* Optical Fibre

In 1970 Cornings Glass Works produced low loss glass fibres.
By 1977, commercial communication systems based optical fibres made their appearance.
* Fibre Optics is a technology in which signals are converted from electrical into optical signals, transmitted through a thin glass fibre & reconverted into electrical signals.

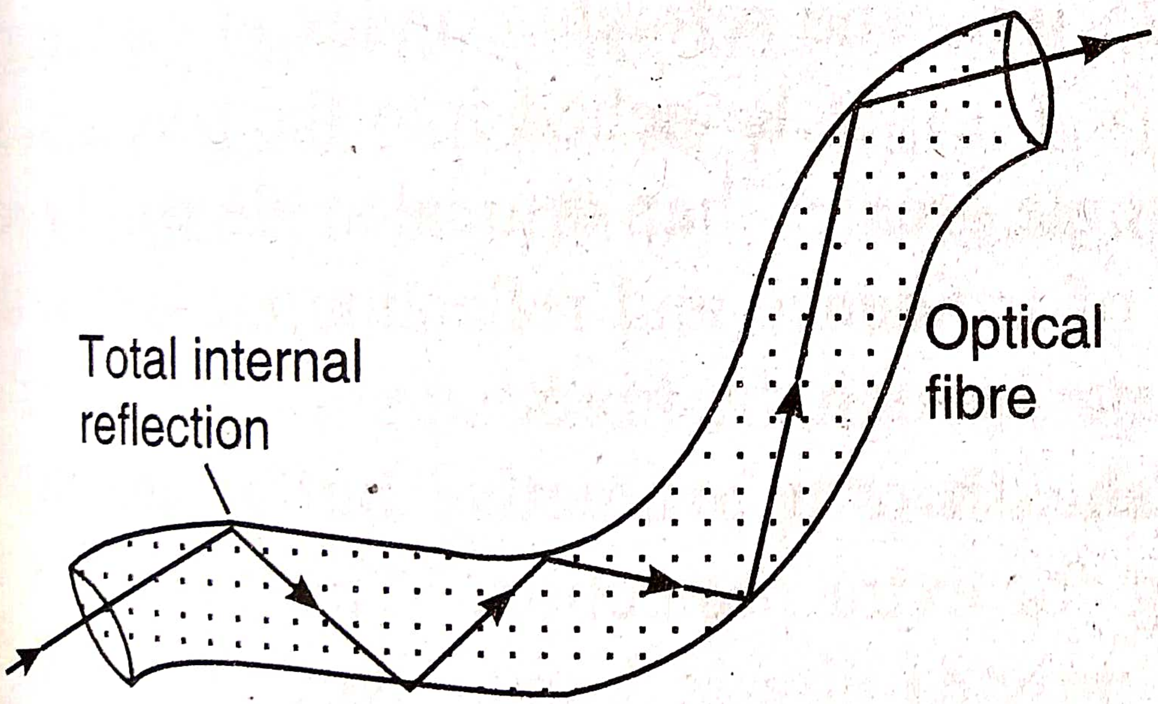
Optical Fibre is a cylindrical wave guide made of transperent dielectric (glass / clear plastic) which guides light waves along its length by total internal reflection.

Principle:
Propagation of light in optical fibre from one end to other end is based on principle of total internal reflection.
When light entres one end of fibre, it undergoes successive total internal reflections from sidewalls & travels down the length of fibre along a zigzag path.

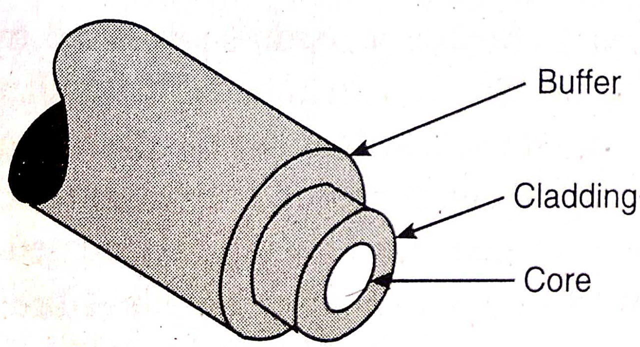
A typic Optical fibre which is cylindrical in shape consists of three co-axial regions :-

(i) Core :
Light guiding innermost region.
Diameter in range 8.5 μm to 62.5 μm.

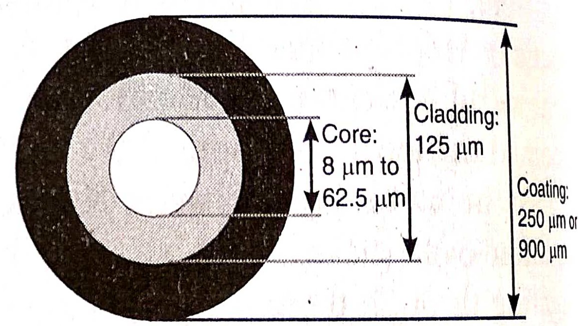
(ii) Cladding :
Core ~~surr~~ is Surrounded by a coaxial region


Total internal reflection
Optical fibre

Structure:



(a)



(b)

~~cal~~ cladding.

