15/02/2022

UNIT-V

OPTICAL FIBRES:

→ Narendra Singh Kapany : Father of optical fibres.

→ Optical fibres: Cylindrical wave guides made up of dielectric material (glass/or plastic)

plastic → used for short distance communication
→ due to losses ; no signal is lost however.

→ They carry the signal from one point to another point. They carry in optical form along its length

* Fibre optics : It is a technology in which signals are converted from electrical to optical form transmitted through thin glass fibres (optical fibres) and reconverted into electrical signal.

→ They work on the principle of Total Internal Reflection.

→ Light should travel from optically denser medium to rarer medium.

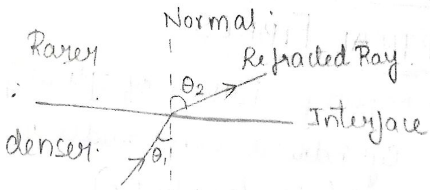
→ angle of incidence > critical angle.

denser medium : high refractive index.

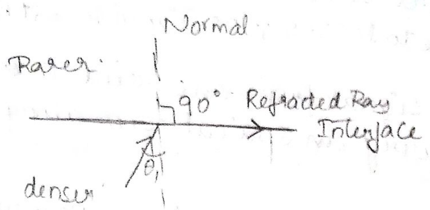
Rarer medium : low refractive index.

$$\text{Refractive Index} = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in medium}}$$

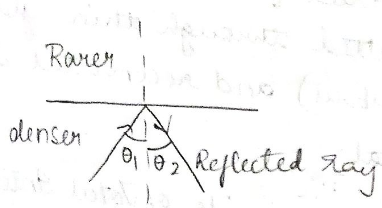
1) $\theta_1 < \theta_c$



2) $\theta_1 = \theta_c$.

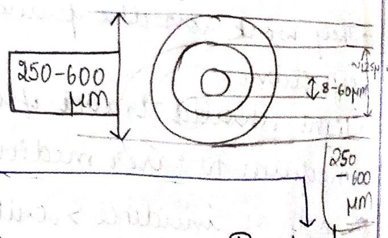


3) $\theta_1 > \theta_c$



* Optical Fibre:

3 PARTS



- **Core** — Innermost part (n_1) → Signal is trapped in this layer.
- **Cladding** — Middle layer (n_2) $\boxed{n_2 < n_1}$ → It helps in TIR to the ...
- **Buffer/Jacket** — Outermost layer.

Cladding helps the core in TIR and stops the data from escaping / loss of data.

TWO TYPES OF FIBRES:

1) Single Mode → Diameter is small → lasers are used. Long range comm. $\boxed{\text{Losses are less}}$
Cost is high.
↓
Process is called launching.

2) Multi Mode → Diameter is a bit large → LED → Short range

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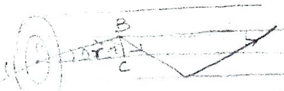
CRITICAL ANGLE OF PROPAGATION:



In ΔABC

$$\sin \theta_c = \frac{AC}{AB} = \frac{n_2}{n_1}$$

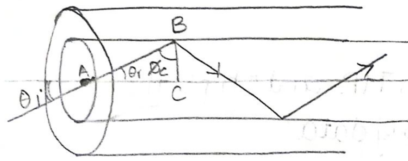
$$\cos \theta_c = \frac{AC}{AB} = \frac{n_2}{n_1}$$

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

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

Any angle greater than θ_r, TIR does not take place.

* ACCEPTANCE ANGLE :



$n_2 \sin\theta_1 = n_1 \sin\theta_2$

$$\boxed{\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_1}{n_2}}$$

Fiber axis

In $\triangle ABC$ $\theta_r = 90 - \phi$

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

When $\phi = \phi_c \Rightarrow \theta_i = (\theta_i)_{max}$

$$(\sin\theta_i)_{max} = (\cos\phi_c)\frac{n_1}{n_2}$$

$$(\sin\theta_i)_{max} = \frac{n_1}{n_0}\sqrt{1-\sin\phi_c}$$

$$= \frac{n_1}{n_0}\sqrt{1-\left(\frac{n_2}{n_1}\right)^2}$$

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

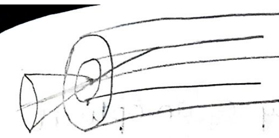
$$\boxed{\sin\theta_0 = \frac{\sqrt{n_1^2-n_2^2}}{n_0}}$$

If the light signal is launched in air ;

$n_0 = 1$

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

Acceptance angle depends on refractive indices and refractive index of medium



→ Acceptance angle: It is the maximum angle that a light ray can have relative to the axis of fibre and propagate down the fibre.

