Fibre Optics

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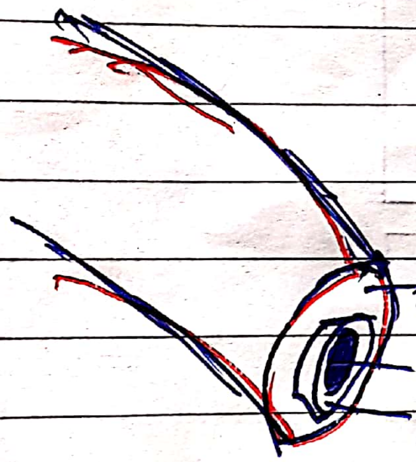
Optic fibre is a cylindrical wave-guide made of transparent dielectric (glass or clear plastic) which guides light waves along its length by total internal reflection. They are approximately 70μm in diameter.



Core :- Innermost region, light carrying member
8.5μm to 62.5μm

Cladding 125μm $n_2 < n_1$ (core)
Confines light in fibre

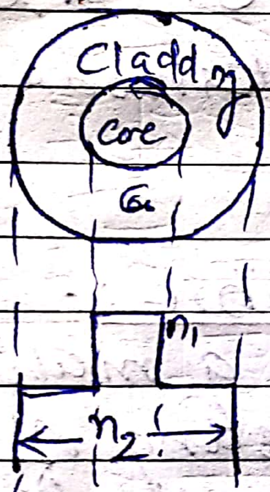
Sheath or Buffer coating : 250μm to 900μm.
Protects from physical damage and environmental effects.

Classification of Optic fibres

- Based on RI Profile
  - Step Index Fibre
  - Graded Index Fibre
- Based on modes
  - S.I Single Mode Fibre
  - S.I Multi mode Fibre
  - G.I Multi mode Fibre
- Based on materials
  - Glass/Glass
  - Plastic/Plastic
  - PCS Plastic Cladded Silica

Step Index Fibre:-

Here refractive index of the core is constant along the radial direction and falled to a lower value at the core cladding boundary.



Single mode step index fibre:-

⇒ Has a very fine thin core of diameter of 8μm to 12μm. Usually made of germanium doped silicon. Cladding of silica doped with phosphorous have diameter 125μm. NA and Δn (Fractional refractive index) are very small.

⇒ Dispersion is small

⇒ Only one mode possible.

Multimode Step Index Fibre.

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Graded Index Fibre :-

G.I fibre is a multimode fibre with a core consisting of concentric layers of different refractive indices. ie It has a maximum RI at the centre and decreases gradually towards the outer edge of core. Refractive index of cladding is constant. Core diameter is of range 50 - 100μm. Material dispersion is present. No: of modes in a graded index fibre is about half than in a similar multimode step index fibre. They are used in telephone links.

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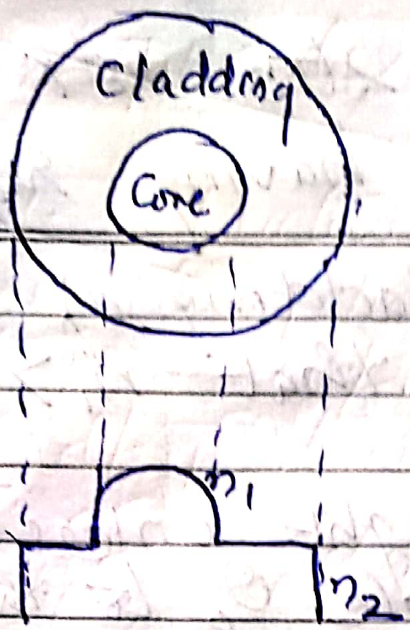


Expression for N.A (Numerical Aperture)

Total internal reflection at the fibre wall can occur only if two conditions are satisfied.