Diameter in range of order of 125 μm

R.I of cladding (n_2) always lower than that of core (n_1) to get total internal reflection.

(iii) Sheath / Protective Buffer coating :-

Plastic coating given for extra protection

Coating is applied during manufacturing process to provide physical & environmental protection to fibre.

Also it is elastic in nature

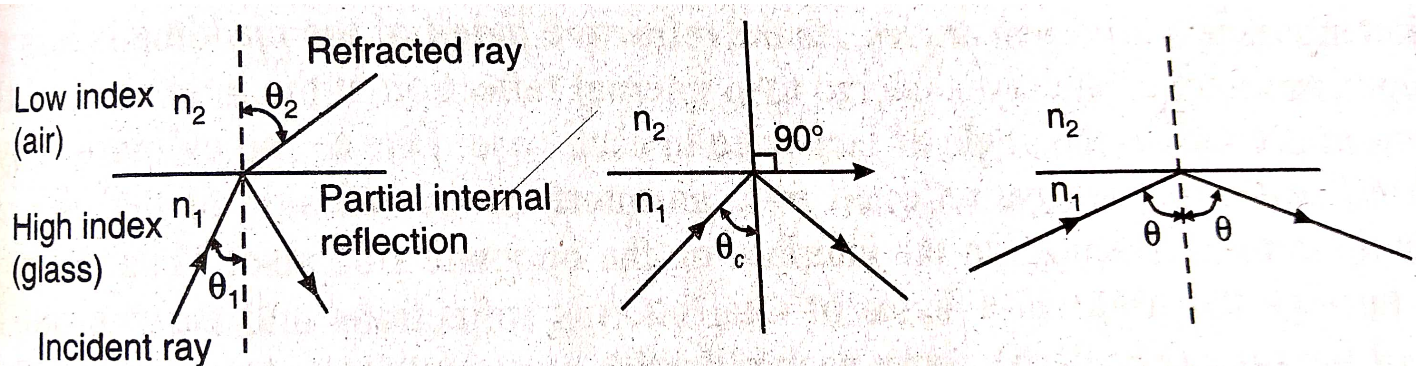
Coating size vary from 250 μm to 900 μm.

* Cladding performs important fucn :-

- Keep the size of fibre constant & reduces loss of light from core into surrounding
- Protects the fibre from physical damage
- Prevents leakage of light energy from fibre
- Reduce the cone of acceptance & increases rate of transmission of data.

* Total Internal Reflection ?

- medium having lower Refractive Index (R.I) is Rarer medium
- Medium having higher R.I is Denser medium
- When light travels from one medium to other, it changes its direction.
- Denser to Rarer medium → bend away from normal
- Rarer to Denser medium → bend toward the normal.



Refracted ray
Low index
(air)
n_2
θ_2
High index
(glass)
n_1
θ_1
Partial internal
reflection
Incident ray
n_2
90°
n_1
θ_c
n_2
n_1
θ
θ

(a) (b) (c)

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If $\theta_1 < \theta_c \Rightarrow$ Ray refracts into rarer medium.

If $\theta_1 = \theta_c \Rightarrow$ Ray just grazes interface (travel along interface)

If $\theta_1 > \theta_c \Rightarrow$ Ray is reflected back into denser medium.

The phenomenon in which light is totally Reflected from denser-to-rarer medium is Total Iternal Reflection

↳ To find critical angle ⇒

At, $\theta_1 = \theta_c$, $\theta_2 = 90°$

$\therefore \sin(90) = \left(\frac{n_1}{n_2}\right) \sin\theta_c$ (snell's law)

$$\therefore \boxed{\sin\theta_c = \frac{n_2}{n_1}}$$

for air, $n_2 = 1$ & $n_1 = n$.

$$\therefore \boxed{\sin\theta_c = \frac{1}{n}}$$

Critical Angle :-

$$\boxed{\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

In Optical Fibre total internal Reflection will occur, if following conditions are satisfied:

(I) Refractive index of core (n_1) must be slightly greater than R.I. of clad (n_2)

(II) Angle of incidece at core-cladding interface must be greater than critical angle.

