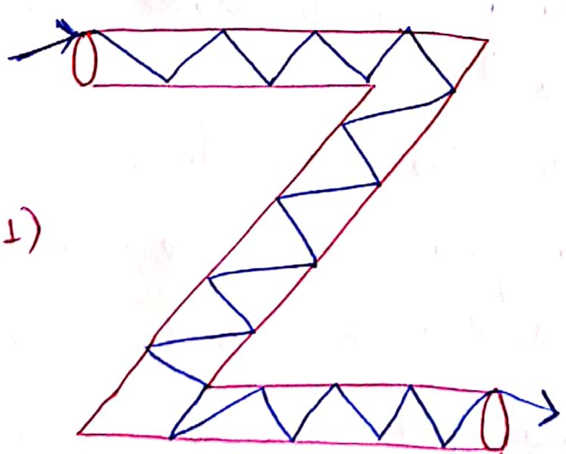
FIBRE OPTICS

Mechanism of Light transmission in Optical fibres or Propagation of light in optical fibres.

Optical fibres are glass or plastic conduits as thin as a human hair, designed to guide light wave along their length.

Optical fibre works on the principle of total internal reflection.

When light enters one ends of the fibre, it undergoes successive total internal reflections from the side walls and travels down the length of the fibre along a zig-zag path, as in fig (1).



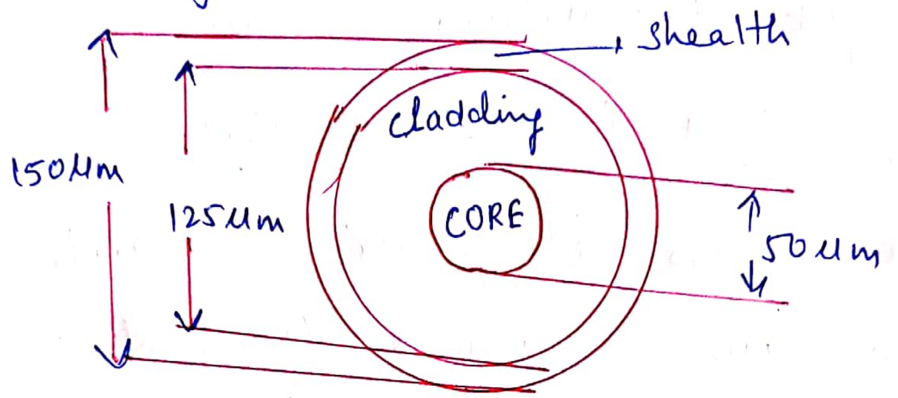
fig(1)

(A transparent fibre guiding light along its length)

A small portion of light may escape through the side walls but a major fraction emerges out from the other end of the fibre.

→

A practical fibre has a general three coaxial region as shown in fig (2).



{cross-sectional view of an optical fibre}

1) The inner most region, the light guiding region is known as the core.

2) It is surrounded by a coaxial middle region known as cladding. & outermost region is called as sheath.

3) The refractive index of cladding is always lower than that of the core.

4) The purpose of the cladding is to make the light to be confined to the core.

5) Light is launched into the core and striking the core to cladding interface at greater than critical angle will be reflected back into the core. Since, the angles of incidence and reflection are equal the light will continue to rebound and propogate through the fibre.

6) The sheath protects the cladding and the core from abrasions, contamination and harmful influence of moisture. ∴ it increases mechanical strength.

