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CLASS: III B.Sc., PHYSICS

Fibre Optic Communication

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2.11. INTRODUCTION TO FIBRE OPTICS

The development of lasers and optical fibre has brought about a revolution in the field of communication systems. Experiments on the propagation of information – carrying light waves through an open atmosphere were conducted. The atmospheric conditions like rain, fog etc. affected the efficiency of communication through light waves.

To have efficient communication systems, the information carried by light waves should need a guiding medium through which it can be transmitted safely.

This guiding mechanism is optical fibre. The communication through optical fibre is known as light wave communication or optical communication.

A light beam acting as a carrier wave is capable of carrying more information than that of radio waves and microwaves due to its larger bandwidth.

Currently in most part of the world, fibre optics is used to transmit voice, video and digital data signals using light waves from one place to other place.

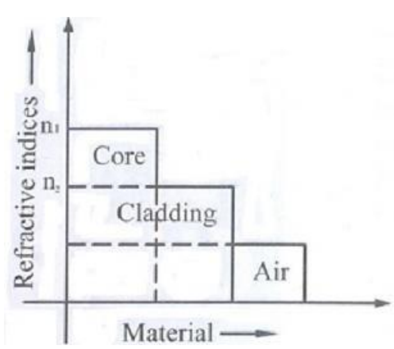
2.12. OPTICAL FIBRE

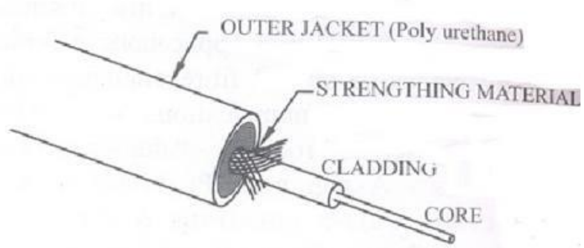
The optical fibre is a wave guide. It is made up of transparent dielectrics (SiO_2), (glass or plastics).

2.13. STRUCTURE OF OPTICAL FIBRE

Fibre Construction

It consists of an inner cylinder made of glass or plastic called core. The core has high refractive index n_1. This core is surrounded by cylindrical shell of glass or plastic called cladding.

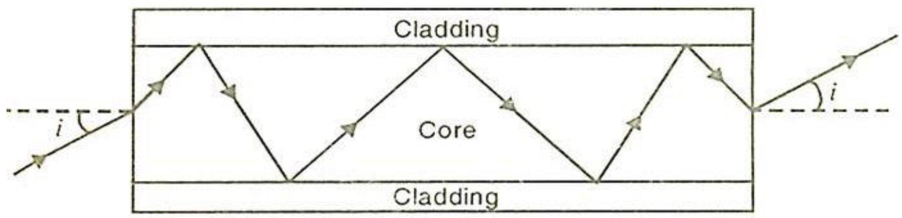




The cladding has low refractive index n_2. This cladding is covered by a jacket which is made of polyurethane. It protects the layer from moisture and abrasion.

2.14. PRINCIPLE OF PROPAGATION OF LIGHT IN AN OPTICAL FIBRE

The light launched inside the core at one end of the fibre propagates to the other end due to total internal reflection at the core and cladding interface.



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

1. The refractive index of the core material n_1 must be higher than that of the cladding n_2 surrounding it ($n_1 > n_2$).

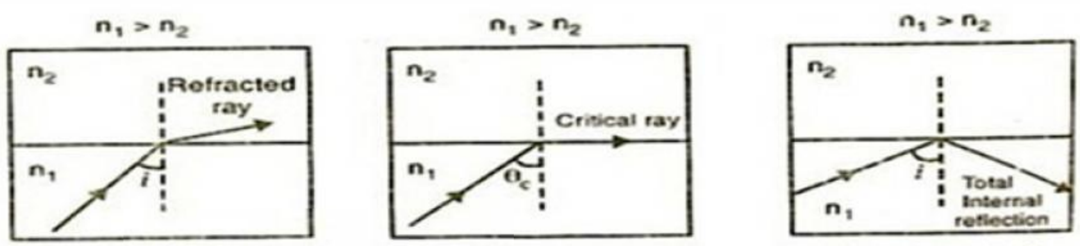
2. At the core – cladding interface, the angle of incidence (between the ray and normal to the interface) must be greater than the critical angle $(\theta_i > \theta_c)$

a) When, $i < \theta_C$ it is refracted into rarer medium

b) When $i = \theta_C$, it traverses along the interface so that angle of refraction is 90^0

c) When $i > \theta_C$, it is totally reflected back into the densermedium itself.