1) The core must have a slightly higher refractive index n_1 than that of refractive index n_2 of cladding

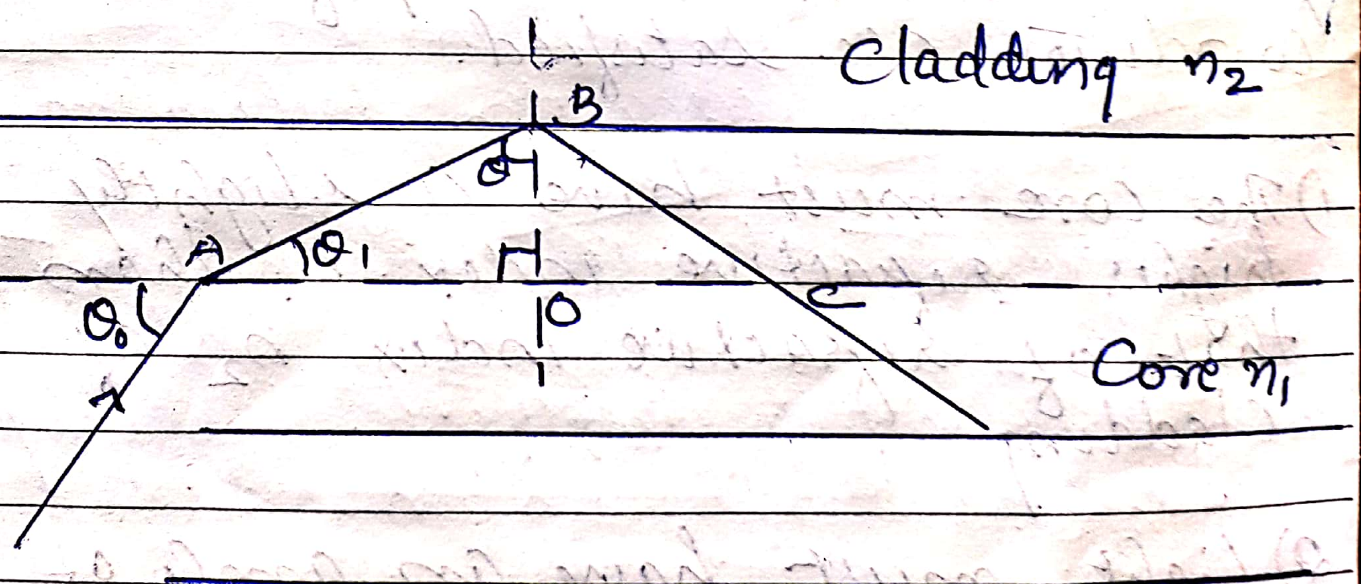
2) Light must have an angle of incidence θ at the cladding which is greater than critical angle θ_c of core w.r.t cladding.

The critical angle θ_c is given by

$$\sin\theta_c = \frac{n_2}{n_1} \rightarrow (1)$$

Consider a step index profile fibre with core having refractive index n_1 and cladding of refractive index n_2 such that $n_1 > n_2$.

A ray of light enters the fibre end at an angle θ_0 to the axis of the fibre. It is refracted at A at an angle of refraction θ_1 and is then reflected from the core wall at point B at an internal angle of incidence θ



From Δ^{le} AOB, $\theta_1 = 90 - \theta$.

$$\sin\theta_1 = \sin(90-\theta)$$

$$\sin\theta_1 = \cos\theta \longrightarrow (2)$$

According to Snell's law,

$$\frac{\sin i}{\sin r} = n \longrightarrow (3)$$

$$\frac{\sin\theta_0}{\sin\theta_1} = \frac{n_1}{n_0} \longrightarrow (4)$$

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$$\sin\theta_0 = \frac{n_1}{n_0}\sin\theta_1$$

$$\sin\theta_0 = \frac{n_1}{n_0}\cos\theta \longrightarrow (5)$$

As long as light enters the fibre at an angle θ_0 such that the internal incident angle θ is not smaller than critical angle θ_c, the light will stay in the fibre and propagate to the far end. However if $\theta < \theta_c$, light entering the fibre will be refracted out through core wall and be lost. As θ_0 increases θ_1 increases and θ decreases. As a result there is a critical max. value for θ_0 within which alone the light propagates through the fibre.

$\{\cos\theta_c = \sqrt{1-\sin^2\theta_c}$

From (2) $\cos\theta_c = \sqrt{1 - \frac{n_2^2}{n_1^2}}$

$$\cos\theta_c = \sqrt{\frac{n_1^2 - n_2^2}{n_1}} \longrightarrow (6)$$

The max value of θ_0 is obtained when $\theta = \theta_c$

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$$\sin(\theta_0)_{max} = \frac{n_1}{n_0} \cos\theta_c$$

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

$$\sin(\theta_0)_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

$$(\theta_0)_{max} = \sin^{-1} \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

This is called acceptance angle.

Rotating the acceptance angle about the fibre axis describes the acceptance cone of the fibre. Any light aimed at the fibre will be accepted and propagated to the far end. The larger the acceptance ~~cong~~ cone made, the easier ~~to~~ launching becomes.

