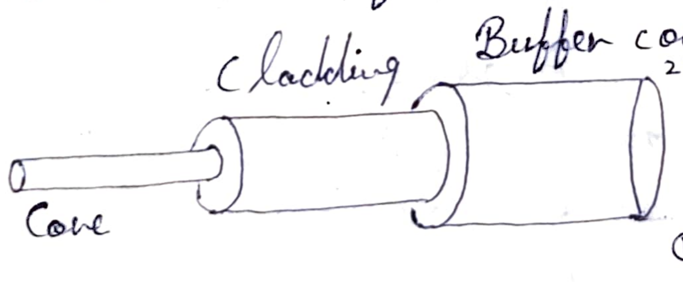
Fiber Optics

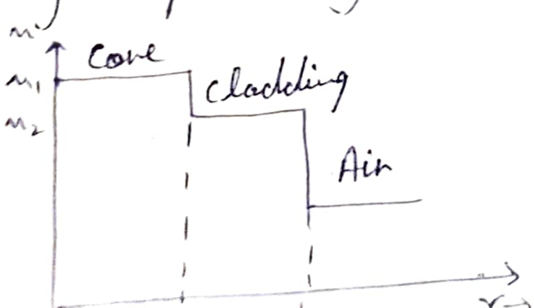
An optical fiber is a dielectric waveguide that operates at optical frequencies (10^{15} Hz). It is transparent, thin, made of glass or plastic, designed to guide light waves along its length. Optical fibers work on the principle of total internal refl^n. It confines em energy in the form of light within its surfaces & guides the light in a dir^n $\parallel$ to its axis. The propagation of light ~~glo~~ along a waveguide can be described in terms of a set of guided em waves called the modes of the waveguide. These guided modes are referred to as the bound or trapped modes of the waveguide.

The optical fiber contains a dielectric cylinder of radius a & ref. index n_1 called 'core' & a 'cladding' which has a ref. index $n_2 < n_1$. The cladding reduces scattering loss, adds mechanical strength to the fiber & protects the core from absorbing surface contaminants with which it could come in contact.

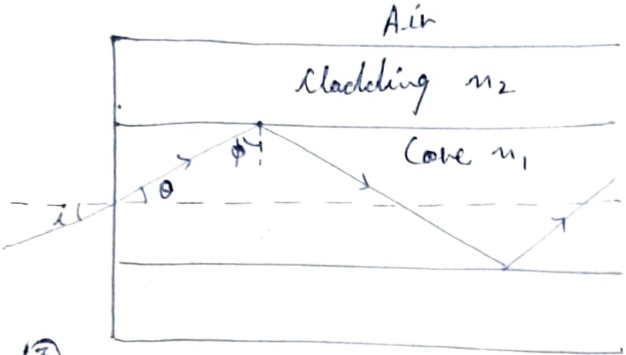


(1)

Typically $n_1 \approx 1.48$, $n_2 \approx 1.46$ & $a = 50\,\mu m$, for optical fibers. Now for a ray entering the fibre, if the angle of incidence (at the core - cladding interface) ϕ is greater than the critical angle $\phi_c = \sin^{-1} n_2/n_1$, the ray will undergo total internal refl^n.



at that interface. ~~Further 'cos of the cylindrical sy in the fiber structure,~~



(3)

In this way, the ray undergoes repeated total internal reflection until it emerges out of the other end of the fiber, even if the fiber is bent. Thus the light ray is guided through the fiber from one end to other end without any energy being lost due to refraction.

4. Classifications:

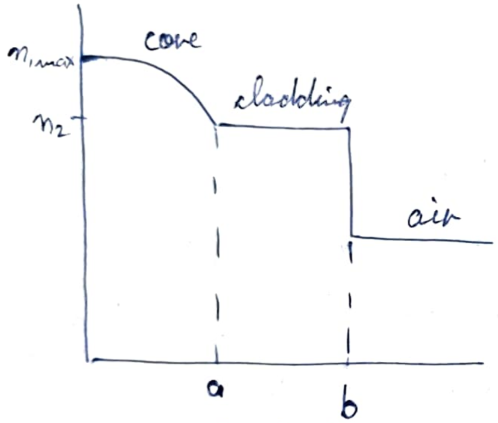
There are two types of optical fibers:

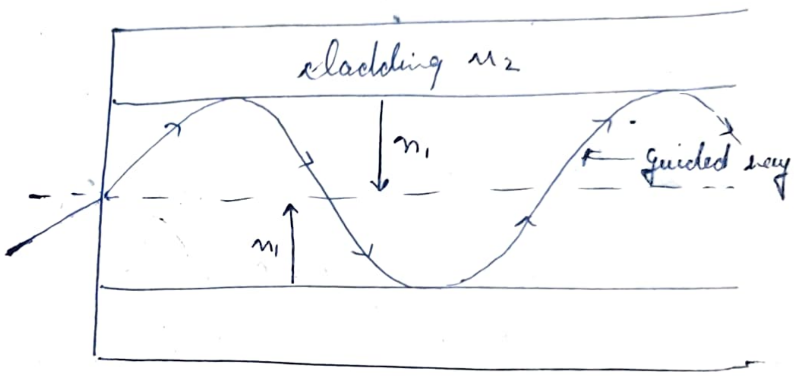
I Step index optical fiber

II Graded " "

Step index optical fiber - It is the simplest type of an optical fiber that consists of a thin cylindrical structure of transparent glassy material of uniform ref. index n, surrounded by a cladding of another material of uniform but slightly lower ref. index n_2. These fibers are referred to as step index fibers due to the step discontinuity of the index profile at the core-cladding interface. (fig (2) & (3))

Graded index optical fiber :- In such type of optical fiber, the ref. index in the core decreases continuously in a nearly parabolic manner from a max^{m} value at the center of the core to a constant value at the core-cladding interface. Since the ref. index decreases as one moves away from the centre of the core, a ray entering the fiber is continuously bent towards the axis of the fiber; this follows from Snell's law because the ray encounters continuously a medium of lower ref. index & hence bends away from normal (ie. it bends towards the axis of the fiber).





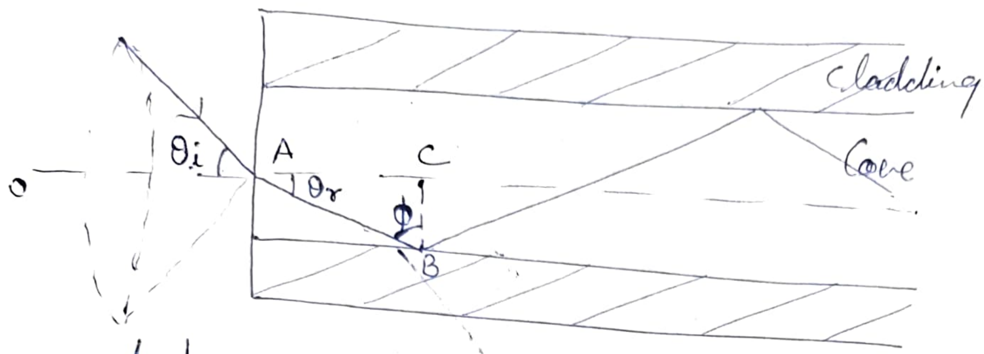
Optical fibers may be classified depending upon the types of propagation of the waveguide

1) ~~On~~ Single-mode fiber — Fibers with narrow cores ($a \sim 10\,\mu m$) allow only one wave mode to pass. These are also called monomode fibers.

2) Multi-mode fiber — Fibers having core diameters $\sim 50\,\mu m$ or more allow various wave modes to pass; Such optical fibers are called multi mode fibers.

✡ Propagation of light in fibers

Let us suppose a step index optical fiber in which light is incident at one end. Let ~~the~~ n_1 is the ref. index of core & n_2 is that of the cladding ($n_2 < n_1$). Let n_0 be the ref. index of the medium from which the light ray is incident. As shown in the figure, let a ray enter at an angle θ_i from axis & refract at core at an angle θ_r. The ray



strikes the core - cladding interface at an angle ϕ. The rays ~~are made to~~ with an angle greater than critical angle ϕ_c, at the core - cladding interface are transmitted by total internal refl^n.
Now, from Snell's law,

$$n_0 \sin\theta_i = n_1 \sin\theta_r$$

as $\theta_r + \phi = 90°$ $\therefore$ $\theta_r = 90° - \phi$

$$\therefore \quad n_0 \sin\theta_i = n_1 \sin(90° - \phi) = n_1 \cos\phi$$

When $\phi = \phi_c$, then $\theta_i = \theta_{imax}$

So, $$\sin\theta_{imax} = \frac{n_1}{n_0}\cos\phi_c \quad \text{——— (1)}$$

From the law of total internal refl^n

$$\sin\phi_c = \frac{n_2}{n_1}$$

$$\therefore \cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \text{——— (2)}$$

