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OPTICAL FIBERS

Optical fibres are long, thin strands of very pure glass usually 125 μm in diameters, surrounded by a glass optical cladding. They make use of total internal reflection to confine light within the core of the fibre.

Parts of optical fibre

1) Core
2) Cladding
3) Buffer

Silica Optical Fibre

Both the core and cladding are made from a type of glass known as silica (SiO_2)

In the case that the refractive index changes in a "step" b/w the core & the cladding. This fiber structure is known step index fibre.

The higher core refractive index (0.3% higher) is typically achieved by doping the silica core with germanium dioxide (GeO_2)

Total Internal Reflection

- The angle of incident angle is always greater than the critical angle for TIR

$\sin\theta_c = \frac{\mu_2}{\mu_1}$ where θ_c = critical angle

- Cladding does not absorb any light from the core

- The extent that the signal degrades depends upon the purity of the glass & the wavelength of the transmitted light

Types of Optical fibres

Based on transmission properties & structure

1) Single Mode fibre

2) Multimode fibre
   - Step Index fibre
   - Graded Index fibre

Mode: A mode is a path that a light wave can follow as it travels down the core of an optical fibre.

Ques: Refractive index of core and cladding is 1.6 and 1.3 respectively. Find critical angle

$$\sin\theta_c = \frac{1.3}{1.6} = 0.81 \Rightarrow \theta_c = \sin^{-1}(0.81)$$

$$\theta_c = 54^\circ$$

Note: Multi-mode fibre: core dia ~ 50 or 62.5 or 100 μm
cladding dia: ~125 μm

Single mode fibre: core dia ~ 8–10 μm,
cladding dia: ~ 125 μm

Single (Mono) Mode:

This is called so because it allows single mode to propagate at a time due to very small diameter of its core. The refractive index of fibre 'step' up as we move from cladding to core.

Advantages:

- Carry signals at very high speed
- No modal dispersion
- Give high data rate for long dist. communication
- Allow the use of high power laser source
- Low loss (~ 0.1 dB/km)

Disadvantages

- Components/Equipments are more expensive
- Difficult to inject light signal due to very small core diameter

Multimode Fibres

This is called because it allow more than one mode to propogate. Over more than 100 modes can propogate through multimode fibres at a time. The size of its core is typically around 50 um, 62.5 um and 100 um

No. of modes

$$N = \frac{2\pi^2 a^2}{\lambda^2} (\mu_1^2 - \mu_2^2)$$

a = Radius of core $(d = 2a)$

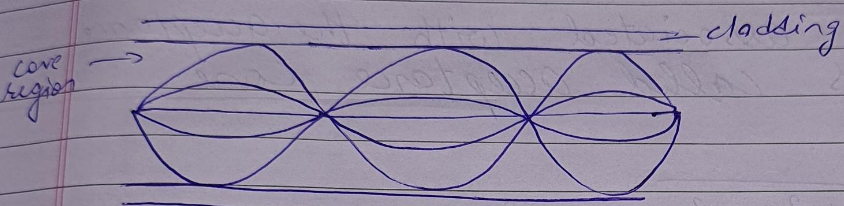
Advantages

- Allow the use of non-coherent optical light source eg: LED's
- Cost effective
- Facillitates connecting together similar fibres

Disadvantages

- More modal dispersion
- High power loss

Gradient Index Optical Fiber



Longer path is now located in lower index region, the larger time taken is compensated by faster travel leading to less pulse broadening.

The advantage of graded index fiber over step index fiber is reduced modal dispersion

Bandwidth: determines the no. of bits of information transmitted in a given time period. Now fibre bandwidth has reached many 10's Gbit over many Km's per wavelength channel.

Acceptance Angle & Acceptance Cone

Acceptance Angle: The angle over which fibre will accept the light directed towards it. It is defined as the half angle of the core with in which light is totally reflected by the fibre core.