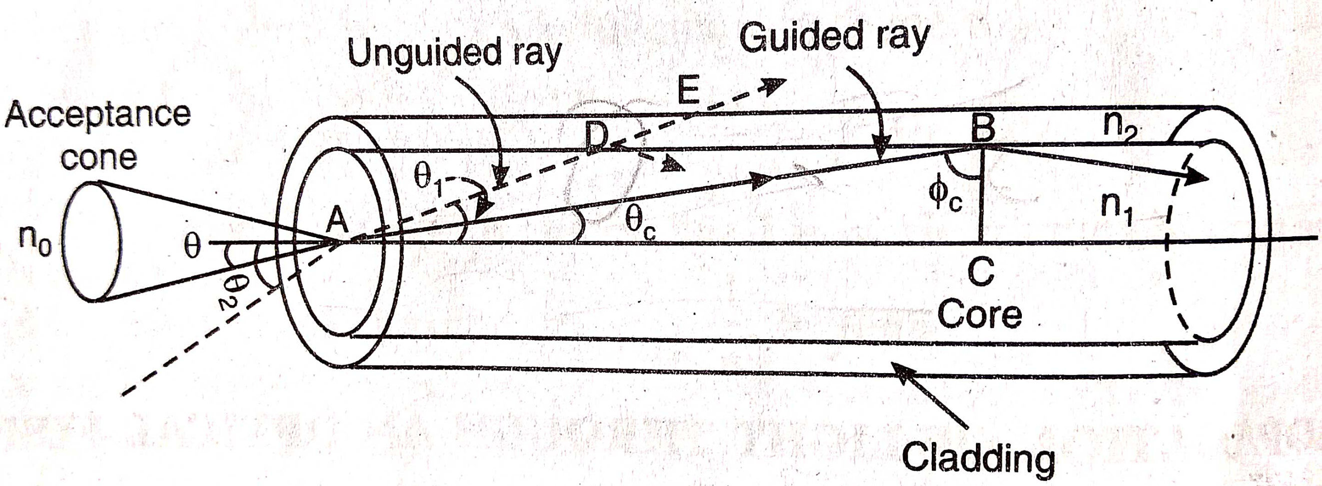

Fig. 10.7: Light rays incident at an angle smaller than critical propagation angle will propagate through the fibre.

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* Critical angle of Propagation :-

Consider an optical fibre , light is incident on it at one end (launching end)

Consider a ray (shown in dotted line) enter the fibre at an angle θ_2 with respect to axis of fibre (normal) This ray will just get refracted from core-cladding interface at point D & lost.

Consider two rays (shown in solid line) incident at an angle 'θ' & it satisfies critical angle condition ($\theta > \theta_c$) Hence, it will get totally reflected from point 'B' on interface

Let angle made by this ray (AB) with ~~normal~~ normal be ϕ_c

For further total internal reflection, it must follow critical angle condition

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

$$\Rightarrow \boxed{\phi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

$\therefore$ The rays incident with angle greater than ϕ_c will undergo total internal reflection in core.

$\therefore$ The ~~at~~ ray making angle $\phi_c \rightarrow$ Critical Ray.

Consider ~~ang~~ Δ ABC,

$$\frac{AC}{AB} = \sin\phi_c \quad \& \quad \frac{AB}{AB} = \cos\theta_c$$

$\therefore \cos\theta_c = \frac{n_2}{n_1}$

$\therefore$ $$\boxed{\theta_c = \cos^{-1}\left(\frac{n_2}{n_1}\right)}$$

Critical Angle of Propagation.

$\therefore$ Only those rays which are refracted into cable at angles $\theta_r < \theta_c$ will propagate in optical fibre.

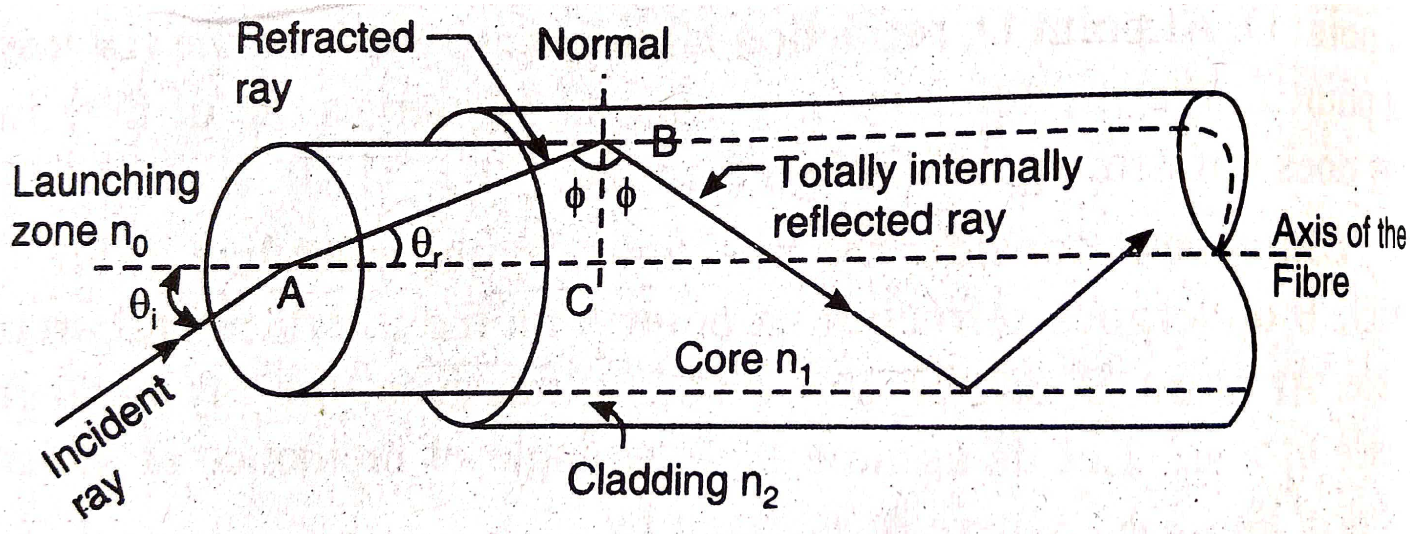


Fig. 10.8: Geometry for the calculation of acceptance angle of the fibre.