When $i = \theta_C$, then by Snell's law,



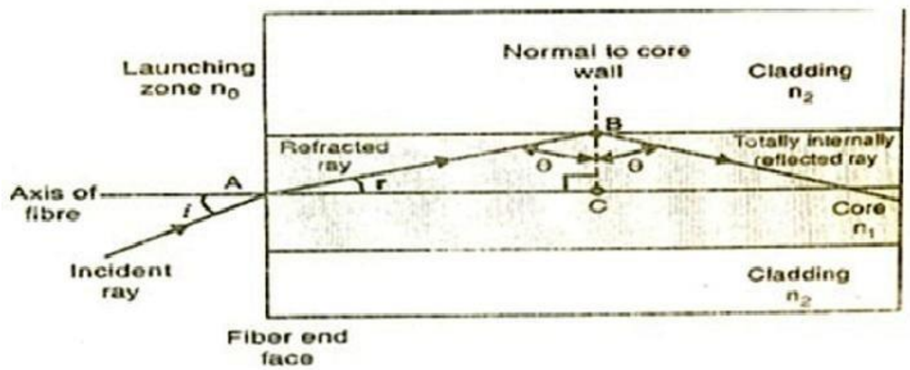
(a) When $i < \theta_c$ (b) When $i = \theta_c$ (c) When $i > \theta_c$

$$n_1 Sin\theta_c = n_2 Sin\ 90^0$$

$$Sin\theta_c = \frac{n_2}{n_1} Sin\ 90^0$$

2.15. PROPAGATION OF LIGHT IN OPTICAL FIBRE (Acceptance Angle and Numerical Aperture Derivation)

Let as consider an optical fibre through which the light is being sent. Let the refractive indices of the core and cladding be n_1 and n_2 respectively; $n_1 > n_2$. Let the refractive index of the medium from which the light is launched be n_0.



Let the light ray enter at an angle 'i' to the axis of the fibre. The ray is refracted along OB at an angle θ in the core as shown in the figure.

The angle of incidence $\phi = (90 - \theta)$ at interface of the core and cladding this angle is more than the critical angle ϕ_c Hence the ray is totally internally reflected

Applying Snell's law at the point of the entry of ray (AO)

$$n_0 \sin i = n_1 \sin\theta$$

$$\sin i = \frac{n_1}{n_0} \sin\theta$$

$$\sin i = \frac{n_1}{n_0}\left(\sqrt{1 - \cos^2\theta}\right) \longrightarrow (1$$

Applying Snell's law at the point B (on interface) $\quad n_1 \sin\phi = n_2 \sin 90^0$

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

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

$$\cos\theta = \frac{n_2}{n_1} \longrightarrow (2)$$

Substituting eqn, (2) in equ. (1)

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

$$\sin i = \frac{n_1}{n_0}\frac{1}{n_1}\sqrt{n_1{}^2 - n_2{}^2}$$

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

If the refractive index of the air n_0= 1 then the maximum value of ***Sin i*** is given as

$$\sin i_{max} = \sqrt{n_1{}^2 - n_2{}^2} \;--\rightarrow (3)$$

2.16. ACCEPTANCE ANGLE

Definition

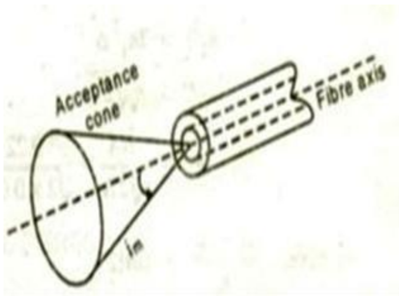
Acceptance angle is defined as the maximum angle that a light ray can have relative to the axis of the fibre and propagate down the fibre. Or the maximum angle at or below which the light can suffer Total Internal Reflection is called acceptance angle.

Acceptance cone

The cone of rays that are accepted by the fibre to have total internal reflection inside the fibre is referred as acceptance cone.

The light rays contained within the cone having a full angle i_m are accepted and transmitted along the fibre. Therefore, the cone is called the acceptance cone.

Light incident at an angle beyond i_m refracts through the cladding and the corresponding optical energy is lost. It is obvious that the larger the diameter of the core, the larger the acceptance angle.



