JESSY

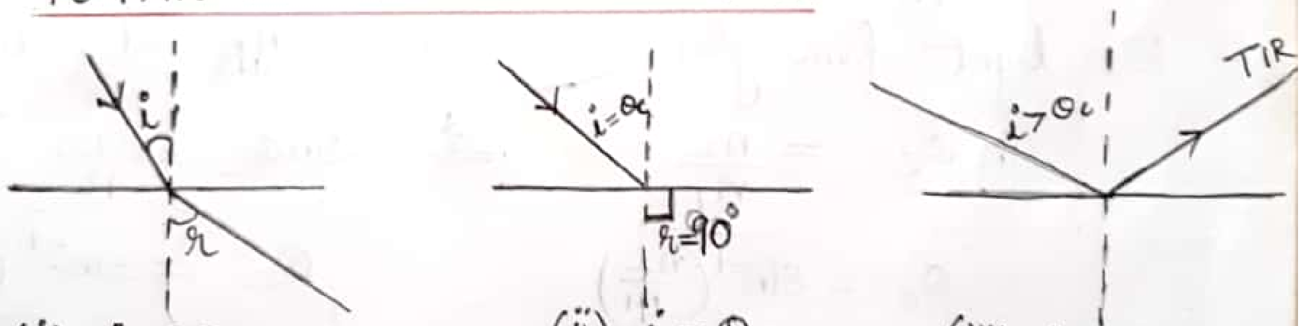
FIBRE OPTICS

Syllabus: Numerical aperture for step index fibre, critical angle, Angle of acceptance, V number, Number of modes of propagation, Types of optical fibres, Fibre optic communication system, (Numericals also)

Fibre optics is a technology in which signals are converted from electrical into optical signals, transmitted through a thin glass fibre and reconverted into electrical signals.

An optical fibre is a cylindrical waveguide made of transparent dielectric (glass or clear plastic), which guides light wave along its length by total Internal reflection.

TOTAL INTERNAL REFLECTION



(i) $i<\theta_c$ (ii) $i=\theta_c$ (iii) $i>\theta_c$

When light is travelling from denser to rarer medium (glass to air), the refracted ray will bend away from normal. As the angle of incidence increases, the angle of refraction also increases. At a particular angle of incidence, the angle of refraction becomes 90°. The corresponding angle of incidence, at which angle of refraction $=90^\circ$ is known as critical angle θ_c. If the angle of incidence is greater than this critical angle, the ray will totally reflected back to same medium.

This phenomenon is known as Total Internal Reflection (TIR)

Critical Angle:– When light is travelling from denser to rarer medium, critical angle is the angle of incidence at which angle of refraction is 90°

Condition for Total Internal Reflection

(i) Light should travel from denser to rarer medium

(ii) Angle of incidence should be greater than critical angle.

Relation between critical angle & refractive index.

Snell's law $\frac{\sin i}{\sin r} = \frac{n_2}{n_1}$

At critical angle $i = \theta_c$; angle of refraction; $r = 90°$

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

For light from glass air, $n_2 = n_{air} = 1$; $n_1 = n_{denser} = n$

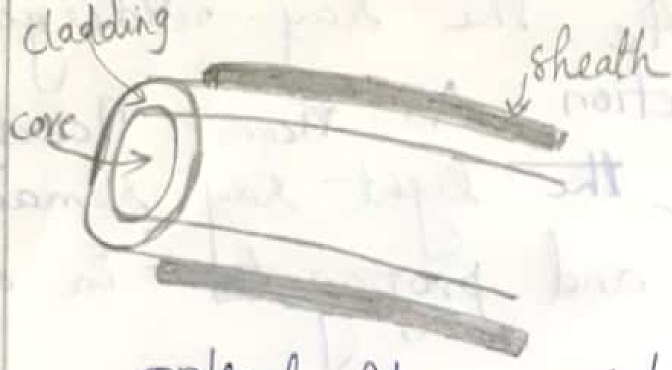
$$\boxed{\sin \theta_c = \frac{n_2}{n_1}} \Rightarrow \sin \theta_c = \frac{1}{n}$$

