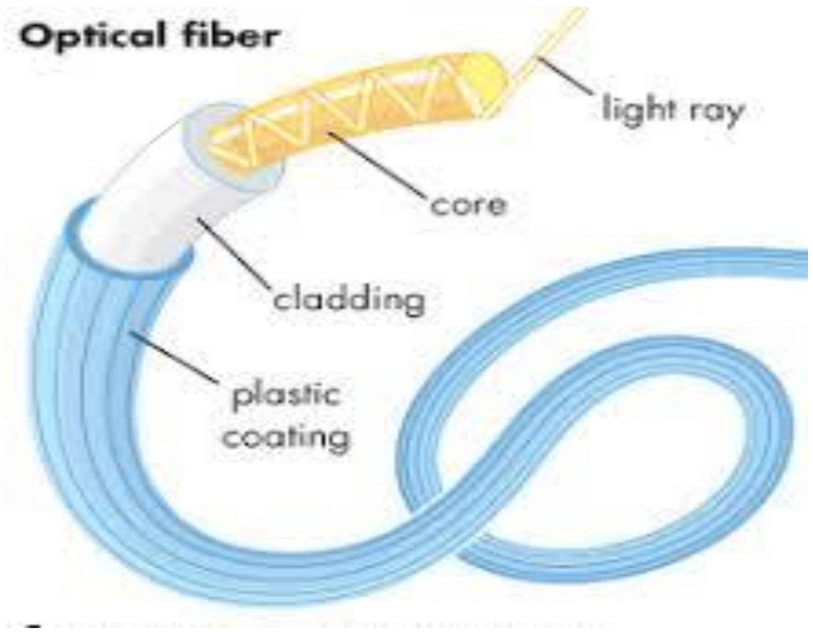
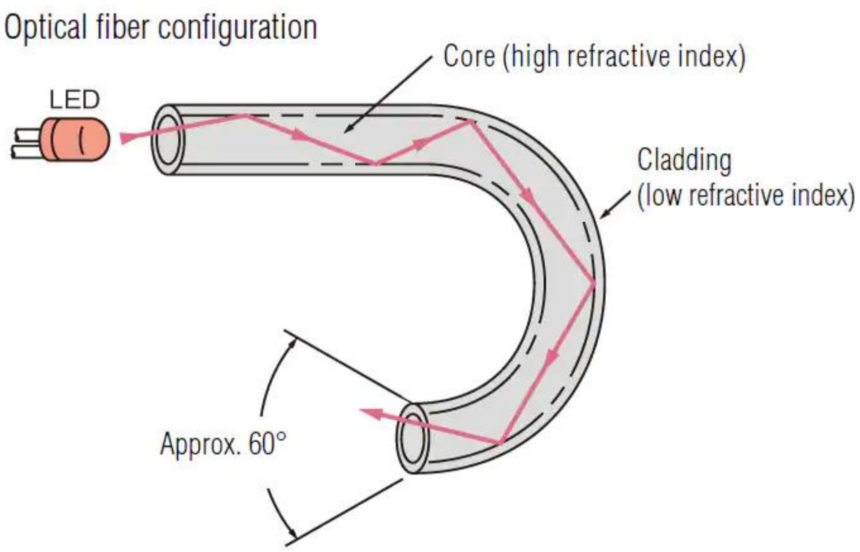
OPTICAL FIBERS

What are optical fibers?

- **Optical fibers are cylindrical light wave guides, which guide the light waves to propagate through them without much energy loss, by the principle of total internal reflection.**
- Optical fibers are thin flexible, strand of glass or plastic which guide the light waves to propagate along curved path by the principle of total internal reflection.
- **A practical optical fiber has three coaxial regions.**



Structure of optical fiber



- The innermost light guiding region is known as the Core.
- It is surrounded by a coaxial middle region known as the cladding.
- This layer serves to confine the light to the core.
- Core and cladding are made up of transparent dielectric materials like glass and plastic.
- The refractive index of cladding is always lower than that of the core.
- The outermost region is called as sheath or buffer.
- This protects the cladding and core from abrasions, contamination and moisture.
- The sheath also increases the mechanical strength of the fiber.