2.17. NUMERICAL APERTURE

Definition

*Numerical aperture (NA) is the light gathering capacity of the fibre, which depends on the acceptance angle. It is also defined as the **Sine** of the acceptance angle of the fibre.*

Numerical aperture determines the light gathering ability of the fibre.

$$NA = \sin i_{max}$$

$$NA = \sin i_{max} = \sqrt{n_1^2 - n_2^2}\ ) - -\rightarrow (4)$$

2.18. FRACTIONAL INDEX CHANGE

It is the ratio of refractive index difference in core and cladding to the refractive index of the core.

$$\Delta = \frac{(n_1 - n_2)}{n_1} - -\rightarrow (5)$$

Relation between NA and Δ

$$n_1\Delta = n_1 - n_2 - -\rightarrow (6)$$

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

$$NA = \sqrt{(n_1 + n_2)(n_1 - n_2)} - -\rightarrow (7)$$

$$NA = \sqrt{(n_1 + n_2)n_1\Delta}$$

If $n_1 \approx n_2$

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

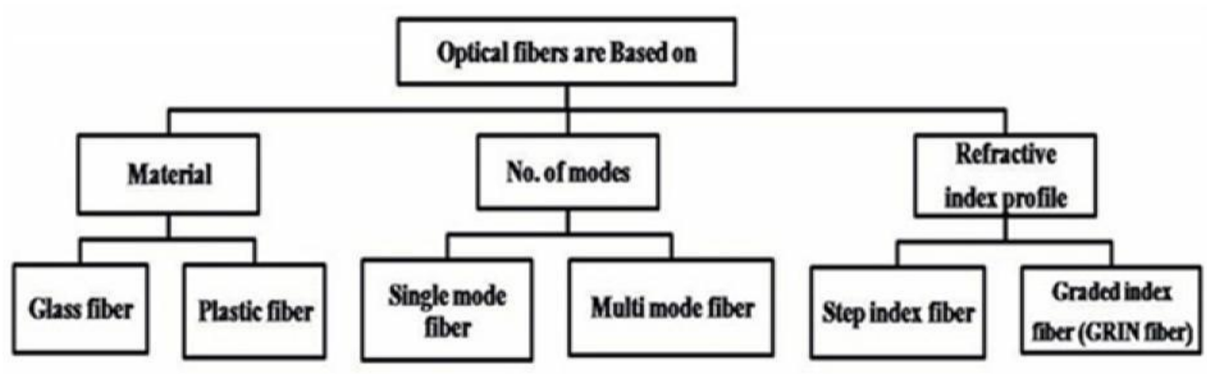
$$NA = n_1\sqrt{2\Delta} - -\rightarrow (8)$$

The above equation gives the relation between Numerical aperture and fractional index change of optical fibre.

2.19. TYPES OF OPTICAL FIBRES BASED ON MATERIALS MODES AND REFRACIVE INDICES

Optical fibres are classified into three major categories

(i). The type of material used (ii). The number of modes (iii). The refractive index profile



2.20. GLASS AND PLASTIC FIBRE

Based on the type of the material used, fibre are classified into two types as follows

Glass fibre: If the optical fibre is made up of mixture of silica glasses and metal oxides, then it is called glass fibre.

Example: (i) Core: GeO_2 *-*SiO_2 *Cladding:* SiO_2

(ii) Core: SiO_2 *Cladding:* P_2O_3*-*SiO_2

Plastic fibre: If the optical fibre is made up of plastic then it is called plastic fibre.

Example: (i) Core: Polymethylmenthacrylate

Cladding: Co- Polymer

(ii). Core: Polystyrene:

Cladding: Methyl menthacrylate

2.21. SINGLE AND MULTIMODE FIBRES

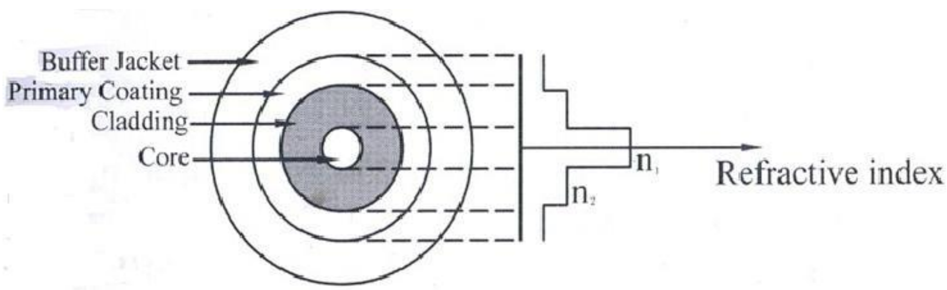
Depending on the number of modes of propagation, the optical fibres are classified into two types they are classified as (i) Single-mode fibre and (ii) Multimode fibre.