* Acceptance Angle :-

Consider an optical fibre & light is incident on launched end.

Let refractive index of core be 'n_1' & refractive index of cladding be 'n_2'

'n_0' be R.I of medium from which light is launched into the fibre.

Assume ray entres the fibre at an angle 'θ_i' to axis of fibre.

This ray refracts at angle 'θ_r' & strikes core cladding interface at angle 'ϕ'

If ϕ > critical angle, ray will undergo total internal reflection. ($\because n_1 > n_2$)

Snell's law,

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_0}$$

If we increase θ_i, ϕ will drop below critical value ϕ_c & ray will escape from sidewalls of fibre.

$\therefore$ Largest value for θ_i occurs when

$$\phi = \phi_c.$$

Consider ΔABC,

$$\sin\theta_r = \sin(90^\circ - \phi) = \cos\phi$$

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

When, $\phi = \phi_c$

$$\sin[\theta_{i_{max}}] = \frac{n_1}{n_0}\cos\phi_c$$

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

$$\therefore \cos\phi_c = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \quad \left[\because \cos\theta = \sqrt{1-\sin^2\theta}\right]$$

$$\therefore \sin[\theta_{i(max)}] = \frac{\sqrt{n_1^2 - n_2^2}}{n_1} \times \frac{n_1}{n_0}$$

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

For medium (air) $n_0 = 1$

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

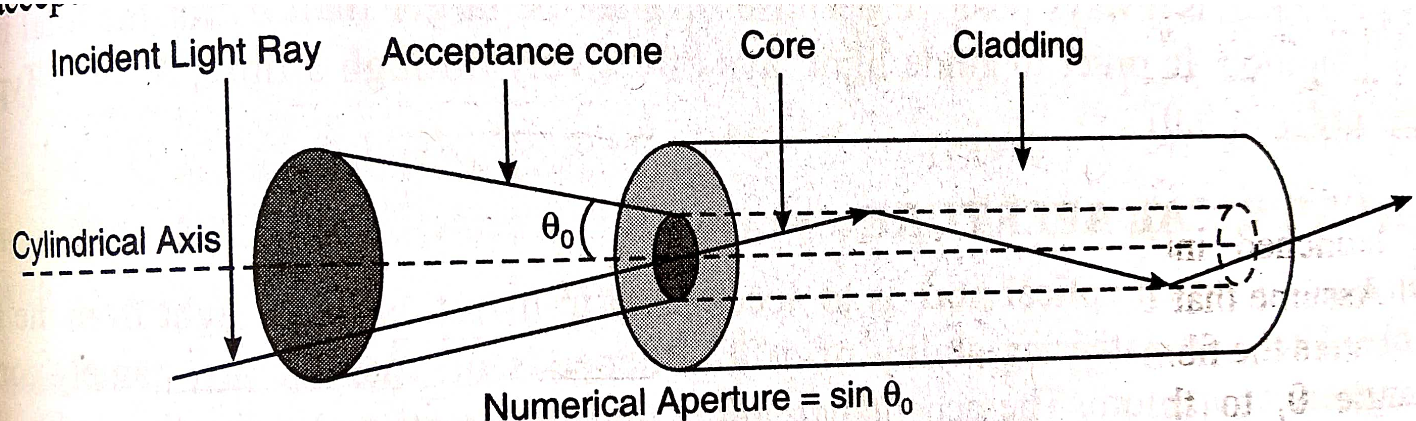
$$\therefore \boxed{\theta_0 = \sin^{-1}\left[\sqrt{(n_1^2 - n_2^2)}\right]}$$

$\theta_0 \rightarrow$ Acceptance Angle.

$\therefore$ Acceptance Angle is the maximum angle that a light ray can have relative to axis of Fibre & propagate down the fibre

$\therefore$ Larger the acceptance angle, it will be easier to launch light into the fibre.

For, 3-Dimensions, light rays are


Incident Light Ray
Acceptance cone
Core
Cladding
Cylindrical Axis
θ0
Numerical Aperture = sin θ0

contained within cone having full angle '$2\theta_0$' are accepted. & cone is acceptance cone.

$\therefore$ Acceptance Angle $\Rightarrow$

$$\theta_0 = \sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right]$$

For a 3-D cone $\Rightarrow$ Acceptance angle of cone

$$2\theta_0 \Rightarrow \boxed{2\sin^{-1}\left[\sqrt{n_1^2 - n_2^2}\right]}$$

* Fractional Refractive Index Change :-
Fractional Difference betn R.I of of core & R.I of cladding is Fractional Refractive index change.

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

$\Delta \rightarrow$ always +ve.
of order of 0.01

* Numerical Aperture :-
Optical fibre accepts & transmit light. Light gathering ability depends on two factors - core size & Numerical aperture
Acceptance Angle & Fractional refractive index determine the numerical aperture of fibre.