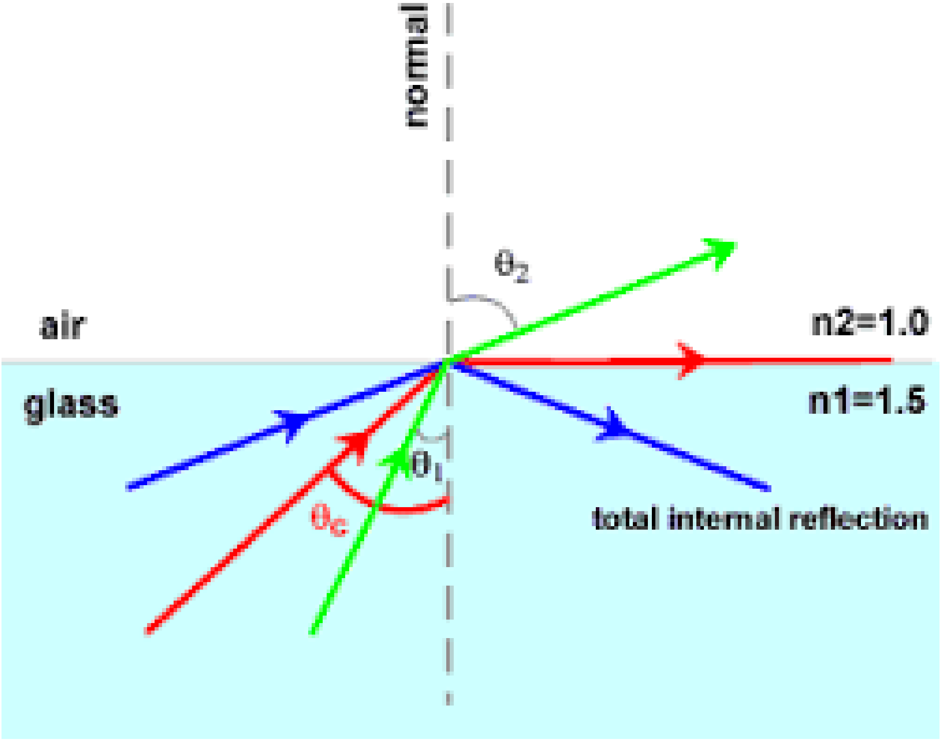
Principle of optical fibers

Mechanism of electromagnetic wave propagation through the optical fiber

- **Optical fibers are based on the principle of total internal reflection.**
- **These are designed in such a way that, light energy launched at one end will under go total internal reflection within the fiber and reaches the other end with negligible energy loss**
- **Light propagates through fibers by means of total internal reflections.**

Total Internal Reflection

Total internal reflection- When light travels from denser to rarer medium and angle of incidence in the denser medium is greater than critical angle for the pair of media, the light gets reflected back in the denser medium. This phenomenon is known as total internal reflection.



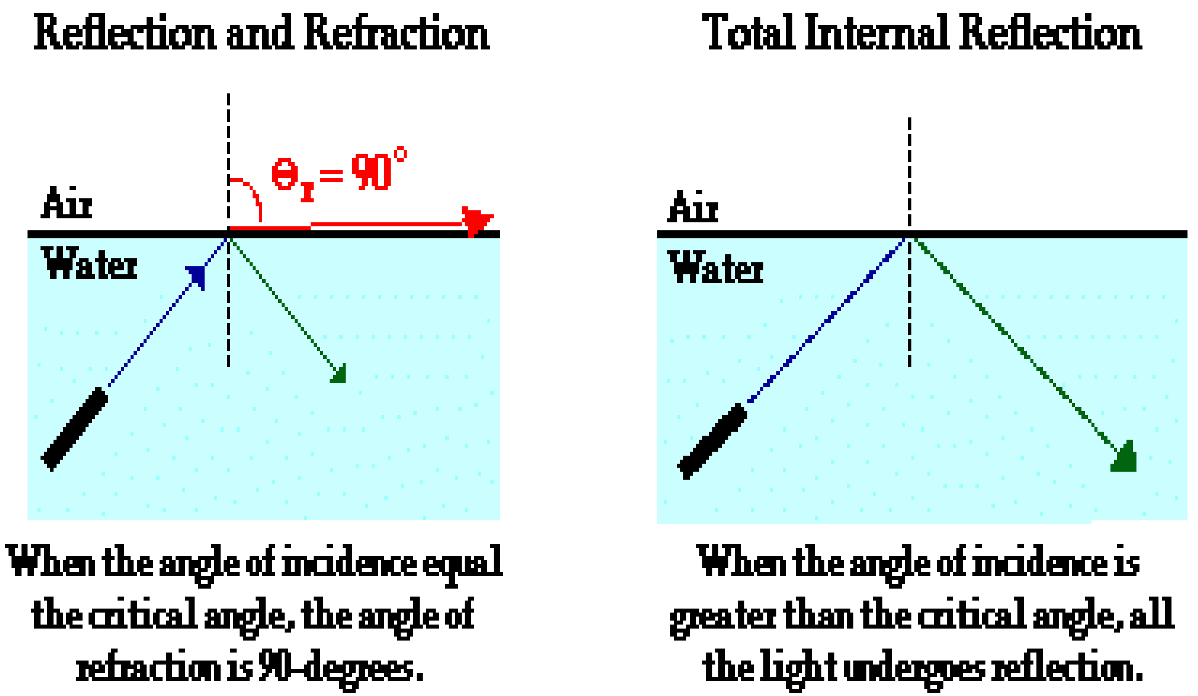
Critical angle:

The angle of incidence in the denser medium for which angle of refraction in the rarer medium is 90^0, is called critical angle for the pair of media.

$$n_1 \sin\theta_c = n_2 \sin 90^0$$

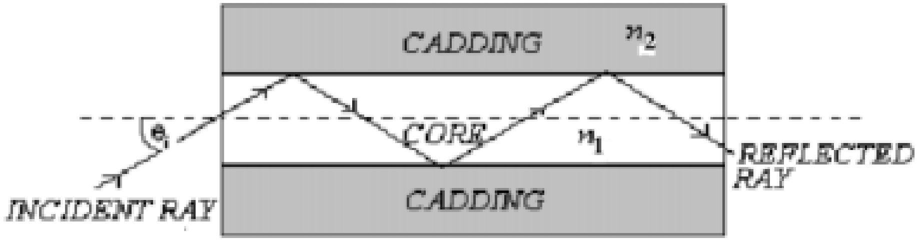
or

$$\sin\theta_c = \frac{n_2 \sin 90^0}{n_1} = \frac{n_2}{n_1}$$



Acceptance angle (θ_o)

❖ **When light is made to incident at the one end of core, for a particular angle of incidence (less than acceptance angle) the light ray will undergo total internal refraction at the boundary of core and cladding which is possible here as n1 > n2, where n1 is refractive index of core and n2 is refractive index of cladding. Here θ^o is the angle of incidence measured with respect to the axis of the core, is called as *acceptance angle.***



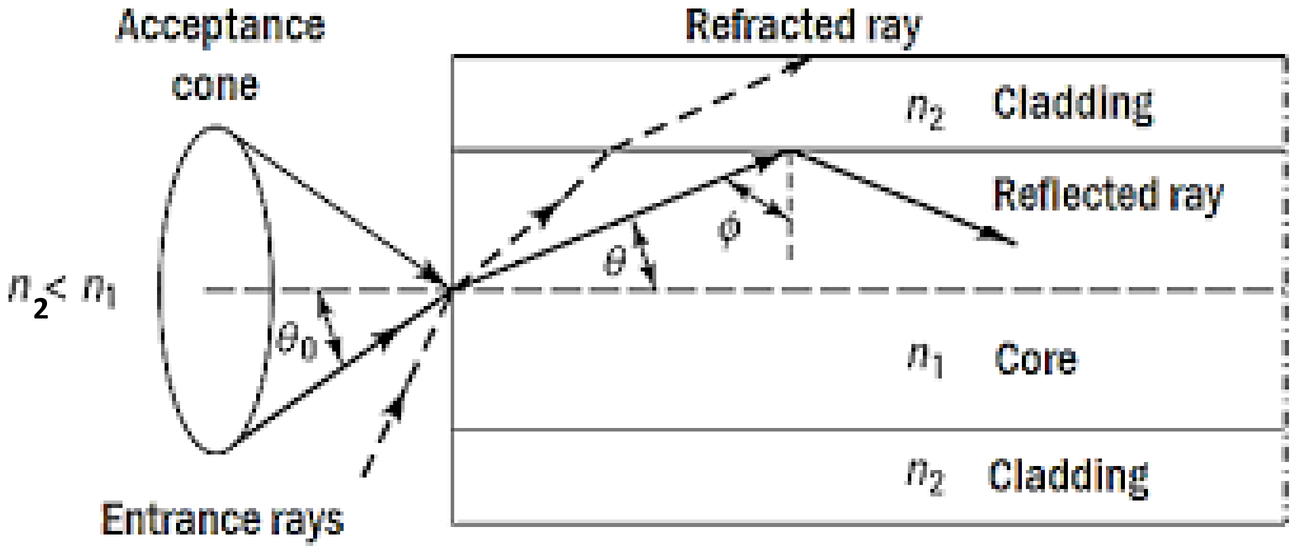
It is the maximum allowed angle that a light ray can have relative to the axis of fiber for transmission through fiber.