Cone: The cone associated with the acceptance angle is called acceptance cone.

$$\sin\theta_0 = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0}$$

acceptance angle $= \theta_0$

$$\theta_0 = \sin^{-1}\left(\sqrt{\frac{\mu_1^2 - \mu_2^2}{\mu_0^2}}\right)$$, acceptance cone $= 2\theta_0$

Usually $\mu_0 = 1$ (for air)

Numerical Aperture

The light gathering ability of an optical fiber and is related to acceptance angle through relation.

$$NA = \sin\theta_0 = \sqrt{\mu_1^2 - \mu_2^2} \quad (\text{for } \mu_0 = 1)$$

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

If we approximate $\frac{\mu_1 + \mu_2}{2} = \mu_1$ then $\mu_1^2 - \mu_2^2 = 2\mu_1^2\Delta$

$$\mu_1^2 - \mu_2^2 = (\mu_1 - \mu_2)(\mu_1 + \mu_2) = \left(\frac{\mu_1 - \mu_2}{\mu_1}\right)\left(\frac{\mu_1 + \mu_2}{2}\right) 2\mu_1$$

$$NA = \sqrt{\mu_1^2 - \mu_2^2} = \mu_1 \sqrt{2\Delta}$$

$$\left[\text{where } \Delta = \frac{\mu_1 - \mu_2}{\mu_1}\right]$$

Δ is relative refractive index difference or fractional refractive index.

<u>Normalised Frequency</u>

The no. of guided modes that can be propagated through the fibre may be related to parameter known as normalised freq or V-parameter

$$N = \frac{V^2}{2} \quad \text{or} \quad N = \frac{V^2}{2} = \frac{2\pi^2 a^2}{\lambda^2}(\mu_1^2 - \mu_2^2)$$

$$V = \frac{2\pi a}{\lambda}\sqrt{\mu_1^2 - \mu_2^2} = \frac{2\pi a}{\lambda} NA$$

$$V = \frac{2\pi a}{\lambda}\sqrt{\mu_1^2 - \mu_2^2} = \frac{2\pi a}{\lambda}\sqrt{2\Delta}$$

for single mode $V \leq 2.405$

<u>Cut-Off Wavelength</u> :

The wavelength below which multiple modes of light can be propagated along a particular fiber i.e. $\lambda >= \lambda_c$ then single mode

if $\lambda < \lambda_c$ then multi-mode

$$\lambda_c = \frac{2\pi a}{2.405} \times NA = \frac{2\pi a}{2.405} (\mu_1^2 - \mu_2^2)^{1/2}$$

Ques: core refractive index = 1.52, dia = 29 mm fractional refractive index = 0.0007. Find no. of modes a fiber can support
$\lambda = 590$ nm

Sol:
$$N = \frac{2\pi^2 a^2 (\mu_1^2 - \mu_2^2)}{\lambda^2}$$
$$= \frac{2\pi^2 a^2 \times 2\mu_1^2 \Delta}{\lambda^2} = \frac{2 \times (3.14)^2 \times (29)^2 \times 10^{-6} \times 2 \times (1.52)^2}{(590)^2 \times 10^{-18} \; 24}$$
$$= 3.85 \times 10^7$$

Attenuation in Optical Fibre

When light travels along the fibre, there is a loss of optical power, which is called attenuation.

Attenuation is ratio of optical input power to the optical output power

Optical Input Power: Power that is transmitted into the fibre from an optical source

Optical Output Power: The power recieved at output end

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

Here unit of attenuation is dB/Km.

Ques: $L = 150\,m$ $P_i = 10\,\mu W$ $P_o = 9\,\mu W$

Compute loss

Sol: $\alpha = \frac{10}{0.15} \log\left(\frac{10}{9}\right)$

$= 3.053\ dB/Km$

7/10 Ques: $L = 10\,Km$ $loss = 2.5$ $P_i = 500\,\mu W$

Compute P_o

Sol: $2.5 = \frac{10}{10} \log\left(\frac{500}{P_o}\right)$

$P_o = 1.58\ \mu W$

Fibre Losses

A. Material Loss (Absorption Loss)

It is due to the absorption of light by the fibre material. The light absorption can be intrinsic or extrinsic due to material components of glass and due to impurities introduced into the glass during fabrication respectively.

