Ray Model

Propagation of Light in an Optic Fibre Basics

- Optical fiber is basically a solid glass rod. The diameter of rod is so small that it looks like a fiber.

- Optical fiber is a dielectric waveguide. The light travels like an electromagnetic wave inside the waveguide. The dielectric waveguide is different from a metallic waveguide which is used at microwave and millimeter wave frequencies.

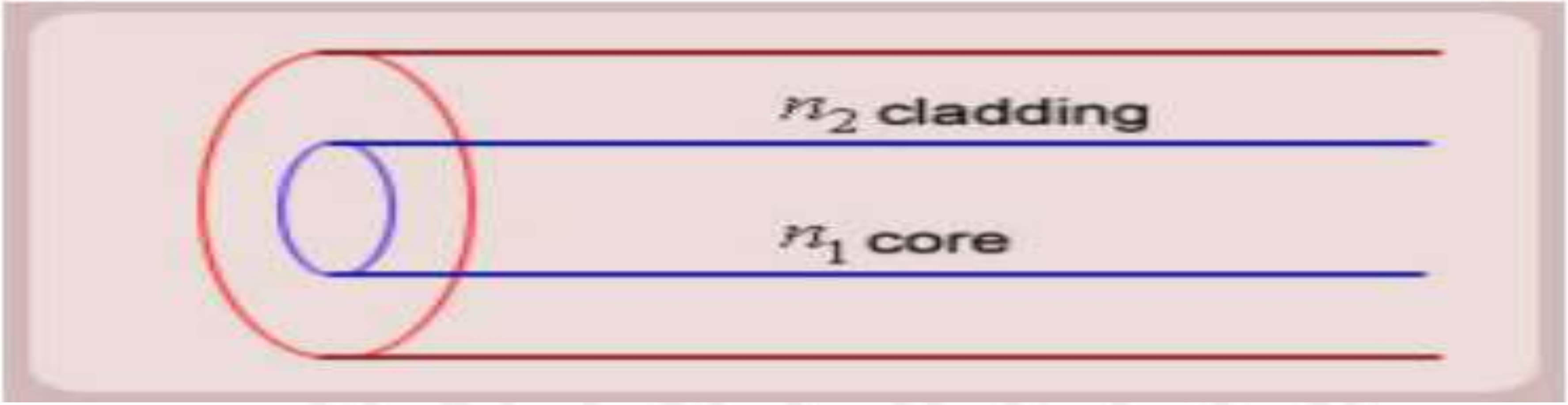
- In a metallic waveguide, there is a complete shielding of electromagnetic radiation but in an optical fiber the electromagnetic radiation is not just confined inside the fiber but also extends outside the fiber

- The light gets guided inside the structure, through the basic phenomenon of total internal reflection .

Basics

- The optical fiber consists of two concentric cylinders; the inside solid cylinder is called the core and the surrounding shell is called the cladding

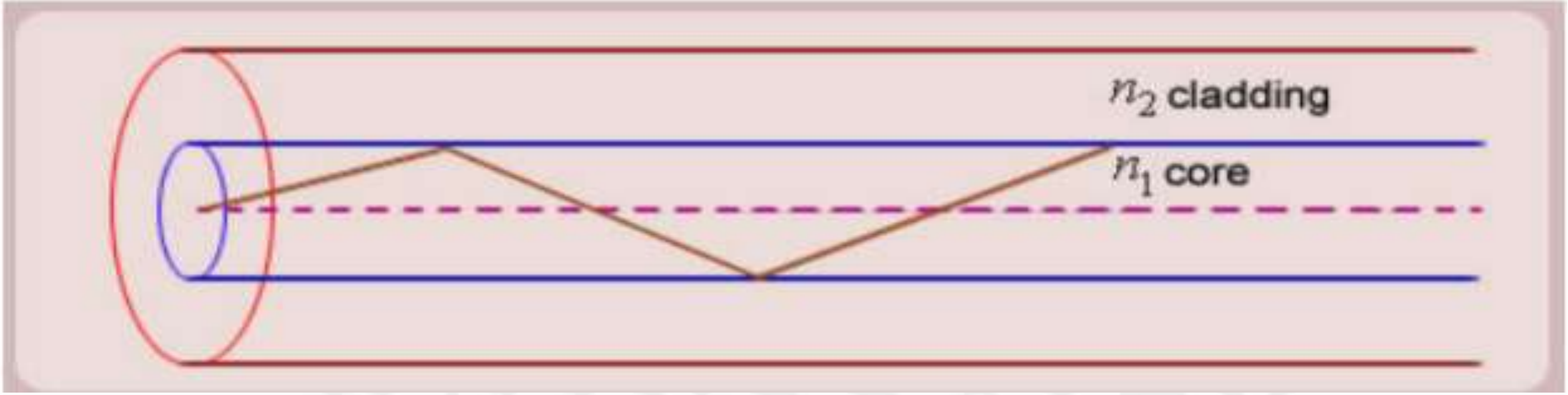
- For the light to propagate inside the fiber through total internal reflections at core-cladding interface, the refractive index of the core must be greater than the refractive index of the cladding. That is n1>n2