The NA of the fibre is used as figure of merit of optical fibres.

NA is defined as

$$\sin(\theta_0)_{max} = \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$$

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Usually launching medium will be air. So $n_0 = 1$

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

Let $\Delta n = \frac{n_1 - n_2}{n_1} = 1 - \frac{n_2}{n_1}$

$$\frac{n_2}{n_1} = 1 - \Delta n$$

$$\frac{n_2^2}{n_1^2} = 1 - 2\Delta n$$

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

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

$$= n_1 \sqrt{1 - (1 - 2\Delta n)}$$

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

Thus NA depends only on the refractive index of the core and

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cladding and is not a function of fibre dimensions.

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Coherent bundle

If a large number of fibres are put together, it forms a bundle. If the fibres are aligned properly i.e if the refractive ~~indices~~ positions of the fibres in the input and output ends are the same, the bundle is said to form a coherent bundle. A coherent bundle will transmit image from one end to another.

The most important application of a coherent bundle is in fibre optic endoscope where it can be put inside a human body and the interior of the body can be viewed from outside.

Applications of Optic fibres:-

1) Illumination and image transmission.
2) Used as waveguides in telecommunications
3) Used in fabricating a new family of sensors.

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Fibre optic sensors :- Transducers which consists of a light source coupled with optic fibre and a light detector held at receiver end. They are of various types.

1) Temperature sensors :- Temp is measured by the modulation of intensity of reflected light from a target, a silicon layer. It is based on 1μm wavelength light absorption characteristics of silicon as a fn of temp. Depending on temp, the amount of light absorbed by the silicon layer varies. The change in intensity of reflected light is proportional to the change in temp.

2) Displacement sensor :- It uses an adjacent pair of fibre optic elements, one to carry light from a remote source to a moving object and other to recieved the reflected light from the object and carry it back to a photodetector

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3) Force sensor :- When we press a fibre, a small change occurs in light propagation due to coupling. Thus a loss in intensity of light transmitted is seen. The change in intensity is proportional to the force applied on the fibre.

4) Liquid level detector :- A multimode fibre with a notch at one end is used. The refractive index of fibre will be less than that of the liquid. The light from a source is incident on one of the faces of the notch. Light turns through 90° and reaches the other end. Thus it ~~gets~~ undergoes total internal reflection if liquid level is below the sensor. If the liquid touches the fibre ~~to~~ the light will not bounce back and detector receives no light.

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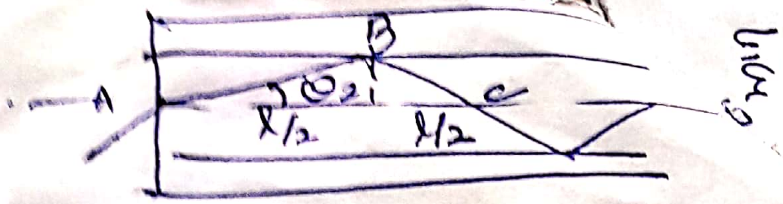
Dispersion:- Light pulses broaden and spread into a wider time interval because of the different times taken by different rays. This is called pulse dispersion. Eventhough two pulses may be well resolved at the input end, they may overlap on each other at o/p. It is expressed in ns/km.

- Dispersion
  - Intermodal
  - Intramodal
    - Material dispersion
    - Waveguide dispersion.

Intermodal :-

While using multimode fibres, lower order rays travel a great distance than higher order rays. Because of this, lower order rays will reach faster than higher order rays.



Due to this, dispersion occurs.

Expression for time delay :-

Total time delay

$$\Delta t = t_{max} - t_{min}$$

Time taken by a ray to traverse the distance ABC is

$$t' = \frac{AB + BC}{v}$$

$\cos\theta = \frac{l/2}{AB}$ $\quad AB = \frac{l}{2\cos\theta}$.