* In 3D ; the light rays contain within the core having a full angle $2\theta_0$ are accepted and transmitted along the core. Therefore; cone is called accepted cone.
* Light rays incident at an angle beyond θ_0 refracts through the cladding and the corresponding optical signal is lost.

* FRACTIONAL REFRACTIVE INDEX CHANGE: (Δ)

* Fractional change in refractive index

The fractional difference between the refractive indices of core & cladding is called fractional refractive index change.

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

Δ is always +ve ; as $n_1 > n_2$

$$\boxed{\Delta << 1 \quad \simeq 0.01}$$

* NUMERICAL APERTURE:

The light collecting capacity of an optical fibre.

The main function of optical fibre is to accept and transmit as much as light possible from source.

→ N.A. depends on core size.

→ If core size is less; light carrying capacity is also less.

$$NA = n_0 \sin\theta_0$$

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

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

NA does not depend on refractive index of medium.

→ Relation b/w NA & Δ.

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

$$n_1^2 - n_2^2 = \frac{(n_1 - n_2)(n_1 + n_2)\, 2n_1}{2 n_1}$$

$$= \Delta n_1 \cdot 2n_1$$

$$= 2n_1^2 \Delta$$

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

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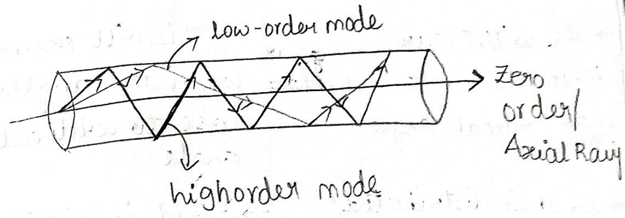
* MODES OF PROPAGATION:

→ Low order mode
→ Zero order
→ High order mode



→ A mode is a path that light can follow as it travels down the core of the fiber. So, modes can be visualised as the possible (TIR takes place) number of allowed parts in an optical fiber.

→ Rays with propagation angle $\theta = 0$ to θ_c will undergo TIR. However all of them will not propagate.

→ If critical angle ↑ses; no. of modes propagating in fiber increase; Increasing the refractive index of core; more no. of modes are formed. If n_2 ↑ses; no. of propagating modes decrease.

→ No. of modes that a fiber can support depends on the ratio $\boxed{\frac{d}{\lambda}}$.

d → diameter of core λ → wavelength of the propagating light.

LOW ORDER	HIGH ORDER
→ This will occur when the angles are ~~close~~ far from ~~the~~ critical angle.	→ This will occur when the angles are close to critical angle.
→ Field is distributed/ ~~in~~ concentrated in the centre of wave guide.	→ Field is distributed at the edge of wave guide.
→ The lower order mode travel shorter distance and therefore time to travel decrease.	→ The higher order mode travel larger distance and therefore time to travel increases.

* V-NUMBER:

V-number or normalised frequency is helpful to decide the number of modes that a fiber can support:

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

where $a \Rightarrow$ radius of core.

$\lambda \Rightarrow$ wavelength of propagated light ray

$n_1 \Rightarrow$ refractive index of core

$n_2 \Rightarrow$ refractive index of cladding

$$\boxed{V = \frac{2\pi a}{\lambda}(NA)}$$

NA = numerical aperture

→ For optical fiber with large V-number, the possible number of supported modes is given by: $\boxed{N \simeq \frac{1}{2}V^2}$

* If $V < 2.405$ → Single Mode.
  $V > 2.405$ → Multi mode.
  $V = 2.405$ → wavelength where the value of V becomes 2.405; wavelength is called cutoff wavelength.

* Various Light Sources in Optical Fibre:

→ LED, laser diode (LD)

→ Photodetectors
- Photo diode
- Pin diode

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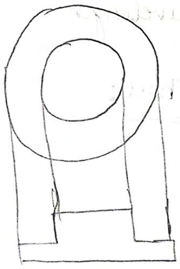
CLASSIFICATION OF OPTICAL FIBRES:

- Based on refractive index
  - Step Index fibre (SI)
  - Graded Index fibre (GRIN)
- Based on mode of propagation
  - Single Mode fibre (SMF)
  - Multi Mode Fibre (MMF)
- Based on materials used
  - Glass/Glass
  - Plastic/Plastic
  - Plastic Clad Silica

Single Mode Fibre:
(SMF)
↓
Step index single mode fibre:

Multimode Fibres.
(MMF)
→ Step Index MMF
→ GRIN MMF.