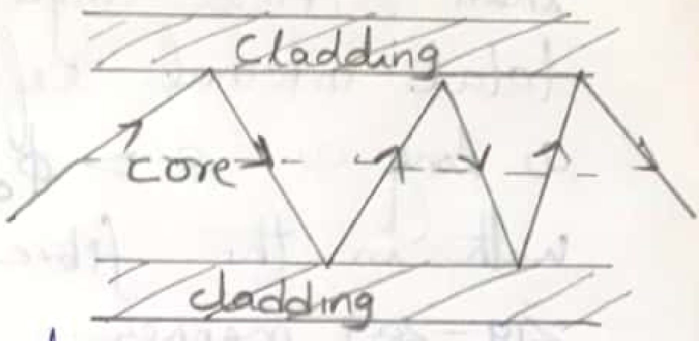
$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \qquad \boxed{\theta_c = \sin^{-1}\left(\frac{1}{n}\right)}$$

Optical fibres

Optical fibres are long thin hair like cables made of glass or plastic to guide light through it. Optical fibres work on the principle of total internal reflection. When light enters at one end of the optical fibre it undergoes multiple total internal reflection and finally comes out through the other end.

Structure of optical fibre





optical fibre consist of three regions: core, cladding and sheath.

Core is the innermost region. The light is guiding through this region. Core is surrounded by a region called cladding. The refractive index of cladding material (n_2) is always lower that than that of the core (n_1). The outermost region is called sheath or protective buffer coating. It is a plastic coating given to the cladding for extra ~~p~~rotection and also provides mechanical strength to the optical fibre.

Propagation of Light wave through optical fibre

Conditions:

1) The refractive index of core should be greater than that of cladding $[(n_{core} > n_{cladding})$ or $(n_1 > n_2)]$
2) The ~~core~~ light should enter at an angle of incidence greater than critical angle $(\theta > \phi_c)$

when light enters the fibre at angle of incidence i to the axis of fibre, it is refracted at an angle r and incident at the core-cladding

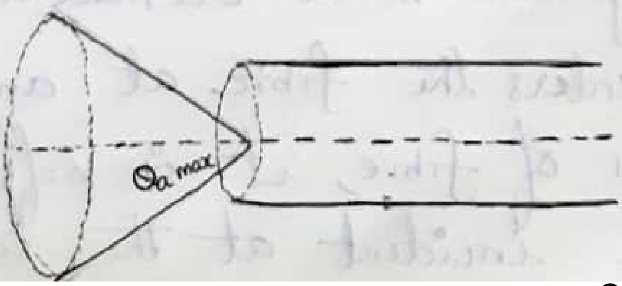
4

interface at an angle θ. If θ is greater than critical angle ϕ_c, the ray undergo total internal reflection. As $n_{core} > n_{cladding}$, as long as $\theta > \phi_c$ the light ray remains with in the fibre and propagates in a zig-zag manner.

The main function of an optical fibre is to accept the light ray and transmit as much as possible. Collection of light waves depends on core size and numerical aperture of fibre. Numerical aperture is determine by acceptance angle.

Acceptance angle ($\theta_{a\,max}$)

The maximum value of external angle for which the light will propagate in the optical fibre is called acceptance angle. A light ray must enter the core with an angle less than acceptance angle to be guided through an optical fibre. A ray which enters the fibre with an angle greater than acceptance angle will be lost in cladding



Acceptance cone

If θ_a is rotated around the core axis, then the cone is formed which is called acceptance cone. If light is followed to fall with in this cone, it will propagagate to far end.

Numerical Aperture (NA)

Numerical Aperture is defined as the sine of maximum acceptance angle.

$$\boxed{NA = \sin \theta_{a\,max}}$$

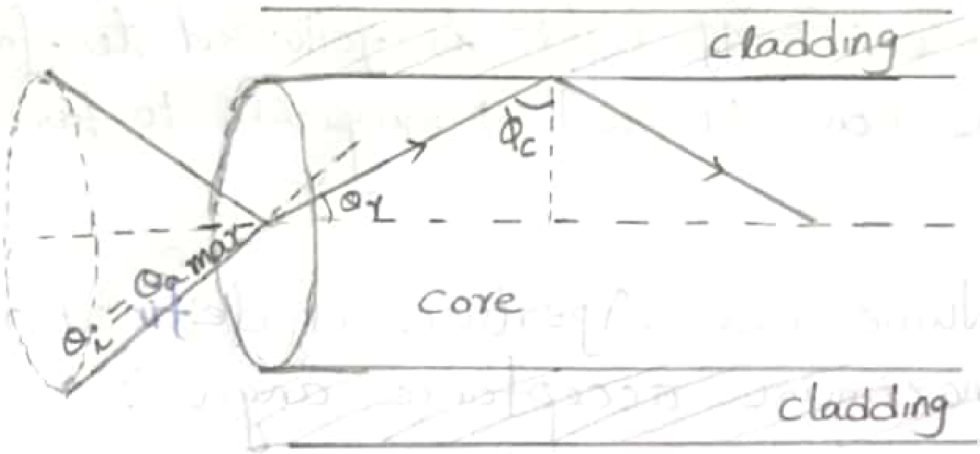
It measures the light gathering capacity of the optical fibre. If numerical aperture is greater, the optical fibre will accept greater amount of external light. Also