* Numerical Aperture is defined as sine of Acceptance Angle

$$\therefore \boxed{N.A. = \sin\theta_0}$$

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

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

$n_1^2 - n_2^2 = \left[\frac{(n_1+n_2)}{2} \frac{(n_1-n_2)}{n_1}\right] 2 \cdot n_1$

Approximating $\frac{n_1+n_2}{2} \approx n_1$

$\therefore n_1^2 - n_2^2 = 2 n_1^2 \Delta$. $\left[\because \frac{(n_1-n_2)}{n_1} = \Delta\right]$

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

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

- Measure of amount of light that can be accepted by a fibre.
- Depends only on R.I of core & ~~to~~ cladding materials. & doesn't depend on physical dimensions of fibre.
- Value of N.A ranges from 0.13 to 0.50
- Large value of N.A. ⇒ fibre can accept large amount of light from source.

* Types & Classification of Optic fibres :-
Light is an electromagnetic waves so there are electric & magnetic waves associated with it.
Depending on transmission of these waves 3 ~~two~~ modes are there :
Transverse electric & magnetic mode (TEM)
Bothe electric & magnetic fields are transverse to travel.
Transverse electric mode (TE), electric fiel

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transverse to direction of propagation &
magnetic field ||ar to it
Transverse magnetic mode (TM) :,
Magnetic field transverse to direction of
propagration & ~~magnetic~~ electric field perpendicular
to it.

In simple words, modes can be visualised
as possible number of allowed paths of light
in an optical fiber.
Light rays paths along which waves are
in phase inside fiber are "modes".

Based on modes, optical fibers classified
as
(a) Single Mode fiber (SMF) &
(b) Multimode Fiber (MMF)

Depending on number relation between
R.I of core & cladding:
(a) Step Index fiber &
(b) Graded Index fiber.

Overall Based on modes & rel^n bet^n
R.I of core & cladding, classified
into :-
(a) Single Mode Step Index fibre
(b) Multimode Step Index fibre
(c) Graded Index (GRIN) Fibre

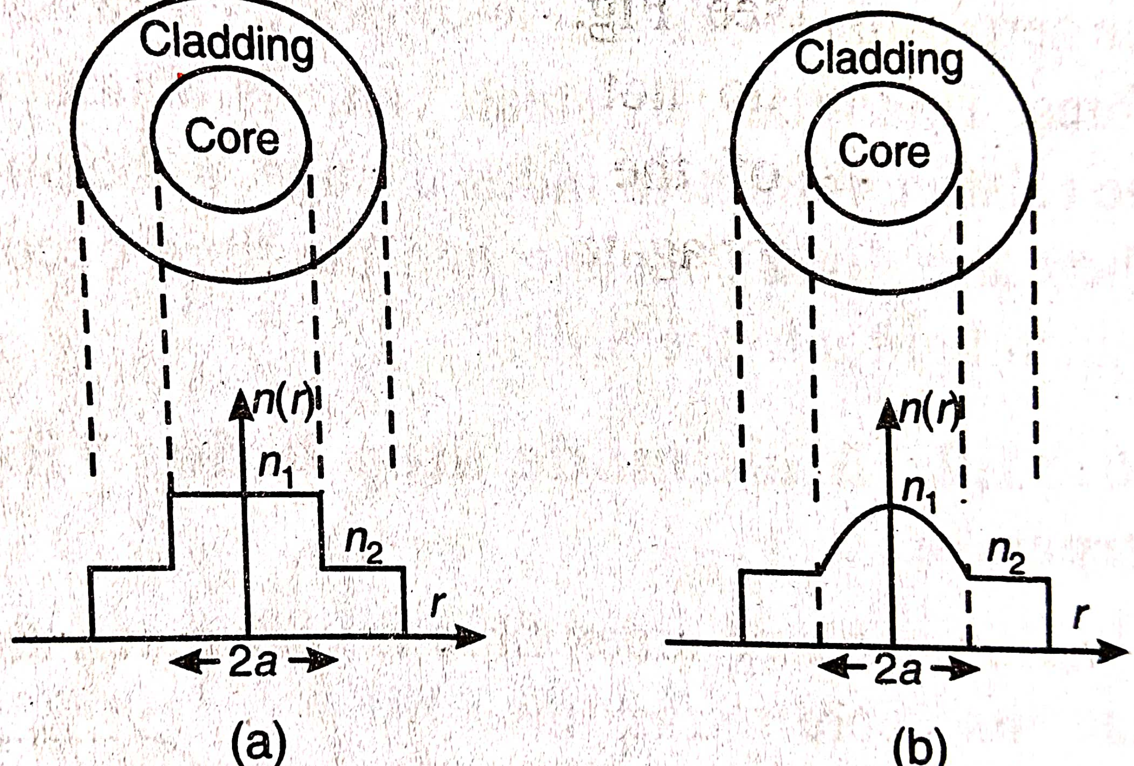


Fig. 10.14: Classification of optical fibres based on R.I. profile (a) Step index fibre (b) GRIN fibre

Step Index fibers :

- R.I of fiber changes ~~art~~ abruptly at core-cladding boundary.
- If 'r' is radial distance from axis & 'a' is diameter, variation of R.I can be represented as

For core → $n(r) = n_1$; $r < a$.

For cladding → $n(r) = n_2$; $r > a$.