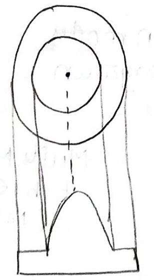
: R.F is const throughout the core and changes (decreases) abruptly at the core cladding interface.



⟹ Step Index ~~Single~~ Fibre (50 – 100 μm).

GRIN: When a signal is passed to a fibre; when the signal is moving away from fibre axis RF decreases and towards fibre axis RF increases and it is constant in cladding.

*Max. at the centre of core and ↓ses ~~towar~~ gradually near the



Graded Index Fibre.

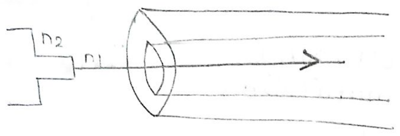
In SMF: • a single mode is carried
• carried along the axis & Zero order / Axial ray.
• Low losses.
• core size is small, NA is small; Δ is small.
• Long range communication.
• Lasers are used.

In Step Index MMF: • Cheaper; not very expensive.
• carries large no. of modes.
• Low order & high order both are used.
• Losses are more. • Path length along axis is shorter while other zig zag paths are longer.
• Short distance communication
• core size is large; NA is large.
• LEDs are used.
• RF is const in core; abruptly ↓ses.

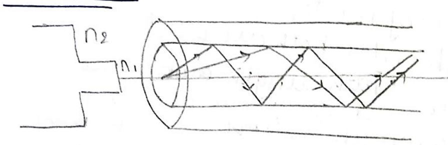
In GRIN MMF: • high cost.
• Losses are less
• RF is changing radially.
• core size is large.
• Fabrication is difficult / complex.
• ~~Short~~ Long distance communication.
• Large no. of modes can be carried.

In step-Index SMF:
• Carries only one mode of propagation
• R.I. const in the core; abruptly ↓ses at the interface
• Low NA; low acceptance angle.
• Launching the light is difficult; lasers are used; So it ↑ses overall cost

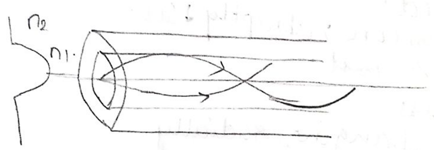
Single Mode Fibre (Step Index Single MF).

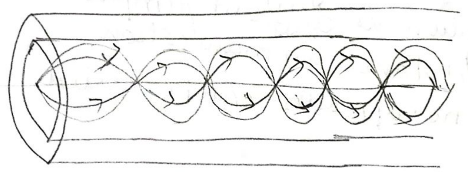


SI MMF:



GRIN MMF:





→ It is a multimode fiber with core consisting of concentric layers of refractive index. i.e. refractive index of core varies with distance from fibre axis.

→ The R.F is max. at the centre of core and is gradually decreasing towards the edge of core.

* **Glass/Glass:**

→ Both core & clad are made of glass.
→ Used for long range communication.
→ Silica is used.

1) core $\left\{ \begin{array}{l} SiO_2 : P_2O_5 \rightarrow \\ \quad\;\; : Ge \rightarrow \end{array} \right.$ R.F ↑ses }

Cladding (SiO_2)

2) Core (SiO_2) = {

Cladding $SiO_2 : B_2O_3$ RF ↓ses.

* **Plastic/Plastic:**

→ Both core & clad are made of Plastic
→ PMMA, Teflon.
→ Used only below 80°C.
→ Losses are more ; used for Short distance commⁿ.

* **PCS:** Plastic Clad Silica.

Core → Quartz.
Cladding → Plastic }

Losses are ~~between~~ medium.

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LOSSES IN OPTICAL FIBRES:

- ATTENUATION (loss in amplitude)
  - INTRINSIC (3-5%)
    - Material absorption
    - Rayleigh Scattering (used 7800nm) $\boxed{\propto \frac{1}{\lambda^4}}$
  - EXTRINSIC (96%) (Bending Losses)
    - Macro bending
    - Micro bending.
- DISTORTION. (Change in shape of pulse).
  - Intermodal dispersion multimode fibre
  - Intra modal dispersion
    - Material dispersion
    - Wave guide dispersion

* Output amplitude is very much less than input amplitude.

*ATTENUATION:

→ When a signal propagates through a fibre; its power reduces exponentially with distance. This is known as attenuation and is defined as = $\frac{\text{OPTICAL OUTPUT POWER}}{\text{OPTICAL INPUT POWER}}$

$$P_o = P_i e^{-\alpha L}$$

Log on both sides

$$\log P_o = \log P_i - \alpha L$$

$$\boxed{\alpha = \frac{\log\left(\frac{P_o}{P_i}\right)}{L}}$$

$$\boxed{\alpha_{dB/km} = \frac{10}{L} \log\left(\frac{P_i}{P_o}\right)}$$

$$\boxed{\alpha = \frac{10}{L} \ln\left(\frac{P_i}{P_o}\right)}$$

For ideal cable $P_i = P_o \Rightarrow \boxed{\alpha = 0}$

⇒ attenuation losses are not there.