Acceptance angle (θ_o)

- It is that angle of incidence made by light ray at the one end of the core of an optical fiber measured with respect to the axis of fiber, for which refracted ray inside the core grazes the interface or boundary between core and cladding.
- For any other angle of incidence $\theta i < \theta o$, light ray undergoes total internal reflection and it propagates through the optical fiber with multiple internal reflection
- For any other angle of incidence greater than the acceptance angle i.e., $\theta i > \theta o$ light ray entering the fiber refracts out of the core and cladding and thus escapes out of the optical fiber without total internal reflection.

Acceptance cone

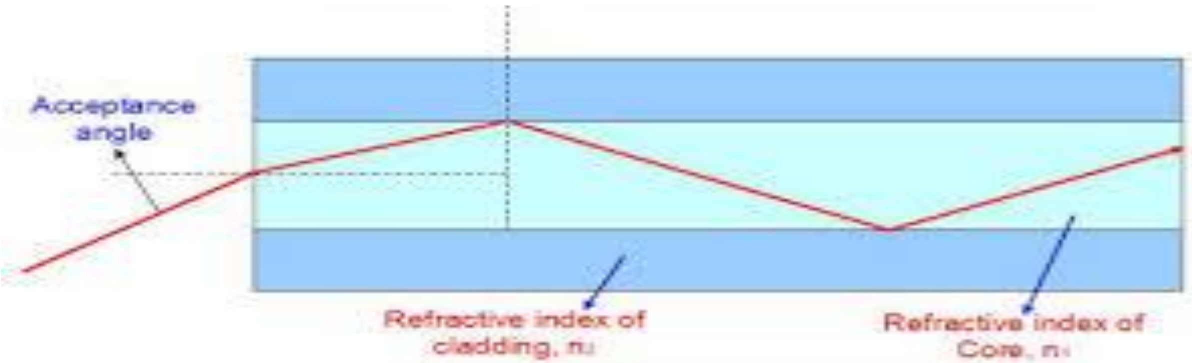
It is the cone in which the light incident at acceptance angle or less than the acceptance angle can propagate through the fiber after total internal reflection. If we imagine a line at angle θo, when rotated about an axis of an optical fiber generates a cone and this cone is called as acceptance cone.



Numerical Aperture (N.A)

N.A determines the light gathering capability of an optical fiber

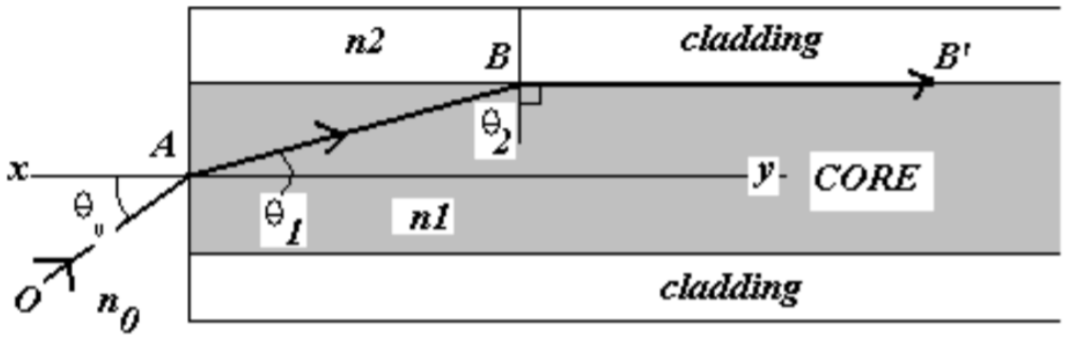
- ***N.A is measured as sine of the angle of acceptance i.e N.A = sin θo***
- ***Larger the N.A, easier to launch the light in to the fiber.***



$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$$

Expression for numerical aperture and condition for propagation:

Let, no be the R.I. of medium in which optical fiber is placed. n1 be the R.I. of core medium and n2 be the R.I. of cladding medium such that, n1 > n2 > no. Let OA be the light ray incident on one end of the core at A, with angle of incidence θo (measured with respect to axis of the fiber XY).