B Light Scattering (Scattering Loss)

Scattering results in attenuation (in the form of

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radiation)

C **Waveguide and Bending Loss**

It is caused by the imperfections and deformations

Dispersion

A pulse of light sent into a fibre broadens in time as it propagates through the fibre. This phenomenon is known as pulse dispersion.

Fibre dispersion results in optical pulse broadening and hence digital signal degradation. The dispersion is produced by the properties of the core material and the line width of the light signal passing through the fibre.

Modal or Intermodal Dispersion

When numerous waveguide modes are propagating they all travel with diff velocities with respect to waveguide axis. Parts of wave arrive at the output before other parts, spreading out the waveform. This is thus known as modal dispersion

Differend modes arrive at the reciever with different delays leading to pulse broadering.

Intramodal dispersion

A Chromatic dispersion or Material Dispersion

B ~~Mat~~ Wave guide Dispersion

⇒ A Chromatic Dispersion may occur in all types of optical fibre. The optical pulse broadering results from the finite spectral line width of the optical source

⇒ Waveguide Dispersion: Light energy of a mode propagates partly in the core and partly in cladding. The mode power distribution b/w the core and cladding depends on λ. This is called waveguide dispersion

⇒ Silica refractive index n is λ dependant which leads to different λ components travel at different speeds in silica. This is known as material dispersion

Dispersion leads to distortion of degradation of the signal quality at the output and due to overlapping of the pulses.

Fibre Optics Communication

Message (input) → Modulator (transmitter) → Optical Source (Laser) → Optical Fiber → Optical detector Photo diodes → Demodulator (Reciever) → Destination (output)

Advantages of Optical Fibre over traditional metal communication lines

1) Low transmission loss and wide bandwidth
2) Immunity and Interference
3) Small size and weights
4) Signal Security

Ques: A step index fibre as core with refractive index = 1.7 & cladding with refractive index = 1.69. Find numerical aperture.

Sol: $\mu_1 = 1.7$ $\mu_2 = 1.69$

$$NA = \sqrt{\mu_1^2 - \mu_2^2} = \sqrt{(1.7)^2 - (1.69)^2} = 0.184$$

Ques: The cladding refractive index = 1.5 of a step index fibre. NA = 0.12. Find ref. index of core

Sol: $\mu_1 = ?$ & $\mu_2 = 1.5$ $NA = 0.12$

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$NA = \sqrt{\mu_1^2 - \mu_2^2}$

8 $0.12 = \sqrt{\mu_1^2 - (1.5)^2}$

$0.0144 = \mu_1^2 - (1.5)^2$

$\mu_1 = 1.5$

Ques: How many modes can propagate with core dia of 50 μm in a step index fibre. Core & cladding ref. index are 1.12 & 1.1. $\lambda = 5500$ Å

Sol: $N = \frac{2\pi^2 a^2}{\lambda^2} (\mu_1^2 - \mu_2^2)$

$= \frac{2\pi^2 (25 \times 10^{-6})^2}{(5500 \times 10^{-10})^2} (0.04)$

$= 1.63 \times 10^{-5} \times 10^{-12} \times 10^{+20} = 1.631 \times 10^{3}$

$= 1631$

Ques: $\theta_c = ?$, $\theta_0 = ?$, $NA = ?$, $\Delta = ?$, $\mu_1 = 1.62$, $\mu_2 = 1.58$, $\mu_0 = 1$

Sol: $\sin\theta_c = \frac{\mu_2}{\mu_1} = \frac{1.58}{1.62}$

$\theta_c = 77.2°$

$\theta_0 = \sin^{-1}\sqrt{\mu_1^2 - \mu_2^2} = 21°$

$NA = 0.36$

$\Delta = \frac{1.62 - 1.58}{1.62} = 0.025$