If there are more losses; we can change the composition of the fibre.

⇒ MATERIAL ABSORPTION:

Due to the presence of impurities/OH^- groups during the manufacture of the fibre causes intrinsic losses. Remedy: keeping the environment clean.

⇒ RAYLEIGH SCATTERING:

When the fibre contains impurities in groups; when the signal passes through that; signal gets reflected before reaching the end due to which there is loss in the power.

⇒ MICROBENDING:

These losses are produced by mishandling the device, temperature; core gets damaged; due to which acceptance angle gets affected and TIR does not take place. Remedy: Use a good quality of plastic for the cladding.

⇒ MACRO BENDING:

If the core of the optical fibre is bent ; macro bending losses take place because when a signal passes through the ~~bending~~ bent part ; the signal gets ~~diverted~~. ~~and~~

* DISTORTION:

→ Intermodal dispersion take place in multimode fibre.

→ In intermodal dispersion ; when low order & high order wave guides travel together ; they reach the end at different times ; due to which there is distortion in the pulse.

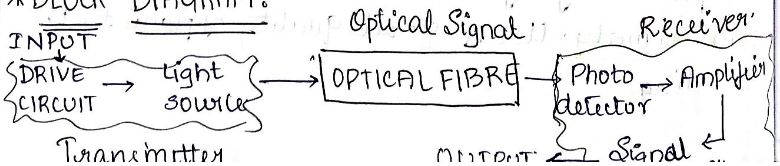
→ In intramodal dispersion ; ~~these~~ signals of different velocities ; reach the end at different times ; which cause distortion in the pulse.

* EVANESCENT FIELD:

* Few signals escape into the cladding ; the field created by them is evanescent field.

* The band of wavelengths at which the attenuation is minimum is called optical window / transmission window or low-loss window.

* BLOCK DIAGRAM:



* transmitter : Electrical to Light/optical signals.
* optical fibre : transmits the optical signal.
* Receiver : receives optical signal at the other end of fibre and converts to audio signals.

* Advantages:

→ Low cost, Light weight, flexible.
→ High data carrying capacity
→ No electromagnetic interference
→ Non-hazardous.
→ Longer lifespan
→ Wider Bandwidth.

* APPLICATIONS:

→ Internet
→ Telephone industry
→ Military applications ⇒ Security.
→ Medical field.
→ computer networking.
→ Broadcasting.

* DISADVANTAGES:

→ Low Power
→ Point to Point connections are required.
→ Fragile
→ Need expensive transmitters & receivers.

24/02/2022

1) $NA = 0.039$ $\Delta = 0.05$ $n_1 = ?$

$$\Delta = \frac{n_1 - n_2}{n_1} \qquad (NA)^2 = n_1^2 - n_2^2$$

$$0.05n_1 - n_1 = -n_2$$

$$n_2 = 0.95n_1$$

$$0.1521 = n_1^2 - (0.9025)n_1^2$$

$$= 0.0975 n_1^2$$

$$n_1^2 = 1.56$$

$$\boxed{n_1 = 1.24}$$

2) $n_1 = 1.43$ $n_2 = 1.4$

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

$$= 0.97$$

$$\boxed{\theta_c = 11.75}$$

3) $\theta_0 = ?$ $n_1 = 1.563$

$n_2 = 1.498$

$$\theta_0 = \sin^{-1}\sqrt{n_1^2 - n_2^2}$$

$$= \sin^{-1}(\sqrt{2.44 - 2.244}$$

$$= \sin^{-1}(0.44$$

$$\boxed{\theta_0 = 26.2^\circ}$$

4) A fibre is surrounded by air, $NA = 0.27$. will light entering $\theta_c = 5^\circ$ remain in fibre or not.

$$\theta_0 = \sin^{-1}(NA)$$

$$\boxed{\theta_0 = 15.66^\circ}$$

The light will not escape the fibre.