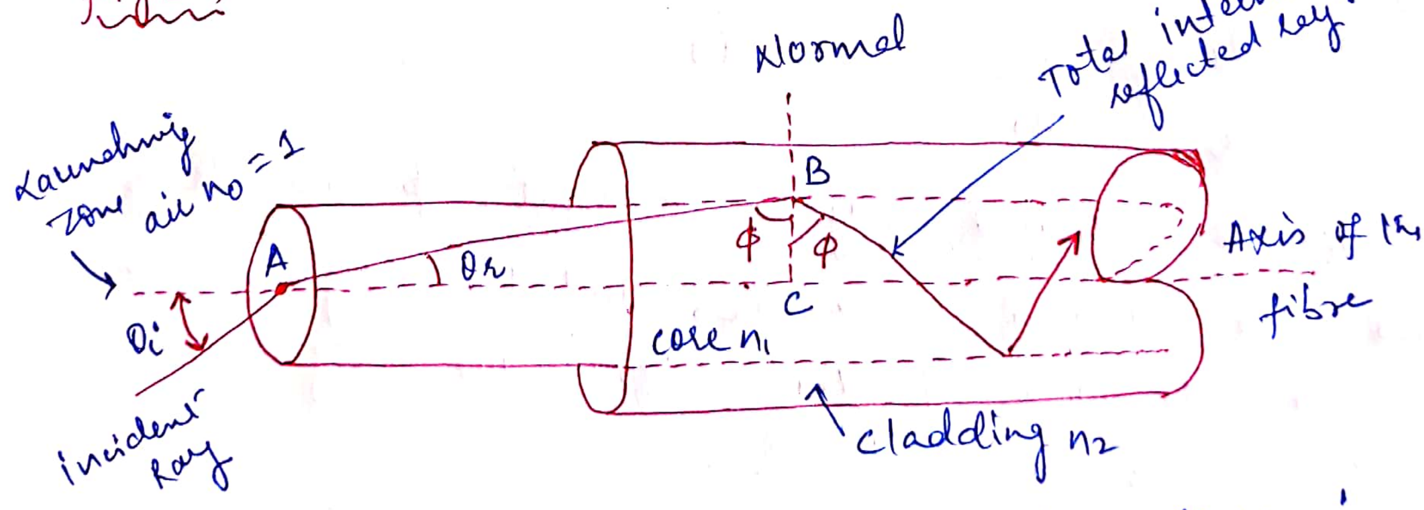
Derivation for the expression of Numerical Aperture: is defined as a measure of amount of light that can be accepted by the fibre. The main function of an optical fibre is to accept and transmit as much light from the source as possible.

The light gathering ability of a fibre depends on two factors, the core size and numerical aperture.

The numerical aperture of a fibre is determined by the acceptance angle and the fractional refractive index change.

Acceptance angle

fig.(3)



Consider an optical fibre in to which light is launched. The end at which light enters the fibre is called the launching end (medium is air, $n_0 = 1$) as shown in fig.(3)

Let the refractive index of core be n_1 and refractive index of cladding be n_2 and $n_2 < n_1$. Let n_0 be the refractive index of the launching medium.

Let a light ray enter the fibre at angle 'θ_i' to the axis of the fibre. The ray refracts at an angle 'θ_r' and strike the core-clading interface at an angle ϕ.

If 'ϕ' is greater than ϕ_c (critical angle), then ray undergoes total internal reflection at the interface. As long as the angle $\phi > \phi_c$, the light will stay within the fibre.

Applying Snell's law to launching face of the fibre we get.

$$\frac{\sin \theta_i}{\sin \theta_r} = \frac{n_1}{n_0} \quad \text{— (i)}$$

If 'θ_i' is increased beyond a limit, ϕ will drop below the critical value ϕ_c, and the ray escapes from the side walls of the fibre. The largest value of θ_i occurs when $\phi = \phi_c$.

from Δ ABC

$$\sin \theta_r = \sin(90° - \phi) = \cos \phi \quad \text{— (ii)}$$

from (i) & (ii), we get.

$$\sin \theta_i = \frac{n_1}{n_0} \cos\phi$$

when $\phi = \phi_c$

then $\sin[\theta_{i(max)}] = \frac{n_1}{n_0} \sin \alpha_c$ { from i)

and $\therefore \sin(\theta_{i(max)}] = \frac{n_1}{n_0} \cos\phi_c$ (from ii) — (iii)

{ as $\phi = \phi_c \Rightarrow \cos\phi = \cos\phi_c$ }

But from the condition of total internal reflection the refractive angle (θ_r) corresponding to critical angle (ϕ_c) is 90°, so,

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

$$\therefore \cos\phi_c = \sqrt{1-\sin^2\phi_c} = \sqrt{1-\frac{n_2^2}{n_1^2}} = \sqrt{\frac{n_1^2-n_2^2}{n_1^2}} = \frac{\sqrt{n_1^2-n_2^2}}{n_1}$$

$\therefore$ Equation (iii) becomes.

$$[\sin\theta_i (max)] = \frac{\cancel{n_1}}{n_0} \cdot \frac{\sqrt{n_1^2-n_2^2}}{\cancel{n_1}}$$

$$[\sin\theta_i (max)] = \frac{\sqrt{n_1^2-n_2^2}}{n_0}$$

as launching medium is air, so $n_0 = 1$

$$\sin\theta_i (max) = \sqrt{n_1^2-n_2^2}$$

$$\boxed{\theta_i (max) = \sin^{-1}\left(\sqrt{n_1^2-n_2^2}\right)} \rightarrow \text{Acceptance angle of the fibre.}$$

defined as:- The max. angle that a light ray can have relative to the axis of the fibre and propagate down the fibre.