$BC = \frac{l}{2\cos\theta}$ $\quad \therefore AB + BC = \frac{l}{2\cos\theta} + \frac{l}{2\cos\theta}$

$$= \frac{2l}{2\cos\theta} = \frac{l}{\cos\theta} = \frac{AC}{\cos\theta_r}$$

$$v = c/n_1$$

$$\therefore t' = \frac{n_1 AC}{c \cos\theta_r} \longrightarrow (1)$$

Time taken to travel whole length is $t = \frac{n_1 L}{c \cos\theta_r}$

t_{min} is when $\theta_r = 0$

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$$t_{min} = \frac{n_1 L}{c} \longrightarrow (2)$$

t_{max} occurs when $\theta_r = \theta_c$

$$\therefore t_{max} = \frac{n_1 L}{c \cos\theta_c}$$

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

$$\therefore t_{max} = \frac{n_1^2 L}{n_2 c} \longrightarrow (3)$$

Sub: (2) and (3) in (1),

$$\Delta t = \frac{n_1 L}{c}\left[\frac{n_1}{n_2} - 1\right].$$

But $n_1 - n_2 = \Delta n$

$$\therefore \Delta t = \frac{n_1 L}{c}\left[\frac{\Delta n}{1-\Delta n}\right]$$

~~or~~ $$\Delta t = \frac{n_1 L}{c}\left[\frac{n_1 - n_2}{n_2}\right] = \frac{n_1 L}{c}\left[\frac{n_1 - n_2}{n_2}\right].$$

$$= \frac{n_1 L}{c}\left[\frac{n_1 - n_2}{n_2}\right]\frac{(n_1+n_2)}{(n_1+n_2)}$$

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

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

$$\because \frac{n_1+n_2}{2} = n_1 \quad \therefore n_1 + n_2 = 2n_1$$

$$\therefore \Delta t = \frac{L (NA)^2}{2 n_2 c}$$

$\therefore$ time delay $\propto NA^2$

$\therefore$ a large NA fibre allows more no: of modes resulting in more modal dispersion

Intramodal dispersion.

It is the spreading of light pulse within a single mode. They are of two types a) Material dispersion.
b) Waveguide dispersion

a) Material dispersion :- A light pulse is a packet of different wavelengths components. They will propagate at different speeds along the fibre. Short wavelength components go slower than longer wavelengths components. This type of distortion is called material dispersion or chromatic dispersion.

Expression for time delay

Plane wave $\psi \propto e^{(kx-\omega t)}$

Wave number $k = \frac{2\pi}{\lambda} = \frac{2\pi}{\lambda_0} \times \frac{\lambda_0}{\lambda}$

or $\frac{2\pi}{\lambda_0} \times n = \frac{2\pi\nu}{c} \cdot n$

$k = \frac{\omega n}{c}$ and $\omega = 2\pi\nu = \frac{2\pi \times c}{\lambda}$

Group velocity of a wave packet is

$$V_g = \frac{d\omega}{dk}$$

$$\frac{1}{V_g} = \frac{dk}{d\omega} = \frac{d}{d\omega}\left(\frac{\omega n}{c}\right) = \frac{n}{c} + \frac{\omega}{c}\frac{dn}{d\omega}$$

$$= \frac{1}{c}\left[n + \omega \frac{dn}{d\omega}\right]$$

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$$\frac{dn}{d\omega} = \frac{dn}{d\lambda} \cdot \frac{d\lambda}{d\omega} = -\frac{\lambda^2}{2\pi c} \cdot \frac{dn}{d\lambda}$$

$$\frac{1}{V_g} = \frac{1}{c}\left[n - \frac{\omega\lambda^2}{2\pi c}\frac{dn}{d\lambda}\right] = \frac{1}{c}\left[n - \lambda\frac{dn}{d\lambda}\right]$$

Time delay per unit length

$$t_{mat} = \frac{L}{V_g} = \frac{L}{c}\left[n - \lambda\frac{dn}{d\lambda}\right]$$

Pulse spread Δt_{mat} is given by

$$\Delta t_{mat} = \frac{dt_{mat}}{d\lambda}\Delta\lambda = -\frac{L\lambda}{c}\frac{d^2n}{d\lambda^2}\Delta\lambda$$

$$= D_{mat}(\lambda) L \Delta\lambda$$

where $D_{mat}(\lambda)$ is material dispersion

$$D_{mat}(\lambda) = \frac{-\lambda}{c}\frac{d^2n}{d\lambda^2}$$

So material dispersion can be reduced either by choosing monochromatic sources with low spectral width or by operating at longer wavelengths