5) Optical power of 1mW is launched into optical fibre whose length is 100m. The output power = 0.3mW

$P_o = 0.3mW$

$P_i = 1mW$

$L = 100m$.

$$\alpha = \frac{10}{L} \ln\left(\frac{P_i}{P_o}\right)$$

$$\cancel{= \frac{1}{100 \times 10^{-3}} \ln\left(\frac{0.3}{1}\right)} = \frac{10}{L} \ln\left(\frac{P_i}{P_o}\right)$$

$$\cancel{= 10 \times}$$ $$\cancel{= \frac{10}{100}}$$

$$\cancel{= 12.}$$

$$= \frac{10}{0.1} \ln\left(\frac{1}{0.3}\right) = 100 \times 0.522$$

$$\boxed{\alpha = 52.2 \text{ dB/km}}$$

6) $\alpha = ?$ 85% of the power fed at the launching end of $\frac{1}{2}$ km; lost during propagation

$$P_o = P_i \times \frac{15}{100}$$

$$\alpha = \frac{10}{L} \log\left(\frac{P_i}{P_o}\right)$$

$$= \frac{10}{0.5} \log\left(\frac{100}{15}\right)$$

$$= 20 \times 0.823$$

$$\boxed{\alpha = 16.48 \text{ dB/km}}$$

7) $\alpha = 3.5\ dB/km$

$P_i = 0.5mW \qquad P_o = ? \qquad L = 4km$

(3M)

$$\alpha = \frac{10}{L}\log\left(\frac{P_i}{P_o}\right)$$

$$\frac{4\times 3.5}{10} = \log\left(\frac{P_i}{P_o}\right)$$

$$1.4 = \log\left(\frac{P_i}{P_o}\right)$$

$$10^{1.4} = 25.11 = \frac{P_i}{P_o}$$

$$P_o = \frac{0.5}{25.11}$$

$$= 0.0199mW$$

$$\boxed{P_o = 19.9\mu W}$$

8) $n_1 = 1.5$

cladding is doped to give $\Delta = 0.005$

$n_2 = ?$

$\phi_c = ? \qquad \theta_0 = ?\ ; \qquad NA.$

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

$$0.0075 + 1.5 = -n_2$$

$$\boxed{n_2 = 1.49}$$

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

$$\phi_c = 84.07^\circ$$

$$\theta_0 = \sin^{-1}\sqrt{2.25 - 2.226}$$

$$\theta_0 = 8.9^\circ$$

$$\boxed{NA = 0.15}$$

9) $n_1 = ? \quad n_2 = ? \qquad NA = 0.22$

$\Delta = 0.012$

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

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

$$(0.012 n_1 - n_1) = n_2$$

$$n_2 = 0.988 n_1$$

$$0.0484 = 0.023856 n_1^2$$

$$\boxed{n_1 = 1.42}$$

$$\boxed{n_2 = 1.402}$$

10) $n_1 = 1.5 \quad n_2 = 1.4$

$$n = \frac{V_{vac}}{V_m} = \frac{c}{v}$$

$$1.5 = \frac{3\times 10^8}{v}$$

$$\boxed{v = 2\times 10^8\ m/sec}$$

$$\theta_0 = \sin^{-1}\sqrt{2.25 - 1.96}$$

$$= 32.5^\circ$$

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

$$= 65.9^\circ$$

11) $n_1 = 1.42$

$\theta_0 = 8.5$ for light travelling in the fibre from air

find NA

$\theta_0 = \sin^{-1} NA$

$$\boxed{NA = 0.147}$$

2) $\sin\theta_0 = \frac{\sin^{-1}\left(\sqrt{n_1^2 - n_2^2}\right)}{n_0} = \frac{\sin^{-1}(0.147)}{1.33}$

$$\boxed{\theta_0 = 6.34^\circ}$$

$NA = 0.147$

NA remains the same.

12) A step index optical fibre has diameter = 50 μm

$NA = 0.23$ $\lambda = 0.82\,\mu m$. no. of modes in cable = ?

$V = \frac{2\pi a}{\lambda}(NA)$ $N \sim \frac{1}{2}V^2$

$a = \frac{50\,\mu m}{2}$

$\lambda = 0.82\,\mu m$

$NA = 0.23$

$V = \frac{2 \times 3.14 \times 25 \times 10^{-6}}{0.82 \times 10^{-6}} \times 0.23$

$V = 44.036$

$$\boxed{N = 969.5.}$$

13) Step index fibre $NA = 0.16$

$n_1 = 1.45$.

$d = 60\,\mu m$

$\lambda = 0.9\,\mu m$

normalised frequency = V = ?

$V = \frac{2\pi a}{\lambda}(NA) = \frac{2 \times 3.14 \times 60 \times 10^{-6} \times 0.16}{0.9 \times 2}$

$= \frac{60.288}{0.9 \times 2}$

$\boxed{\cancel{V = 66.98}}$

$=$

$$\boxed{V = 33.49}$$