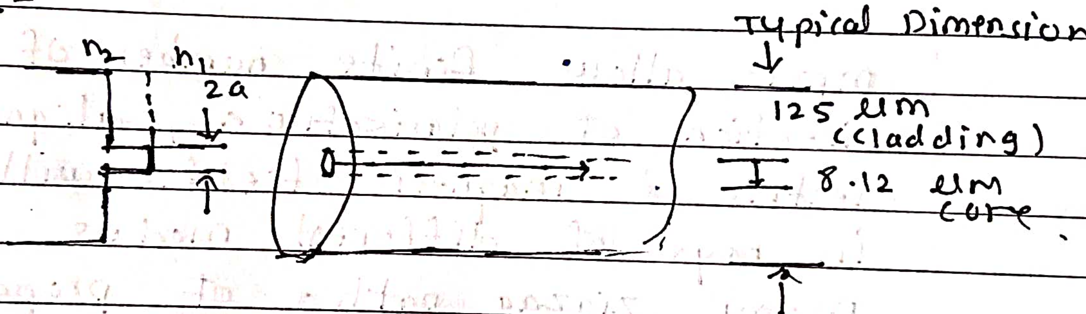
Rel^n bet^n R.I ⟹ $n_2 = n_1(1-\Delta)$

Δ → difference in R.I of core & cladding

* Single Mode Step Index Fibre :-

Structure :-

A very fine thin core of diameter of 8 μm to 12 μm.



Usually made of germanium doped silicon.

Core surrounded by thick cladding of lower R.I

Core composed of silica slightly doped with phosphurous oxide.

Diameter of cladding (external) ~ 125 μm.

Fibre surrounded by opaque sheath

$$n(r) = n_1 \quad (r < a \text{ inside core})$$

$$= n_2 \quad (r > a \text{ in cladding})$$

Δ & N.A. are very small for SMF.

low N.A. ⟹ low acceptance angle.

∴ Light coupling into fibre become difficult

∴ ~~Cost~~ Costly laser diodes are required to launch light into SMF.

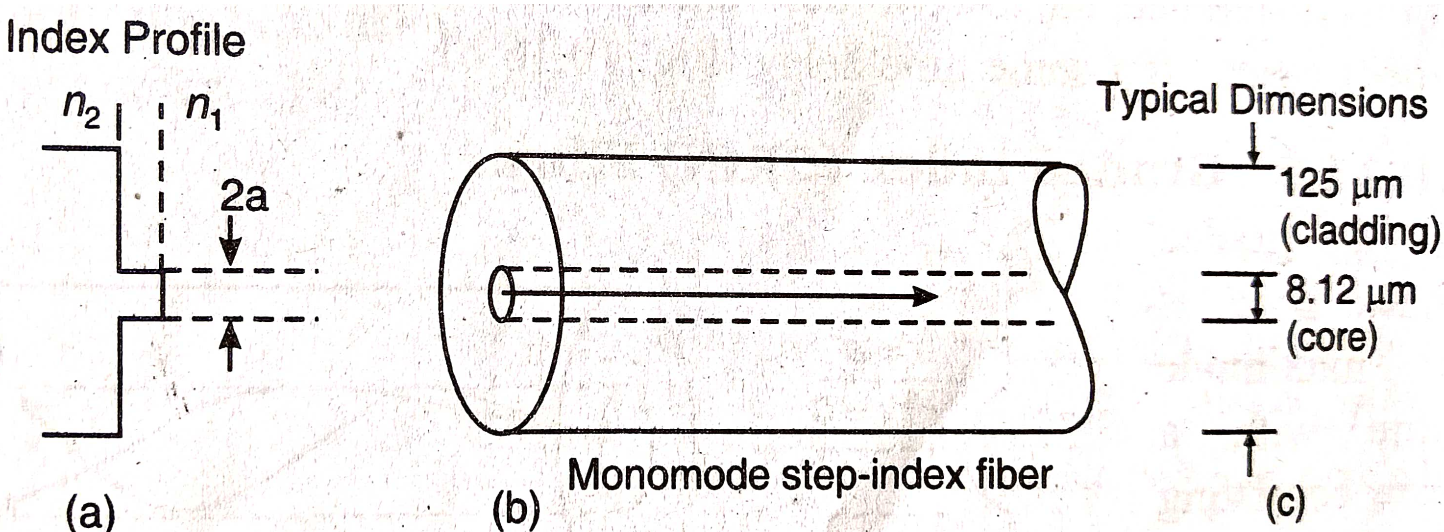


Fig. 10.15: Single mode step index fibre (a) R.I. profile (b) ray paths (c) typical dimensions