Numerical aperture is sine of acceptance angle.

$$NA = \sin \theta_0$$

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

Fractional difference (Δ) between the refractive indices the core and cladding is known as fractional refractive index change

$$\Delta = \frac{n_1 - n_2}{n_1}$$. This is always positive.

NA determines the light gathering ability of the fibre. Its value ranges from 0.13 to 0.50.

MODES OF PROPAGATION

Light propogates as an electromagnetic wave thru an optical fibre. All the waves having ray direction above the critical angle, will be trapped within the fibre due to total internal reflection. But not all the trapped waves propogates along the fibres. Only certain ray directions are allowed to propogate.

Light rays travelling through a fibre are classified as axial rays and zig-zag rays. As a ray get repeatedly reflected at the wall of fibre, phase shift occurs.

The waves travelling along certain zig-zag paths will be in-phase & intensified, while the waves coursing along certain other path will be out-of-phase and diminish due to destructive interference. The light ray paths along which waves are in-phase inside the fibre are known as modes.

The number of modes that a fibre will support depends on the $\boxed{\text{ratio } d/\lambda}$.

d - diameter of core

λ - wavelength of the wave being transmitted.

Types of optical fibres

Single Mode (SMF)

i) Has smaller core diameter

ii) support only 1 mode of propogation

Multimode (MMF)

i) Has large core diameter

ii) Supports a large no. of modes.

iii) further, distinguished on the basis of index profile.

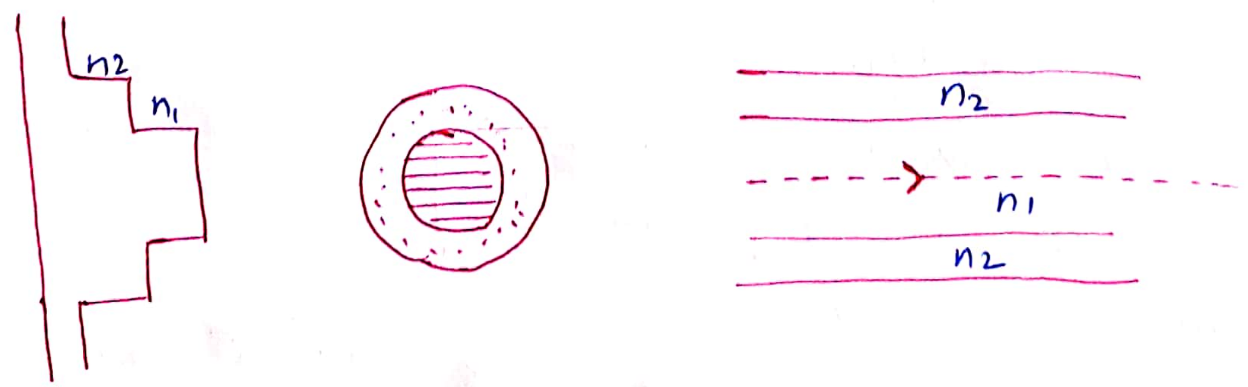
Index profile: is a plot of refractive index drawn on horizontal axis versus the distance from the core axis drawn on vertical axis. On this basis the fibres as classified as

(a) Single mode step index fibre. (SMF)

(b) Multimode step index fibre. (MMF)

(c) Multimode Graded index fibre.

(a) Single mode step index fibre :-



1) Single mode step index fibre has a very thin core of uniform refractive index of higher value which is surrounded by a cladding of lower refractive index.

2) The refractive index changes abruptly at the core - cladding boundary as shown in fig.( ) because of which it is known as a step index fibre.

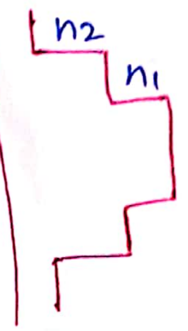
3) This fibre has a core diameter of 4 um, which is of the order of a few wavelength of light.

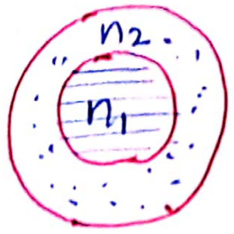
4) In SMF, light travels along a single path i.e along the fibre axis. It A SMF is characterized by a very small value of Δ i.e. fractional refractive Index change, of order of 0.002.

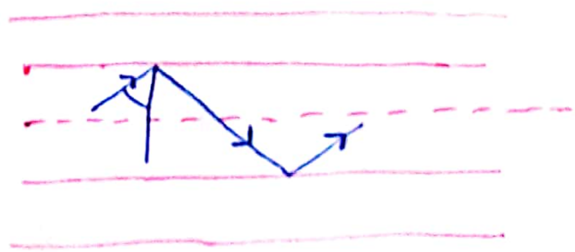
B) Multimode step index fibre.

