mu_1^2} sin^2 i = 1$$

$$or, \qquad sin^2 i = \frac{\mu_1^2 - \mu_2^2}{\mu_0^2}$$

$$\therefore \sin i = \sqrt{\frac{\mu_1^2 - \mu_2^2}{\mu_0^2}}$$

For air medium, $\mu_0 = 1$, in such case $\sin i$ can have a maximum value;

$$i.e. \sin i_{max} = \sqrt{\mu_1^2 - \mu_2^2}$$

The quantity $\sqrt{\mu_1^2 - \mu_2^2}$ is known as **numerical aperture (NA)** of the optical fiber and it measure the light gathering power of fiber.

$$i.e. NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$= [(\mu_1 - \mu_2)(\mu_1 + \mu_2)]^{\frac{1}{2}}$$

$$= [\frac{\mu_1 - \mu_2}{\mu_1} . \frac{\mu_1 + \mu_2}{2} . 2\mu_1]^{\frac{1}{2}}$$

$$when, \qquad \mu_1 \cong \mu_{2,} \, then \ \frac{\mu_1 + \mu_2}{2} = \mu_1$$

$$= [\frac{\mu_1 - \mu_2}{\mu_1} . \mu_1 . 2\mu_1]^{\frac{1}{2}}$$

$$= [\Delta . 2\mu_1^2]^{\frac{1}{2}}$$

$$\therefore \quad NA = \mu_1\sqrt{2\Delta} \qquad where, \Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

It is seen that NA only depends on the refractive indices of core and cladding.

Normalized frequency (V-number):-

The V-number determines the number of modes that can propagate through a fiber. It is an important parameter that characterized an optical fiber.

Mathematically it is given by;

$$V = \frac{2\pi a}{\lambda}\sqrt{\mu_1{}^2 - \mu_2{}^2}$$

Where a is the radius of wire λ is the wavelength, μ_1 and μ_2 are refractive indices of core and cladding.

- For $V < 2.405$, fiber can support only one mode and is called single mode fiber.
- For $V > 2.405$, fiber can support number of modes simultaneously and is called multimode fiber.

Acceptance angle:-

It is a maximum value of angle of incidence 'i' for which light ray can propagate through fiber. It is the angle made by incidence ray with fiber axis.

Application of optical fiber:-

- Fiber optics essentially deals with the communication including voice signal, video signal or digital data. This is done by transmission of light through optical fiber.
- The fiber optics are used in the fabrication of fiber scope in endoscopy in medical science. Such fiber scopes are used in visualization of internal organ of human body.
- The fiber optics is also useful in industry. It can be used to examine welds nozzle and combustion chamber inside aircraft engine.

Advantages:-

Optical fiber has many advantages that are not found in conducting wire.

- Cheaper:- Optical fiber are made from silica(SiO_2), which is one of the most easily available material on the earth.
- Optical fibers are light in weight and flexible.
- Optical fiber transmit light wave not electrical so they are not hazardous.
- Band width of light wave is greater than that of electrical wave so greater amount of information carried over in optical fiber.
- There is less interference of waves so the cross talk is negligible in fiber communication.
- Optical fibers have longer life time.
- Low loss per unit length.

Numerical Examples:-

1. **An optical fiber has fractional index difference of 0.2 and cladding refractive index 1.59. Determine the acceptance angle for the fiber for water in which, have refractive index of 1.33.**

Solution:-

$\text{Fractional index difference } (\Delta) = 0.2$

$\text{Cladding refractive index } (\mu_2) = 1.59$

$\text{Refractive index of water } (\mu_0) = 1.33$

$\text{Acceptance angle (i)} = ?$

We know that;