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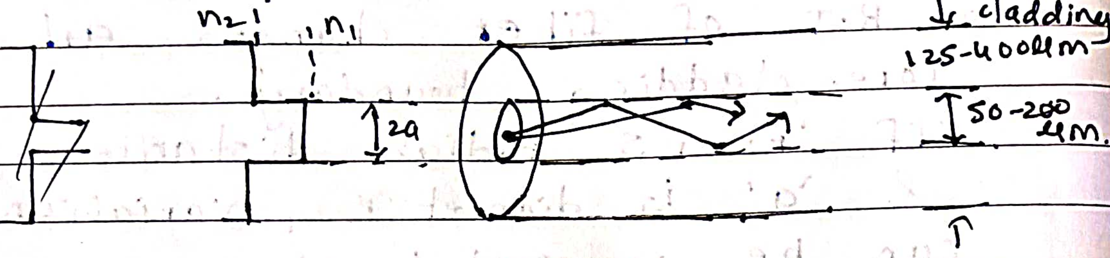
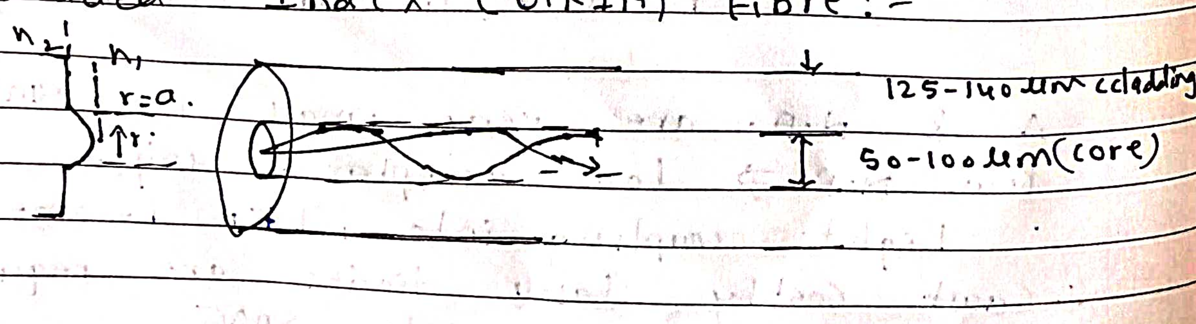
② Multimode Step Index Fibre :-



Similar to single mode step index fibre only diameter of core is of order of 50-100 μm which is very large compared to wavelength of light. Outer diameter of cladding is about 150-250 μm.

MMF allow finite number of guided modes. Direction of polarisation, alignment of electric & magnetic fields will be different in rays of different modes.
Many zigzag paths of propagation are permitted in a MMF.
~~Path~~ Rays moving close to axis will cover shorter path length as compare to other zigzag paths.
Because of which lower order modes reach end of fiber earlier while higher order modes reach after some time delay.

③ Graded Index (GRIN) Fibre :-



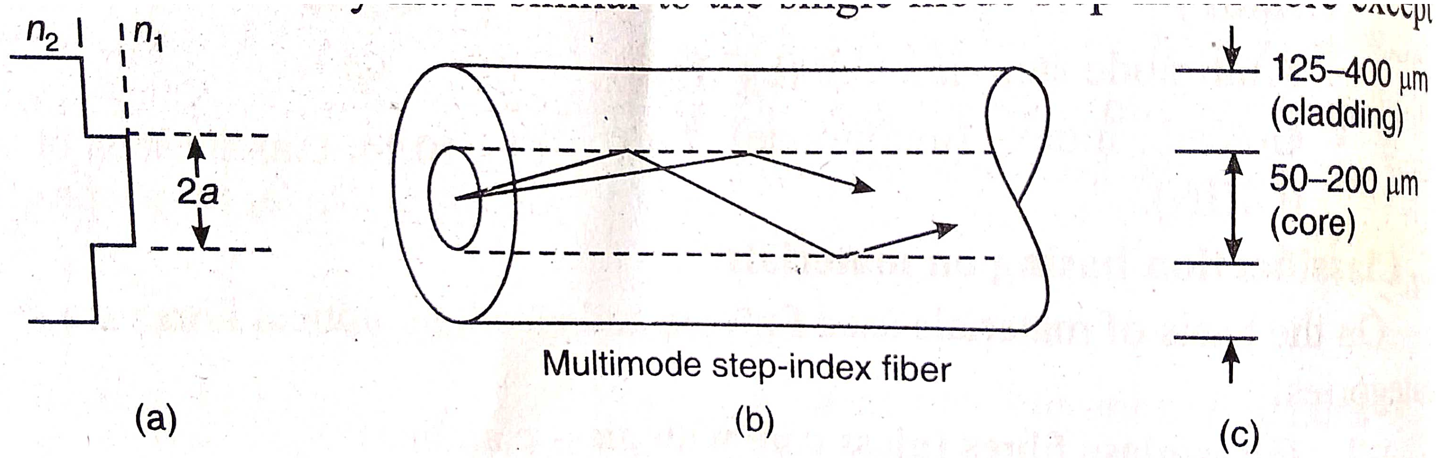


Fig. 10.16: Multimode step index fibre (a) R.I. Profile (b) Ray paths (c) Typical dimensions

Graded index (GRIN) Fibres - refractive index of core is not constant but varies smoothly over diameter of core.
It has maximum value at the centre & decreases gradually with increasing radial distance from the axis.
Variation of R.I. of core with radius measured from center is

$$n(r) = \begin{cases} n_1 \sqrt{1 - \left[2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]} \; ; & r < a \text{ inside core} \\ n_2 \; ; & r > a \text{ in cladding} \end{cases}$$

$n_1 \rightarrow$ maximum R.I at core axis,
$a \rightarrow$ core radius
$\alpha \rightarrow$ Grading profile index vary from 1 to ∞
- $\alpha = 2 \rightarrow$ index profile is parabolic & is preferred for different applications.