Ray Model

- A simple ray model provides an idealized **model** of light, obtained by choosing a line that is perpendicular to the wavefronts of the actual light, and that points in the direction of energy flow.

- The incident light travels using the phenomenon total internal reflection.



Ray Model

Operations

- For propagation of light inside the core there are two possibilities.

1. A light ray is launched in a plane containing the axis of the fiber. We can then see the light ray after total internal reflection travels in the same plane i.e., the ray is confined to the plane in which it was launched and never leave the plane. In this situation the rays will always cross the axis of the fiber. These are called the Meridional rays.

2. The other possibility is that the ray is not launched in a plane containing the axis of the fiber. For example if the ray is launched at some angle such that it does not intersect the axis of the fiber, then after total internal reflection it will go to some other plane. We can see that in this situation the ray will never intersect the axis of the fiber. The ray essentially will spiral around the axis of fiber. These rays are called the Skew rays.

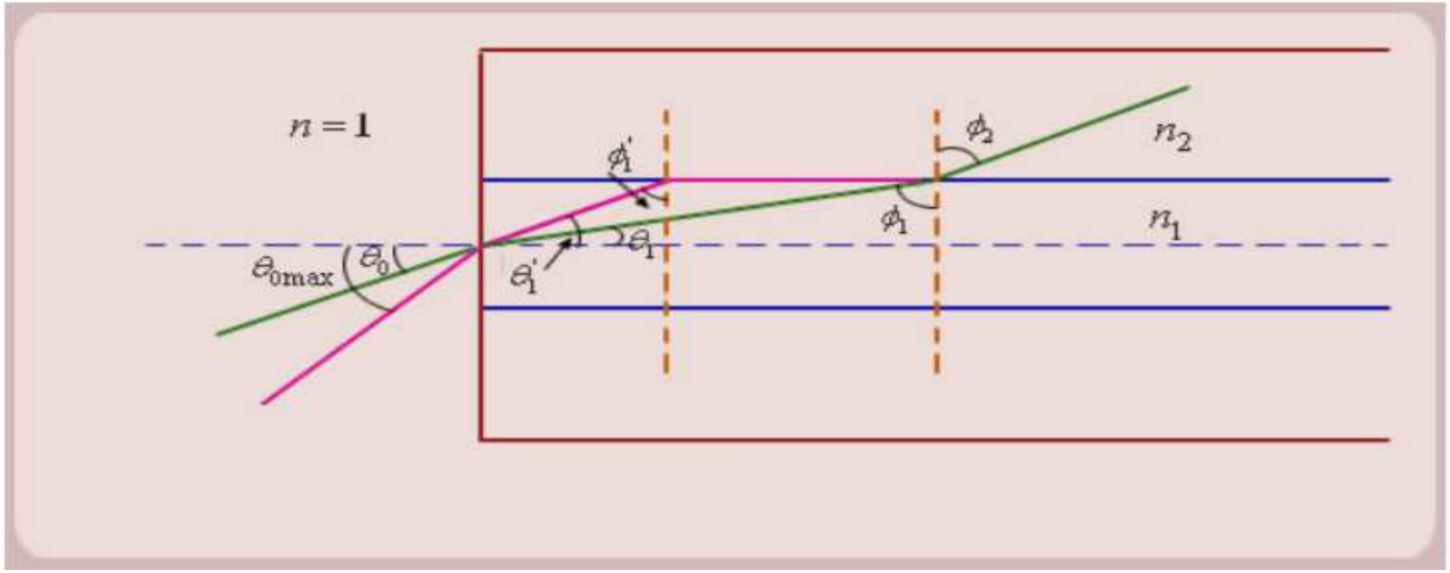
- So it can be concluded that if the light is to propagate inside an optical fiber it could be through two types of rays

a) Meridional rays: The rays which always pass through the axis of fiber giving high optical intensity at the center of the core of the fiber.

b) Skew Rays : The rays which never intersect the axis of the fiber, giving low optical intensity at the center and high intensity towards the rim of the fiber.