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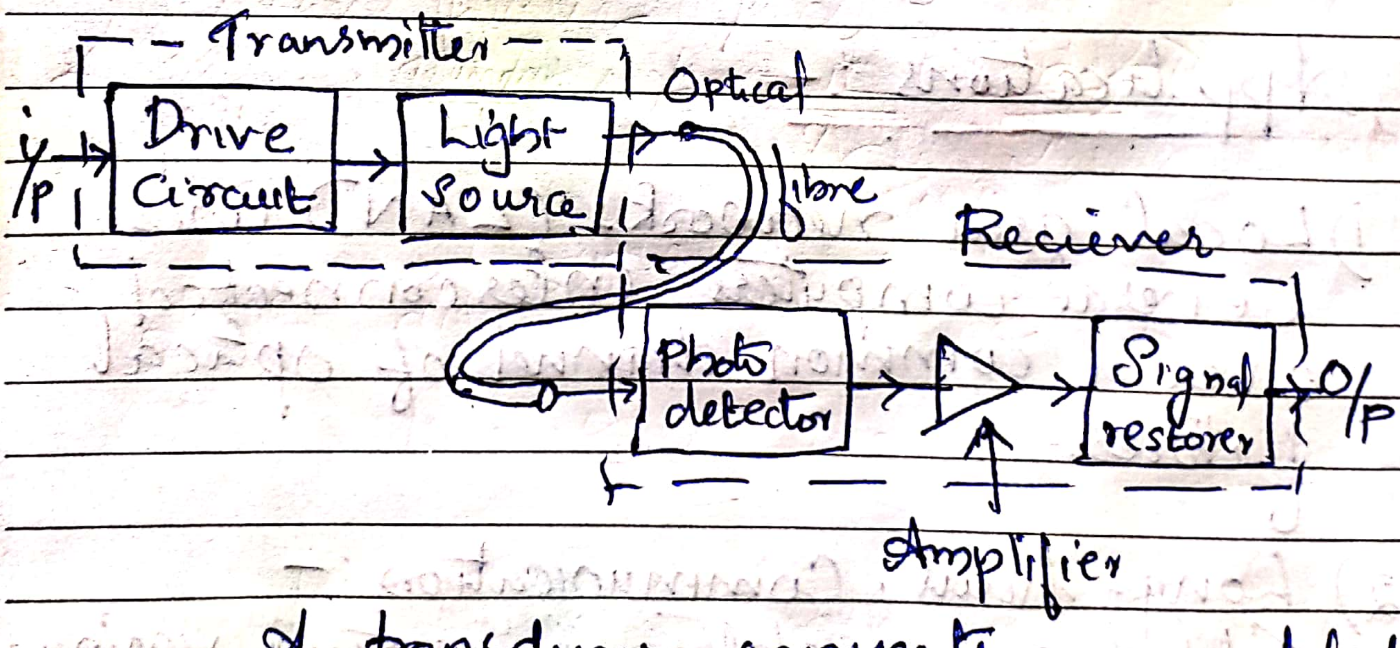
Waveguide dispersion :- Arises from the guiding properties of fibre. When wavelength increases, group velocity decreases. So transmission delay occurs. Waveguide dispersion is small in multimode fibres.

Intermodal dispersion is smaller in GRIN fibres. In SMF only material and waveguide dispersions exist.

Fibre Optic Communication System



A transducer converts a non-electrical message to an electrical signal and it is fed to a light source like laser or LED. By varying intensity of light, analog modulation is achieved.

By flashing the LED on and off, digital modulation is achieved. The ~~[illegible]~~

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transmitter feeds the modulated light wave to the transmission channel or optical fibre link. To reduce attenuation and distortion, repeaters are used at specific intervals. At the end, an output coupler directs the light into a photodiode which converts light signals into electrical signals. They are then amplified and decoded to obtain the message.

Applications :-

1) Local area networks (LAN) uses several computers interconnected over a common channel of optical fibres.

2) Long-haul Communication :-
Telephones cables connecting various countries are established using optic fibres.

Advantages

1) Cheaper
2) Smaller in size, light in weight, flexible yet strong.
3) Not hazardous.
4) Immune to electromagnetic interference (EMI) and radio frequency interference (CRFI)
5) No cross talk.
6) Wider bandwidth :- A copper telephone cable composed of 900 wires can handle 10,000 calls while ~~a copper~~ an optic fibre of 1mm can handle 50,000 calls.
7) Low loss per unit length :- Transmission loss is about 4dB/km. So repeaters can be used after 100 km or more. In copper cable networks repeaters must be used at intervals of about 2km.

Disadvantages :-

Installation and maintanance of optic fibres require a new set of skills. They require specialised and costly equipments like optical time domain reflectometers.