$$\boxed{NA = \sin \theta_{a\,max} = \sqrt{n_1^2 - n_2^2}}$$

where $n_1 \rightarrow$ refractive index of core

$n_2 \rightarrow$ refractive index of cladding

(6) # Derivation of Numerical Aperture & Acceptance Angle



Considering a light ray entering at the core of a step index optical fibre at an angle of incidence θ_i to the core axis. The ray refracts at an angle θ_r and fall on the core cladding interface at an angle ϕ. If ϕ is greater than critical angle ϕ_c, the ray undergoes total internal reflection at the interface, since $n_1 > n_2$. As long as $\phi > \phi_c$, the light will stay within fibre.

By snell's law at launching face (entrance of light) of fibre, we get

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

$$\theta_i = \theta_{a\,max}$$

$$\frac{\sin \theta_{a\,max}}{\sin \theta_r} = \frac{n_1}{n_0} \qquad \text{--- (1)}$$

By Snell's law at core cladding interface (for angle of incidence $\phi = \phi_c$)

[$\because$ when $\phi = \phi_c$ angle of refraction $= 90^\circ$]

$$\frac{\sin \phi_c}{\sin 90} = \frac{n_2}{n_1}$$

[But from ΔABC $\phi_c = 90 - \theta_r$]

$$\sin(90 - \theta_r) = \frac{n_2}{n_1}$$

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

[using eqn (1) $\sin \theta_r = \frac{n_0}{n_1} \sin \theta_{a\,max}$.]

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

$$\sqrt{1 - \frac{n_0^2}{n_1^2} \sin^2 \theta_{a\,max}} = \frac{n_2}{n_1}$$

$$1 - \frac{n_0^2}{n_1^2} \sin^2 \theta_{a\,max} = \frac{n_2^2}{n_1^2}$$

$$1 - \frac{n_2^2}{n_1^2} = \frac{n_0^2}{n_1^2} \sin^2 \theta_{a\,max}.$$

$$n_1^2 - n_2^2 = n_0^2 \sin^2 \theta_{a\,max}.$$

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

Numerical aperture $NA = \sin \theta_{a\,max}$.

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

The incident ray is launched from air, for which $n_0 = 1$

$$\boxed{NA = \sin \theta_{a\,max} = \sqrt{n_1^2 - n_2^2}}$$

$$\boxed{\text{Acceptance angle; } \theta_{a\,max} = \sin^{-1}(NA) = \sin^{-1}\sqrt{n_1^2 - n_2^2}}$$

(8) Numerical Aperture in terms of Fractional Refractive index change

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

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

$n_1 + n_2 \simeq 2n_1$

$$\boxed{\begin{aligned} NA &= \sqrt{2n_1^2\Delta} \\ NA &= n_1\sqrt{2\Delta} \end{aligned}}$$

where $\Delta = \frac{n_1-n_2}{n_1}$ is called Fractional Index Change.

i.e fractional difference between the refractive indices of the core and cladding.

Modes of propagation

In optical fibre the light propagates in the same way as electromagnetic wave propagation. When the light ray is guided through an optical fibre, it propagates in different types of modes. Each of these guided modes consists of a variety of electromagnetic field configurations, such as transverse electric (TE), transverse magnetic (TM) and hybrid modes. Hybrid modes are combination of TE and TM modes.

Modes can be visualised as the possible number of allowed paths of light in an optical fibre. The paths are all zig zag paths excepting the axial direction. The waves travelling along certain zig-zag paths will be in phase and undergo constructive interference while the waves alonge certain other paths, in which the waves are out of phase will diminish due to destructive interference. The light ray paths along which the waves are in phase ~~are~~ inside the fibre are known as modes.

Increasing the core refractive index increases the number of propagating modes. On increasing the clad refractive index decreases the number of propagating modes. The number of modes that a fibre will support will depend on the ratio d/λ, where d is the diameter of the core and λ is the wave length of the wave being transmitted.