(i) Single-mode fibre

If only one mode is transmitted through an optical fibre, then the optical fibre is called single-mode fibre.

In general, the single mode fibres are step – index fibres. These types of fibres are made from doped silica. It has a very small core diameter so that it can allow only one mode of propagation and hence called single mode fibres.

The cladding diameter must be very large compared to the core diameter. Thus in the case of single mode fibre, the optical loss is very much reduced. The structure of a single mode fibre as shown in figure.



Structure

Core diameter:	5-10μm Cladding diameter
Cladding diameter:	Generally around 125μm
Protective layer:	250 to 1000μm
Numerical aperture:	0.08 to 0.10
Band width:	More than 50MHz km.

Application:

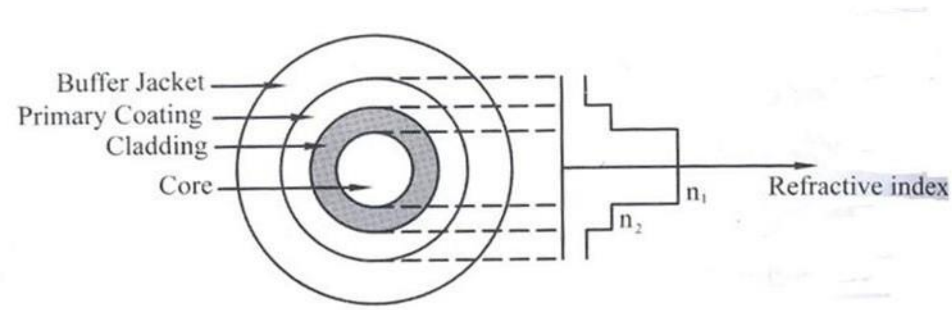
Because of high bandwidth, they are used in long haul communication systems.

(ii). Multi- Mode Fibres

If more than one mode is transmitted through an optical fibre, then the optical fibre is called multimode fibre.

The multi modes fibres are useful in manufacturing both for step – index and graded index fibres. The multi-mode fibres are made by multi-component glass compounds such as Glass – Clad -Glass, Silica – Clad – Silica, doped silica etc.

Here the core diameter is very large compared to single mode fibres, so that it can allow many modes to propagate through it and hence called as Multi mode fibres. The cladding diameter is also larger than the diameter of the single mode fibres. The structure of the multimode fibre is as shown in the figure.



Structure:

Core diameter:	50-350μm
Cladding diameter:	125μm - 500μm
Protective layer:	250 to 1100μm
Numerical aperture:	0.12 to 0.5
Band width:	Less than 50MHz km.

Application:

Because of its less band width it is very useful in short haul communication systems.

2.22. STEP INDEX AND GRADED INDEX (GRIN) FIBRE

Based on the variation in the refractive index of the core and cladding, the optical fibres are classified into two types (i) Step-index fibre and (ii) Graded-index fibre.

(i). Step-index fibre

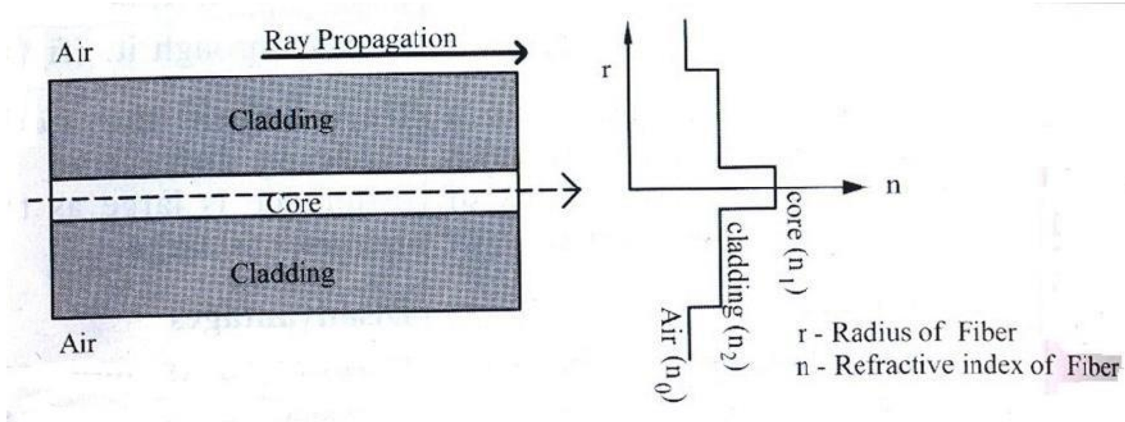
In step fibre, the variation in refractive indices of air, cladding and core vary step by step. Hence, this type of fibre is known as step index fibre.