Propagation of light in GRIN fibre:-
Light goes from higher RI medium to lower R.I medium, it is bent away from normal. When total internal reflection condⁿ is met, ray travels back towards the core axis, again continuously refracted.
Turning around may take place even before reaching core-cladding interface.
Continuous refraction is followed by total internal reflection & again continuous refraction toward axis.
Rays making larger angles with axis traverse longer path but they travel in a region of lower R.I. & hence at higher

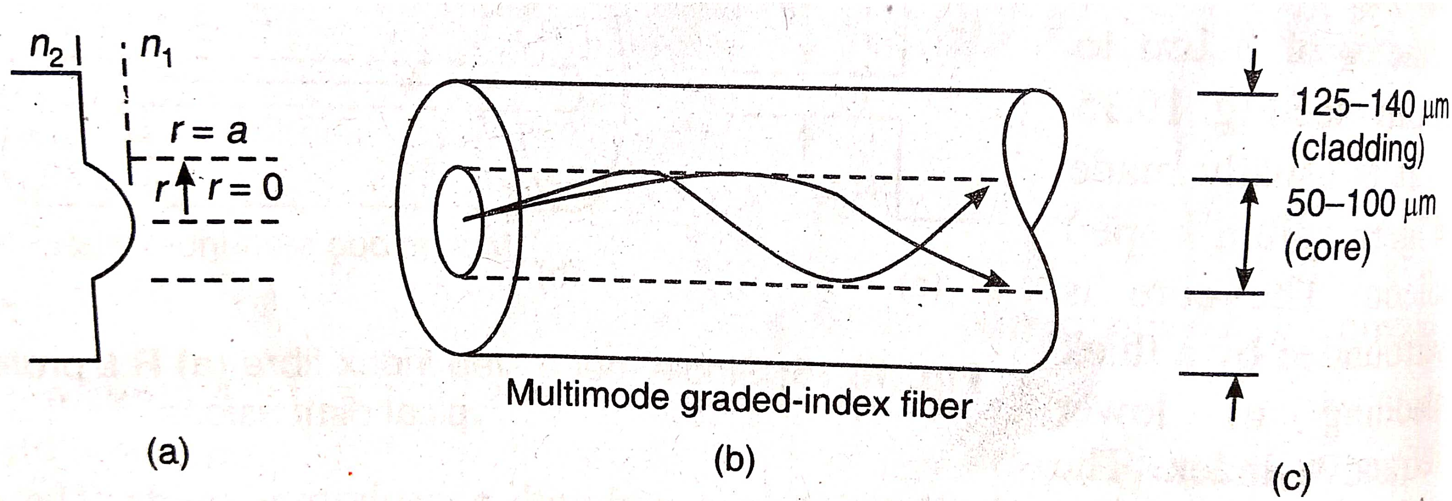


Fig. 10.17: GRIN fibre (a) R.I. Profile (b) Ray paths (c) Typical dimensions

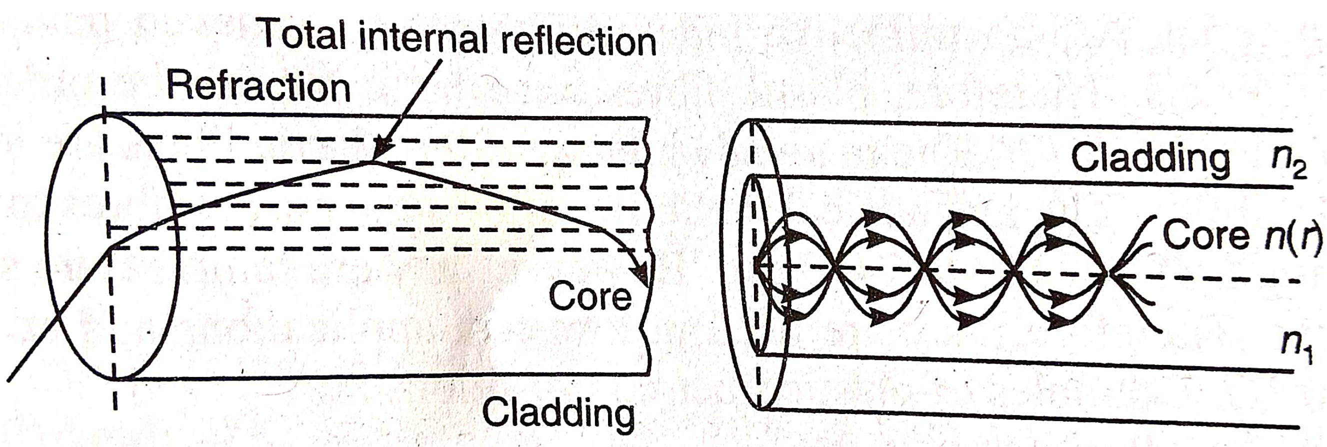


Fig. 10.18: (a) An expanded ray diagram showing refraction at the various high to low index interfaces within graded index fibre, giving an overall curved ray path. (b) Light transmission in a graded index fibre.