V number

The number of modes that an optical fibre can support is determined by a parameter called V number. It is also known as normalised frequency or cut off frequency of fibre.

$$V = \frac{\pi d}{\lambda_0}\sqrt{n_1^2 - n_2^2}$$

$$V = \frac{\pi d}{\lambda_0}(NA)$$

$$V = \frac{\pi d}{\lambda_0} n_1 \sqrt{(2\Delta)}$$

where
$n_1 \rightarrow$ RI of core
$n_2 \rightarrow$ RI of cladding
$d \rightarrow$ diameter of core
$d = 2a$ ($a \rightarrow$ radius)
$\lambda_0 \rightarrow$ wavelength of light (free space wavelength)
NA $\rightarrow$ Numerical Aperture

Significance:

Each mode has a defenite value of V-number below which the mode is cut off.

The Maximum number of modes N_m supported by a fibre is

$$N_m = \frac{V^2}{2} \quad \text{for step Index (SI) fibre}$$

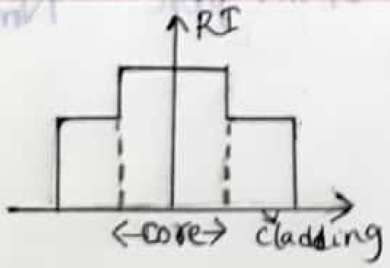
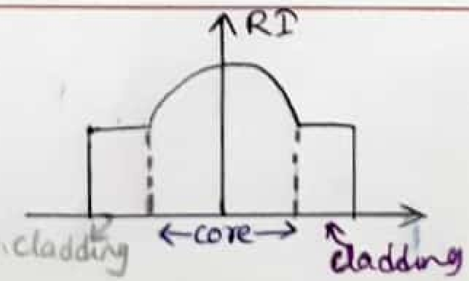
$$N_m = \frac{V^2}{4} \quad \text{for GRIN fibre (Graded Index).}$$

- For $V < 2.405$, the fibre can support only mode. $\Rightarrow$ Single mode fibre (SMF)
- For $V > 2.405$, the fibre can support many modes. $\Rightarrow$ Multi mode fibre (MMF)

TYPES OF OPTICAL FIBRES

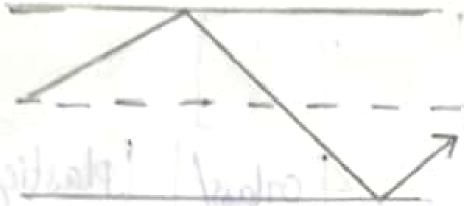
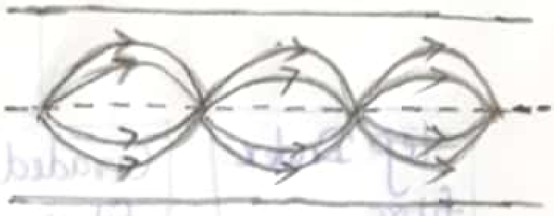
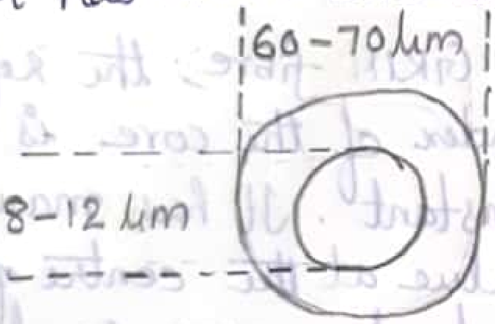
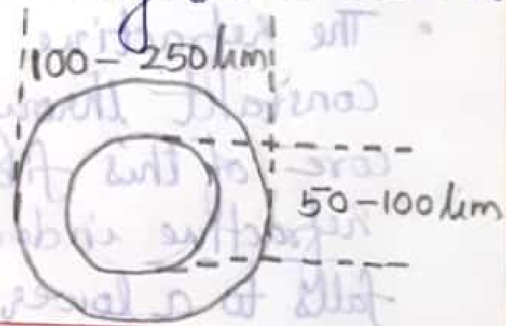
- Based on Refractive Index Profile
  - Step Index fibre
  - Graded Index fibre
- Based on modes
  - Single mode fibre (SMF)
  - Multimode Fibre (MMF)
- Based on materials
  - Glass/Glass
  - Plastic/plastic
  - Plastic/clad silica

A classification based on Refractive Index (RI) profile

1. Step Index fibre (SI)	2. Graded Index fibre (GRIN)
• The refractive index is constant throughout the core of this fibre. This refractive index value abruptly falls to a lower value at core-cladding boundary (i.e step change) Due to the discontinuity of index profile at core-cladding interface, these fibres are called step index fibre	In GRIN fibre, the refractive index of the core is not constant. It has maximum value at the centre of core and decreases gradually towards the outer edge of core.
• 	
• High attenuation	Low attenuation
• For a given diameter, the numerical aperture (NA) is greater. Light rays entering at different angles will take different time to reach at other end	For a given diameter the NA is smaller compared to SI fibre. Light rays take same time to reach other end irrespective of angle of incidence