Based on the refractive index and the number of modes, further step – index Fibre is classified into two types as,

(i) Step index – single mode fibre (ii) Step index – multi mode fibre

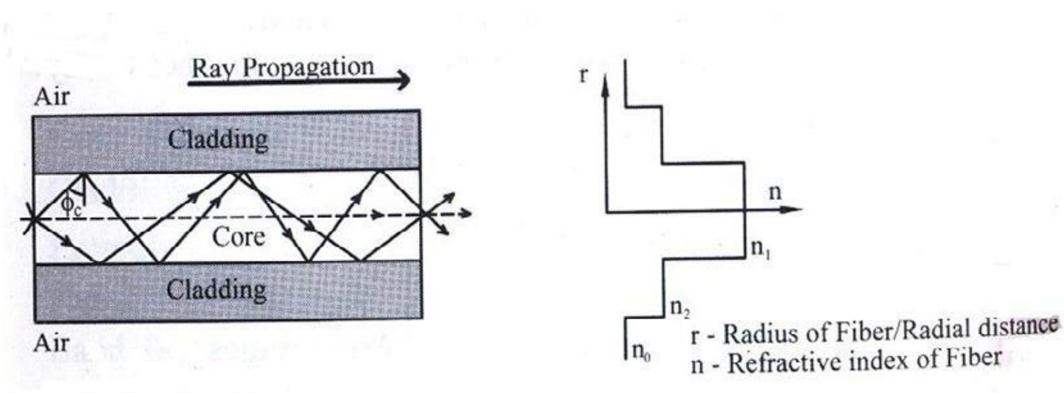
(i). SINGLE MODE STEP INDEX FIBRE

A single mode step index fibre consists of a very thin core of uniform refractive index surrounded by a cladding of refractive index lower than that of core. The refractive index abruptly changes at the core cladding boundary. Light travels along a side path, i.e., along the axis only. So zero order modes is supported by Single Mode Fibre.



(ii). MULTIMODE STEP INDEX FIBRE

A multimode step index fibre consists of a core of uniform refractive index surrounded by cladding of refractive index lower than that of the core. The refractive index abruptly changes at the core cladding boundary.

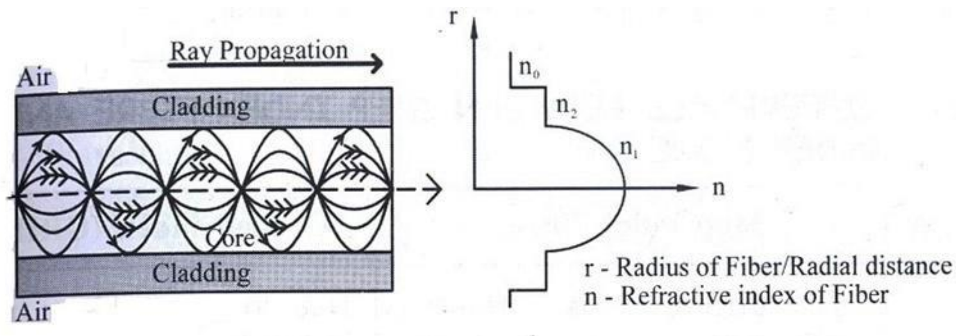


The core is of large diameter. Light follows zigzag paths inside the fibre. Many such zigzag paths of propagation are permitted in Multi-Mode Fibre. The Numerical Aperture of a Multi-mode fibre is larger as the core diameter of the fibre is larger.

(iii). GRADED INDEX FIBRE

GRIN fibre is one in which refractive index varies radially, decreasing continuously in a parabolic manner from the maximum value of n_1, at the center of the core to a constant value of n_2 at the core cladding interface.

In graded index fibre, light rays travel at different speeds in different parts of the fibre because the refractive index varies throughout the fibre. Near the outer edge, the refractive index is lower. As a result, rays near the outer edge travel faster than the rays at the center of the core. Because of this, rays arrive at the end of the fibre at approximately the same time.