Putting the value from eq^n (2) in eq^n (1), we get

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

For air $n_0 = 1$

$$\therefore \sin\theta_{imax} = \sqrt{n_1^2 - n_2^2}$$

If we write $\theta_{i\,max} = \theta_a$

then $\theta_a = \sin^{-1}\sqrt{n_1^2 - n_2^2}$

θ_a is known as acceptance angle. It is defined as the max^m external incidence angle for which light will propagate in the fiber. It is also defined as the half angle of the cone with which light is totally reflected by the fiber core.

The light gathering ability of a fiber is related to its acceptance angle & expressed as the numerical aperture of the fiber.

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

Or, $NA = \sin\theta_a = \sqrt{n_1^2 - n_2^2}$ for $n_0 = 1$, air

The typical values for the NA for single mode fiber are $\sim 0.2 - 0.6$. The low value for the NA means a small θ_a, which indicates the use of laser source with single mode fibers.

For graded index fiber,

$$n(r) = n_1\left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} \quad \text{for } 0 \leq r \leq a$$

$$n(r) = n_1(1 - 2\Delta)^{1/2} \simeq n_1(1 - \Delta) = n_2 \quad \text{for } r \geq a$$

where r = radial distance from the fiber axis.

In this case, local NA is given by

$$NA(r) = \left[n_1^2(r) - n_2^2\right]^{1/2} = NA(0)\sqrt{1 - \left(\frac{r}{a}\right)^{\alpha}} \quad r \leq a$$

$$= 0 \quad r > a$$

axial NA is defined as

$$\cancel{NA(0) = \left[n_1^2(0) - n_2^2\right]^{1/2}}$$

Or, $NA(0) = \left[n_1^2 - n_2^2\right]^{1/2} \simeq n_1\sqrt{2\Delta}$

where Δ = ~~m~~ ref. index difference $= \frac{n_1 - n_2}{n_1}$

The numerical aperture is independent of the fiber core diameter.

α : is the attenuation constant $= \frac{10}{L} \log \frac{P_i}{P_o}$.

P_i : Incident power

P_o : output power.

L : distance

Applications & Uses:

1) Wide application in communication (As fibre communication has large band width)

2) Widely used in defence because high privacy is maintained

3) Transmission of digital data: b) communications c) command & control link on ship & aircraft, data links for satellite earth stations.

4) Used for signaling purposes.

5) Used in cable television, space vehicles, ships, and submarine cable.

6) Wide applications in security, and alarm systems, electronic instrumentation systems. industrial automation and process control.

7) It is possible to study interior of the lungs and the other parts of the body that can not be viewed directly.

Bhavya Bhushan

Numerical Aperture:

NA of an optical fibre is defined as the sine of the acceptance angle and measures the accepting power of the fibre.

$$\sin\theta_{i\,max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

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

So $NA = \sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

Now $n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2)$

$$= \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right) 2n_1$$

putting $\frac{n_1 + n_2}{2} \simeq n_1$ & $\frac{n_1 - n_2}{n_1} = \Delta$: fractional change of R.I.

$$= 2n_1^2 \Delta.$$

$$\therefore \boxed{NA = n_1\sqrt{2\Delta}.}$$

It provides a measure of light gathering capacity of the fibre. It ranges 0.13 → 0.50.

(NA) It depends on R.I. of core 'n_1',
" cladding 'n_2'

Larger the value of NA, larger is the energy gathered by the fibre from the source.

Advantages:

1) Enormous bandwidth.
2) Less weight and small size.
3) Electrical isolation.
4) Low cost.
5) No Interference & cross talk.
6) Security of the signal.
7) Ruggedness & flexibility.
8) Safety against voltage problems.