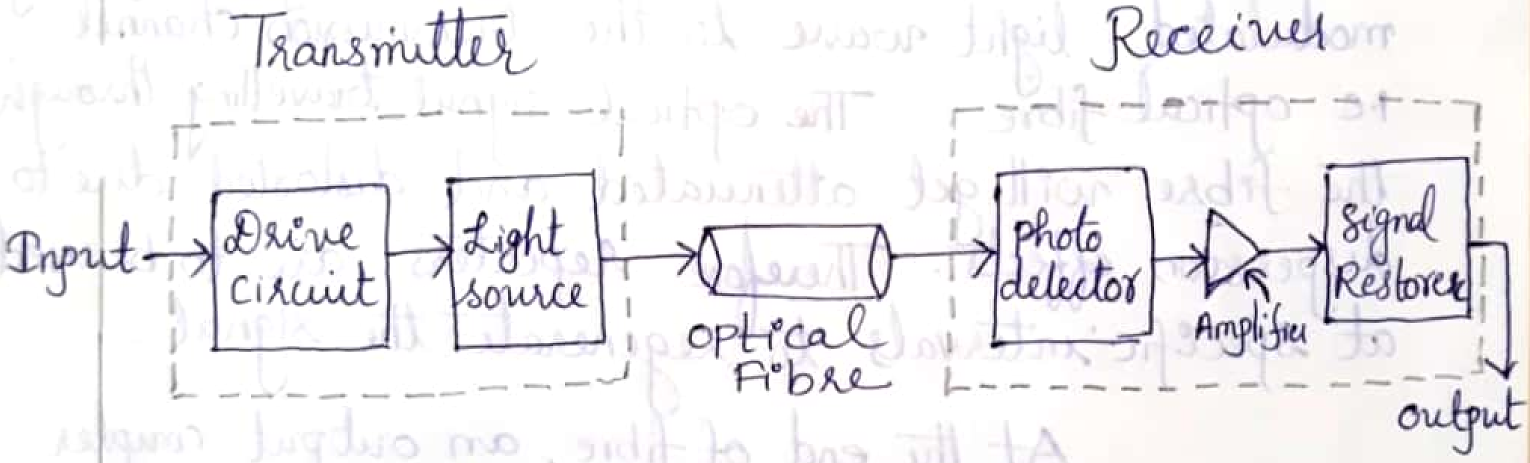
← RI profile →

12 B Classification based on modes of Light propagation

1. Single mode fibres (SMF)	2. Multimode fibres (MMF)
	
It can support only one mode of propagation	It can supports finite number of modes of propagation
It has small core diameter 	It has a larger core diameter 
It is usually step index type	These are further divided as step index and graded Index. The number of modes is given by (i) For stepindex $N_m = \frac{V^2}{2}$ (ii) For GRIN fibre $N_m = \frac{V^2}{4}$

Fibre Optic Communication System

A fibre optic communication system has three major components:
A transmitter converts electrical signal to light signals, an optical fibre transmits the signals and a receiver captures the signals at the other end end of the fibre and converts them to electrical signals.



~~An input device~~ Fig: Block diagram

An input device would be a telephone if voice input ~~to~~ be transmitted across the channel to receiver. The transmitter consists of a light source supported by necessary drive circuits. A transducer converts a non-electrical message into an electrical signal and is fed to a light source. A LED or semiconductor laser is used as the light source.

14

The light waves are modulated with the signal by the method of analog modulation or digital modulation.

Digital modulation requires more complicated devices such as encoders and decoders and also more bandwidth than analog modulation. Digital modulation has widely used nowadays due to the advantage of greater transmission distance.

The transmitter feeds the analog or digitally modulated light wave to the transmission channel, i.e optical fibre. The optical signal travelling through the fibre will get attenuated and distorted due to dispersion effects. Therefore repeaters are to be used at specific intervals to regenerate the signal.

At the end of fibre, an output coupler directs the light from fibre onto a photodetector, which converts the light signals to electrical signals. These electrical signals which are then amplified and decoded to obtain the message. The output is fed to a signal restorer (i.e a suitable transducer) ~~which~~ to convert it into an audio or video form.

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Study well

Regards

JESSY