In effect light rays arrive at the end of the fibre are continuously refocused as they travel down the fibre. All rays take the same amount of time in traversing the fibre. This leads to small pulse dispersion.

2.23. DIFFERENCE BETWEEN STEP INDEX FIBRE AND GRADED INDEX FIBRE

S.No.	***STEP INDEX FIBRE***	***GRADED INDEX FIBRE***
1	The refractive index of the core is uniform throughout and undergoes on abrupt change at the core cladding boundary	The refractive index of the core is made to vary gradually such that it is maximum at the center of the core.
2	The diameter of the core is about 50-200μm in the case of multimode fibre and 10μm in the case of single mode fibre	The diameter of the core is about 50μm in the case of multimode fibre
3	The path of light propagation is zig- zag in manner	The path of light is helical in manner
4	Attenuation is more for multimode step index fibre but for single mode it is very less.	Attenuation is less.
5	This fibre has lower bandwidth	This fibre has higher bandwidth
6	The light ray propagation is in the form of meridional rays and it passes through the fibre axis.	The light propagation is in the form of skew rays and it will not cross fibre axis.

7	No of Mode of propagation $N_{Step} = 4.9\left(\frac{d\times NA}{\lambda}\right)^2 = \frac{V^2}{2}$ Where d= diameter of the fibre core λ= wavelength NA = Numerical Aperture V- V-number is less than or equal to 2.405 for single mode fibres and greater than 2.405 for multimode fibres.	No of Mode of propagation $N_{Graded} = \frac{4.9\left(\frac{d\times NA}{\lambda}\right)^2}{2} = \frac{V^2}{4}$ $N_{Graded} = \frac{N_{Step}}{2}$

2.24. DIFFERENCES BETWEEN SINGLE AND MULTIMODE FIBRE

S.NO	***SINGLE MODE FIBRE***	***MULTIMODE FIBRE***
1	In single mode fibre only one mode can propagate through the fibre	In multimode it allows a large number of paths or modes for the light rays travelling through it.
2	It has smaller core diameter and the difference between the refractive index of the core and cladding is very small.	It has larger core diameter and refractive index difference is larger than the single mode fibre.
3	**Advantages:** No dispersion(i.e. there is no degradation of signal during propagation)	**Disadvantages:** Dispersion is more due to degradation of signal owing to multimode.
4	Since the information transmission capacity is inversely proportional to dispersion the fibre can carry information to longer distances. $\left(T \propto \frac{1}{D}\right)$	Information can be carried to shorter distances only.
5	**Disadvantages:** Launching of light and connecting of two fibres difficult.	**Advantages:** Launching of light and also connecting of two fibres is easy.
6	Installation (fabrication) is difficult as it is more costly	Fabrication is easy and the installation cost is low.

2.25. LOSSES IN OPTICAL FIBRES

When light propagates through an optical fibre, a small percentage of light is lost through different mechanisms. The loss of optical power is measured in terms of decibels per km for attenuation losses.

2.38.1. ATTENUATION

It is defined as the ratio of opticicapower output (Po'out) from abre of length 'L' to the power output (Pin)

$$\text{Attenuation } (\alpha) = \frac{-10}{L} \log \frac{P_{out}}{P_{in}} \, dB/Km$$

Since attenuation plays a major role in determining the transmission distance, the following attenuation mechanisms are to be considered in designing an optical fibre.

1. Absorption

Usually absorption of light occurs due to imperfections of the atomic structure such as missing molecules, (OH^-), hydroxyl ions, high density cluster of atoms etc., which absorbs light.

2. Scattering

Scattering is also a wavelength dependent loss, which occurs inside the fibres. Since the glass is used in fabrication of fibres, the disordered structure of glass will make some variations in the refractive index inside the fibre. As a result, if light is passed through the atoms in the fibre, a portion of light is scattered (elasticcattering). This type of scattering is called Raleigh scattering. Raleigh scattering loss $\propto \frac{1}{\lambda^4}$