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

$$or, \qquad 0.2 = \frac{\mu_1 - 1.59}{\mu_1}$$

$$or, \qquad 0.2\mu_1 - \mu_1 = -1.59$$

$$or, -0.8\mu_1 = -1.59$$

$$\therefore \ \mu_1 = 1.9875$$

Also for acceptance angle, we have;

$$Sin\ i = \sqrt{\frac{\mu_1^2 - \mu_2^2}{\mu_0^2}} = \sqrt{\frac{(1.987)^2 - (1.59)^2}{(1.33)^2}}$$

$$or, Sin\ i = 0.88$$

$$\therefore \text{Acceptance angle (i)} = 62^0$$

2. A glass clad fiber is made with core glass of refractive index 1.5 and cladding is doped to give a fractional index difference of 5×10^{-4}. Determine (i) cladding index (ii) critical angle (iii) acceptance angle, and (iv) Numerical aperture.

Solution:-

Core refractive index $(\mu_1) = 1.5$

Fractional index difference $(\Delta) = 5 \times 10^{-4}$

Cladding index $(\mu_2) = ?$

Critical angle $(C) = ?$

Acceptance angle $(i_{max}) =?$

Numerical aperture $(NA) =?$

(i) We have $\Delta = \dfrac{\mu_1 - \mu_2}{\mu_1}$

$$or, \qquad 5 \times 10^{-4} = \frac{1.5 - \mu_2}{1.5}$$

$$\therefore \text{cladding index } (\mu_2) = 1.49925$$

(ii) Critical angle; $\text{Sin C} = \dfrac{\mu_2}{\mu_1} = \dfrac{1.49925}{1.5}$

$$\therefore C = 88^0$$

(iii) $\text{Sin } i_{max} = \sqrt{\mu_1^2 - \mu_2^2} = \sqrt{(1.5)^2 - (1.49925)^2}$

$$\therefore \; i_{max} = 2.79^0$$

(iv) $\text{NA} = \mu_1\sqrt{2\Delta} = 1.5 \times \sqrt{2 \times 0.005} = 0.0474$

3. The refractive index for core and cladding for a step index fiber are 1. 52 & 1.41 **respectively. Calculate (i)**

critical angle (ii) Numerical aperture, and (iii) The maximum incidence angle.

Solution:-

Refractive index of core $(\mu_1) = 1.52$

Refractive index of cladding $(\mu_2) = 1.41$

(i) Critical angle; $\text{Sin C} = \dfrac{\mu_2}{\mu_1} = \dfrac{1.41}{1.52}$

$$\therefore C = 68.068$$

(ii)We have; $\Delta = \dfrac{\mu_1 - \mu_2}{\mu_1} = \dfrac{1.52 - 1.41}{1.52} = 0.072$

$\therefore \text{NA} = \mu_1\sqrt{2\Delta} = 1.52 \times \sqrt{2 \times 0.072} = 0.576$

(iii) $\text{Sin i}_{max} = \sqrt{\mu_1^2 - \mu_2^2} = \sqrt{(1.52)^2 - (1.41)^2}$

$$\therefore \text{ i}_{max} = 34.591^0$$

Exercise:-

1. Trace the ray diagram that shows the propagation of light through the step and graded index optical fiber. Write the importance of self-focusing in an optical fiber.
2. What is optical fiber? Explain numerical aperture and acceptance angle. Also compare the attenuation property

efficiency and cost of single mode and multimode optical fibers.

3. Discuss the physical significance of numerical aperture (NA). How does it depend on refractive index of core and cladding?
4. What is an optical fiber? Show that Numerical aperture of an optical fiber is given by the expression, $\mathrm{NA} = \mu_1\sqrt{2\Delta}$, where the symbols carry their usual meanings.
5. An optical fiber has a numerical aperture of 0.22 and core refractive index 1.62. Determine the acceptance angle for the fiber in liquid which has a refractive index of 1.25. Also, determine the refractive index change.
6. Calculate the refractive index of the core and materials of a fiber from following data. Numerical Aperture (NA) = 0.22 and fractional refractive index change $\Delta = 0.012$.