1) It is similiar to SMF except that its core is of larger diameters of 100 um, which is very large compared to the wavelength of light being transmitted.

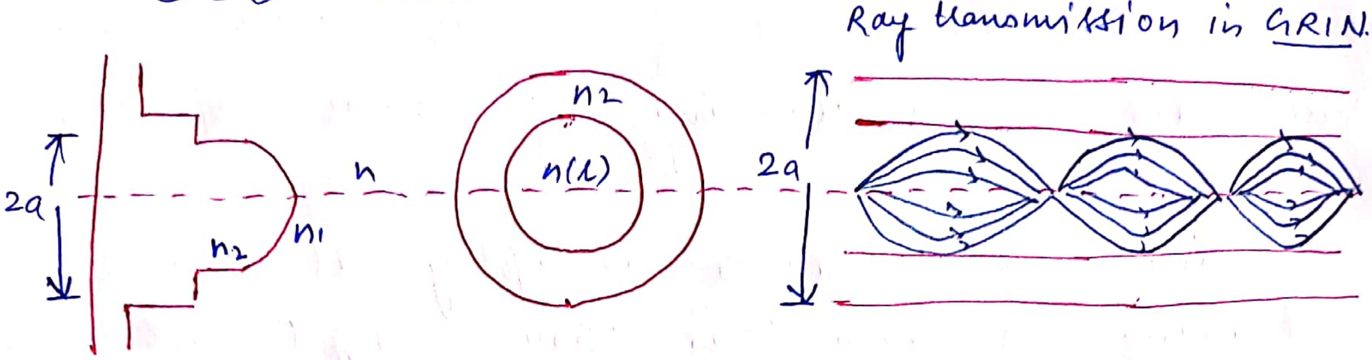
2) Light follows zig-zag paths inside the fibre. Many such zig-zag paths are permitted in MMF.







c) Graded Index (GRIN) fibre :



1) A graded index fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices.

2) ∴ The refractive index of the core varies with the distance from the fibre axis. It has a high value at the centre and falls off with the increasing radial distance from the axis.

3) Such a profile causes a periodic focussing of the light propogating through the fibre.

4) The acceptance angle and numerical aperture decrease with radial distance from the axis in case of GRIN.

Loss mechanism in optical fibre -

fibre losses can takes place in two ways.

1) Attenuation loss in fibre.

2) Dispersion losses.

The loss in the optical fibre is measured in terms of the decibel (dB) which is a logarithmic unit. The decibel loss of optical power in a fibre is calculated through the formula:

$$dB = -10 \log (P_{out}/P_{in})$$

P_{in} → Power launched into the fibre.

P_{out} → Power coming out of the fiber.

1) Attenuation loss in fibre -

when the light passes through the fiber, the loss of light in a fibre occurs due,

a) absorption of light by the material of fibre.

b) scattering of light due to the impurities & imperfections.

c) loss due to the variations in the surface of the core of the fibre. These variations are known as microbends.

Absorption of light, takes place due to the hydroxyl ions (OH^-) in the moisture, which is present in the fibre, absorb the light.

Scattering of light depends on the wavelength.

i.e loss $\propto \frac{1}{\lambda^4}$.

Microbends are caused during manufacturing of the fibre or may occur during the mishandling of the fibre.

2) Dispersion losses: when data is sent along communication fibre, information is generally contained in pulses in the intensity of light. These pulses can become distorted as they travel through the fibre. Three mechanism cause this distortion in the signal

Modal dispersion occurs in fibres that have more than one mode.

Material dispersion is caused by the glass of the fibre.

Wave guide dispersion occurs only in fibres with a single mode. Because of such design, some light starts travelling in the cladding of the fibre, reaches the end of the fibre sooner than light travelling in the core.

Application of fibre optics

1) Medical application:

a) fibrescopes are employed widely in endoscopic applications.

b) In opthalmology, a laser beam guided by the fibres is used to reattach the detached retinas and to correct defect in vision.

c) Laser angioplasty is expected to do away with the balloon angioplastye and bypass surgery.

2) Optical fibre sensors:

a) A smoke detector and pollution detector can be built using fibres.

b) A loop of fibre can be used to determine the level of the liquid in a container.
A LED source a MMF and photodetector are used in building ~~sooon~~ as a liquid level sensor.
These sensors are used to monitor the filling of petroleum tanks.

3) Communication application:

a) Fibre optics deals with communication of audio as well as video signals.

b) An optical fibre data bus offers a great reduction in cost & enormously increases the information handling capacity compared to parallel multiwire data bus.