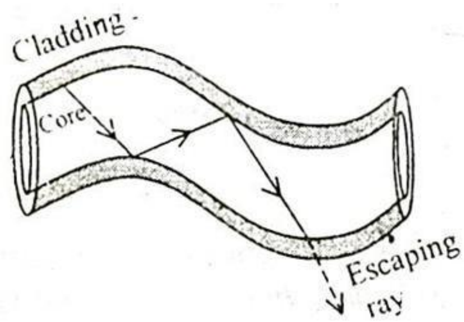
3. Radiative loss or bending loss

Radiative loss occurs in fibres due to bending of finite radius of curvature in optical fibres. The types of bends are

a. Macroscopic bends b. Microscopic bends

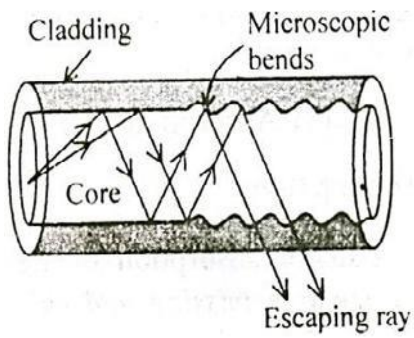
a. Macroscopic bends

If the radius of the core is large compared to fibre diameter, it may cause large-curvature at the position where the fibre cable turns at the corner. At these corners the light will not satisfy the condition for total internal reflection and hence it escapes out from the fibre. This is called as macroscopic / macro bending losses. Also note that this loss is negligible for small bends.



b. Microscopic bends

Micro-bends losses are caused due to non-uniformities or micro bends inside the fibre as shown. This micro bends in fibre appears due to non-uniform pressures created during the cabling of the fibre or even during the manufacturing itself. This is lead to losses of light by leakage through the fibre.



Remedy

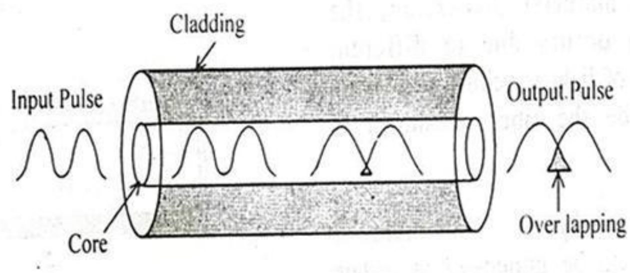
Micro-bend losses can be minimized by extruding (squeezing out) a compressible jacket over the fibre. In such cases, even when the external forces are applied, the jacket will be deformed but the fibre will tend to stay relatively straight and safe, without causing more loss.

2.26. DISTORTION AND DISPERSION

The optical signal becomes increasingly distorted as it travels along a fibre. This distortion is due to dispersion effect.

Dispersion

When an optical signal or pulse is sent into the fibre the pulse spreads /broadens as it propagates through the fibre. This phenomenon is called dispersion as shown in the figure.



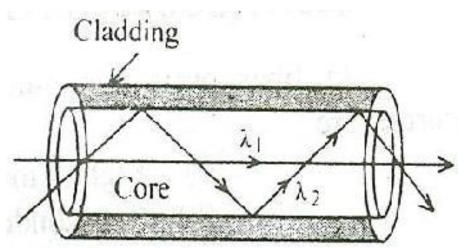
From figure we can see that the pulse received at the output is wider than the input pulse. Hence the output pulse is said to be distorted, due to dispersion effect.

The pulse broadening or dispersion will occur in three ways, viz.,

1. Inter-modal dispersion
2. Material dispersion or chromatic dispersion
3. Waveguide dispersion

2.39.1 Intermodal dispersion

When more than one mode is propagating through the fibre, then the inter modal dispersion will occur. Since, many modes are propagating; they will have different wavelengths and will take different time to propagate through the fibre, which leads to intermodal dispersion.

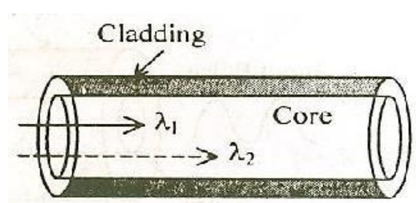


Explanation

When a ray of light is launched into the fibre, the pulse is dispersed in all possible paths through the core, so called different modes. Each mode will be different wavelength and has different velocity as shown in the figure. Hence, they reach the end of the fibre at different time. This results in the elongation or stretching of data in the pulse. Thus causes the distorted pulse. This is called intermodal dispersion.

2.39.2 Material dispersion

In material dispersion, the dispersion occurs due to different wavelength travelling at different speed inside the fibres shown in the figure.



Remedy

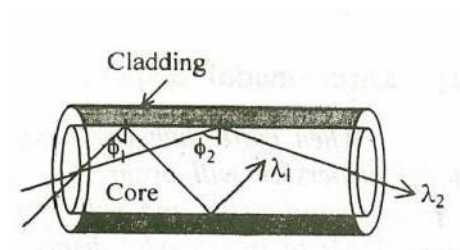
The material dispersion can be minimized at certain wavelengths say 870nm, 1300 nm and 1550 nm; these wavelengths are termed Zero Dispersion wavelengths (ZDW).