Propagation of Meridional Rays

- Let us consider a ray is launched from outside (air) at an angle θ_0,from the axis of the fiber.
- Let the ray makes an angle θ_1 with the axis of the fiber inside the core, and let the ray make an angle ϕ_1 with core -cladding interface. Let be the angle of refraction in the cladding. If ϕ_1< critical angle the ray is refracted in cladding. The ray which goes to cladding is lost and is not useful for communication. The ray which is confined to the core is useful for optical communication.



Propagation of Meridional Rays

Now as we increase the launching angle θ_0, the angle θ_1 also increases.

Since

$$\theta_1 + \phi_1 = \frac{\pi}{2},$$

ϕ_1 decreases and at some point becomes less than the critical angle. When ϕ_1 equals the critical angle, ϕ_2 equals $\pi/2$. The maximum launching angle then corresponds to $\phi_2 = \pi/2$. Let us apply Snell's law at the launching point and at the core-cladding interface for the maximum launching angle

θ_{0max}. For this case let $\theta_1 = \theta_1'$ and $\phi_1 = \phi_1'$

we then have

$$n_1 \sin\phi_1' = n_2 \text{ (since } \phi_2' = \frac{\pi}{2}\text{)}$$

$$\Rightarrow \sin\phi_1' = \frac{n_2}{n_1}$$

now,

$$\sin\theta_{0max} = n_1 \cos\phi_1' = n_1\sqrt{1-\sin^2\phi_1'}$$

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

So the sine of the maximum angle at which the ray will be guided inside the fiber is given by square root of the difference of squares of the refractive indices of the core and cladding. The quantity $\sin\theta_{0max}$ is called the **NUMERICAL APERTURE** of an optical fiber. The NA is a measure of the power launching efficiently of an optical fiber.

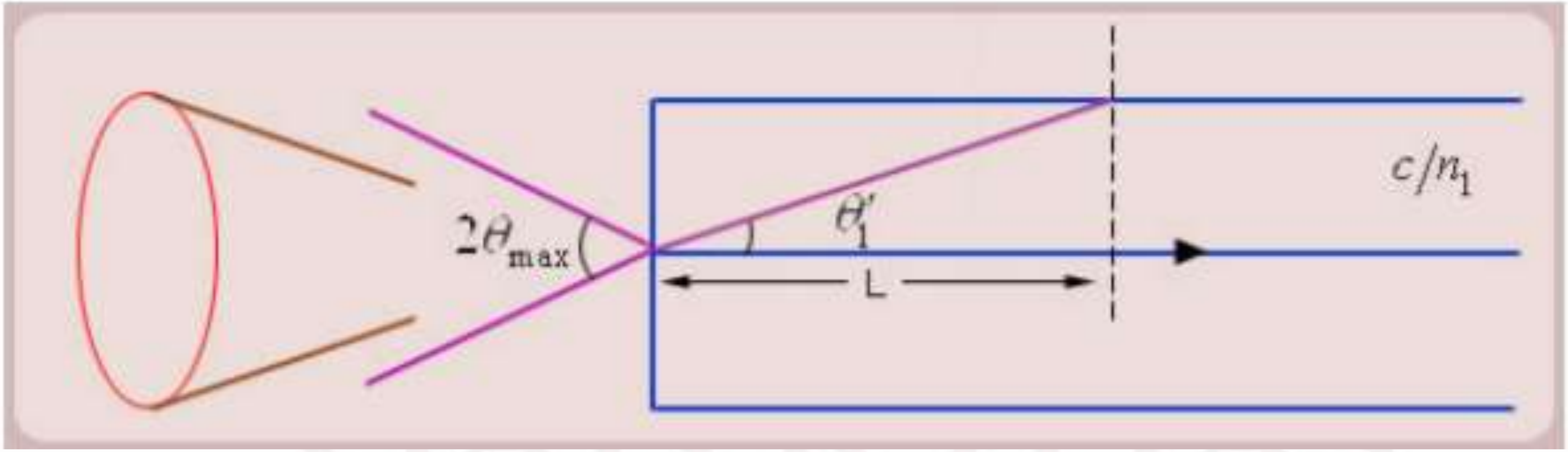
Operations

- Numerical Aperture: This parameter tells us that if we take an optical fiber and put it in front of an optical source then how much light is collected by the fiber from the source. Smaller the value of N.A, smaller the value of θ_{0max} (maximum launching angle) and smaller is the power accepted by the fiber. In other words, if the light is available from various directions from the source, only a portion of light is accepted by an optical fiber and the remaining part of the light is rejected by it.