Let AB be the refracted ray with angle of refraction θ1 in the core. Let θ2 be the angle of incidence made by ray AB at B on the boundary-separating core and cladding such that θ2 is the critical angle for pair of media core and cladding.

Applying Snell's law ($n_i \sin\theta_i = n_r \sin\theta_r$)

for the refraction at A,

We get,

$$n_o \sin\theta_o = n_1 \sin\theta_1 \qquad (1)$$

Similarly applying Snell's law for the refraction at B,

We get,

$$n_1 \sin\theta_2 = n_2 \sin 90^\circ = n_2$$

from geometry $\theta_2 = 90-\theta_1$,

therefore $n_1 \cos\theta_1 = n_2$

$$\cos\theta_1 = \frac{n_2}{n_1}$$

From eq (1) $\sin\theta_o$ = $\dfrac{n_1 \sin\theta_1}{n_0}$

$$= \frac{n_1}{n_0}\sqrt{1-\cos^2\theta_1}$$

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

Therefore

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

Here $\boldsymbol{\theta_o}$ is called acceptance angle and s**in$\boldsymbol{\theta_o}$** is called **numerical aperture**

Condition of propagation:

If the surrounding medium is air, Then no = 1 Therefore, $\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

From the expression for Numerical aperture $N.A. = \sqrt{n_1^2 - n_2^2}$

It is clear that only for the angle of acceptance satisfying $\sin\theta_0 = \sqrt{n_1^2 - n_2^2}$

the light ray will undergo refraction in such way that refracted ray will be within the core of the fiber. If θi, is the angle of incidence at one end of the core of an optical fiber such that θi is less than θo, then θ2 becomes more than the critical angle at B as a result of which the ray undergoes total internal reflection at the boundary separating the core and cladding.

Condition of propagation: The ray will propagate through the fiber if the angle of incidence θi ≤ θo or
sin θi ≤ sin θo ≤ NA
θi ≤ $\sin^{-1}$ (NA)

Fractional index change (Δ)

It is the ratio of the refractive index difference between core and cladding to the refractive index of core of an optical fiber.

$$\Delta = \frac{n_1 - n_2}{n_1}$$

Relation between N.A and fractional index change (Δ).

Fractional index change $\Delta = \frac{n_1 - n_2}{n_1}$

When, $n_1 \rightarrow$ R.I of core $n_2 \rightarrow$ R.I of cladding such that $n_1 > n_2$

We have $N.A. = \sqrt{n_1^2 - n_2^2}$

$$= \sqrt{(n_1 - n_2)(n_1 + n_2)}$$

$$= \sqrt{n_1\Delta(n_1 + n_2)}$$

Generally $n_1 \cong n_2$, by substituting $n_1+n_2= 2\ n_1$

N.A= $\sqrt{2n_1^2\Delta}$

or N.A = $n_1\ \sqrt{2\Delta}$

It is the required relation.

Modes of propagation in an optical fiber.

- Modes can be visualized as possible number of paths for light rays in optical fiber or the number of ways in which light can propagate in a fiber.
- Geometrically these modes can be treated as light rays propagating through the optical fiber. Single mode fiber allows only one path for the propagation where as multimode fiber allows more than one path and each mode can be used as one channel for communication.

The number of modes sustained in an optical fiber depends on radius of the core, refractive index of core(n_1)and cladding (n_2) and wavelength of light used, which can be calculated by parameter called V- number given by is,

$$V = \frac{2\pi r}{\lambda}\sqrt{n_1^2 - n_2^2}$$

.

For multimode fiber of higher order, number of modes supported by fiber, $N = V^2/2$.

V-number is also known as normalized frequency parameter.