- If we want good light launching efficiency then θ_{0max} should be as large as possible. Since Sin θ_{0max} is related to the difference of the squares of the refractive indices of the core and the cladding, the difference of squares of the refractive indices should be as large as possible.

Dispersion

- The amount of light accepted by an optical fiber is only one of the parameters in optical communication. A more important parameter is the data rate which the fiber can handle since the primary purpose here is to send information from one point to another.



Time Difference

As we see from the figure 4, all the rays contained within the cone $2\theta_{0max}$ are accepted by the optical fiber.

Let us take two extreme rays; one at the lowest possible angle (along the axis of the fiber), and one at the highest possible angle (θ_{0max}). Take a length L along the fiber axis traveled by the rays.

Let us now transmit a narrow pulse of light. The light pulse indicates binary information. If there is a pulse then a bit is present, otherwise the bit is absent. When the light is switched on, all the rays are switched on at the same time. The pulse energy is therefore divided between different rays which travel by different paths inside the fiber.

The pulse along the axis of the optical fiber takes less time to travel the distance L, than the pulse which travels at the extreme angle θ_{0max}.

As shown in the figure 4, the distance traveled by the extreme ray is $\frac{L}{\cos\theta_1'}$.

The time difference between the axial ray and the extreme ray then is:

$$\Delta t = \frac{L}{\cos\theta_1'}\frac{n_1}{c} - \frac{L}{c}n_1$$

$$= \frac{Ln_1}{c}\left(\frac{1}{\cos\theta_1'} - 1\right)$$

$$= \frac{Ln_1}{c}\left(\frac{n_1}{n_2} - 1\right)$$

$$= \frac{Ln_1}{cn_2}(n_1 - n_2)$$

where c is velocity of light. Since the core material is glass, $n_1 \approx 1.5$, and since $n_2 \leq n_1$, it can lie between 1 and 1.5.

The ratio n_1 / n_2 then lies between 1 and 1.5 only. The time difference Δt per unit length therefore is more or less proportional to $(n_1 - n_2)$.

Δt per km $\propto (n_1 - n_2)$

The time difference Δt essentially is the measure of pulse broadening on the optical fiber.

Dispersion

- This phenomenon is called DISPERSION of an optical fiber. The dispersion (pulse broadening) has to be small since the data rate is inversely proportional to the pulse broadening. For high speed communication (high speed does not refer to the time taken by data to reach the destination but it refers to the number of bits per sec) the pulse broadening and hence the dispersion should be minimal.

- For low dispersion (n1-n2) should be as small as possible. So for an optical fiber the refractive index of core has to be made as close to the refractive index of cladding as possible.

Contradictory Requirement

- For higher launching efficiency (higher NA),n1-n2 should be as large as possible.
- For high data rate (bandwidth), n1-n2 should be as small as possible

- Since data transfer rate is rather more important in communication, is made as small as the fabrication technology permits.
- So for all practical fibers, Refractive index of the cladding differs from that of the core by only 0.1 to 1%.

Different types of fibers

- STEP INDEX FIBER: For this fiber the refractive index of the core is constant. Since refractive index profile looks like a pulse or step, this kind of fiber is called the STEP INDEX FIBER. This structure is useful for analyzing propagation of light inside an optical fiber. Generally it is not used in practice because data transfer rate in this fiber is the lowest.
- GRADED INDEX FIBER: In this fiber we grade the refractive index profile of the core and consequently it is called the graded index fiber.
- SINGLE MODE OPTICAL FIBER : The optical fiber in which only one ray travels along the axis of fiber is called the single mode optical fiber .

OPTICAL FIBER	DIAMETER(in micrometre)
SM	5-10
Graded Index	50-60
Step Index	50-60

Limitations of the Ray-model

- The ray model gives an impression that during total internal reflection the energy is confined to the core only. However, it is not so. In reality the optical energy spreads in cladding also.
- The ray model does not speak of the discrete field patterns for propagation inside a fiber.
- The ray model breaks down when the core size becomes comparable to the wavelength of light. The ray model therefore is not quite justified for a SM fiber.

Thank You