Whether light wavelength is lesser than Zero Dispersion wavelengths, it travels slower and when it is higher than ZDW it travels faster. Thus the speed is altered and adjusted in such a way that all the waves passing through the fibre will move with constant speed and hence the material dispersion is minimized.

Note: this dispersion will not occur in single mode fibres

2.39.3 Wave guide dispersion

The wave guide dispersion arises due to the guiding property of the fibre and due to their different angles at which they incident at the core-cladding interface of the fibre.



In general:

Inter-modal dispersion > Material Dispersion > Waveguide dispersion

2.27. FIBRE OPTIC SENSORS

Optical sensor is a transducer which converts any form of signal into optical signal in the measurable form. Here optical fibres are used as a guiding media and hence called as wave guides. The block diagram of a sensor system is as follows.

The optical sources used here are LED/Laser. The optical signal produced by the optical source and is transmitted through the transmitting fibre in the modulation zone.

The optical signals are modulated based on any one of these properties, viz., Optical intensity, phase, polarization, Wavelength and spectral distribution. These modulated signals with any one of these properties are received by the receiving / fibre and is sent to the optical detector.

2.40.1. Types of Sensors

There are two types of sensors, viz.

(i). Intrinsic sensors or Active sensors (ii). Extrinsic sensors or Passive sensors

2.40.2. Intrinsic Sensors or Active Sensors

In intrinsic sensors or active sensors the physical parameter to be sensed directly acts on the fibre itself to produce the changes in the transmission characteristics.

Example: ***(i).*** *Temperature / Pressure Sensor (Phase and polarization sensor) and* ***(ii).*** *Liquid level sensor.*

2.40.3. Extrinsic Sensors or Passive Sensors

In extrinsic sensors or passive sensors, separate sensing element will be used and the fibre will act as a guiding media to the sensors. Examples:

Example: (i). Displacement sensor (ii). Laser Doppler velocimeter sensor

2.28. TEMPERATURE SENSOR (*Intrinsic sensors or Active sensors)*

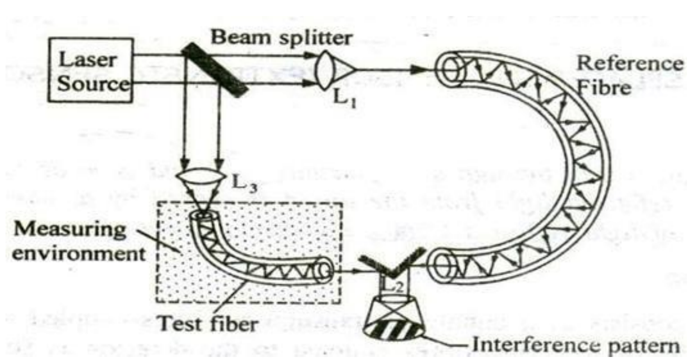
Principle

It is based on the principle of interference between the beams emerging out from the reference fibre and the fibre kept in the measuring environment.

Description

It consists of a Laser source to emit light. A beam splitter, made of glass plate is inclined at an angle 45^0 with respect to the direction of the laser beam. Two fibres viz.,

i. Reference fibre which is isolated from the environment
ii. Test fibre kept in the environment to be sensed, are placed as shown in the figure. Separate lens systems are provided to split and to collect the beam.



Working

1. A monochromatic source of light is emitted from the laser source.
2. The beam splitter kept at an angle 450 inclination divides the beam emerging from the laser source into two beams (i) main beam and (ii) splitted beam, exactly at right angles to each other.

3. The main beam passes through the lens L_1 and is focused onto the reference fibre which is isolated from the environment to be sensed.
4. The beam after passing through the reference fibre then falls on the Lens L_2.
5. The splitted beam passes through the Lens L_3 and is focused onto the test fibre kept in the environment to be sensed.
6. The splitted beam after passing through the test fibre is made to fall on lens L_2.
7. The two beams after passing through the fibres, produces a path difference due to change in parameters such as pressure, temperature etc. in the environment.
8. Therefore a path difference is produced between two beams causing the interference pattern as shown in the figure.
9. Thus the change in pressure or temperature can be accurately measured with the help of the interference pattern obtained.

2.29. DISPLACEMENT SENSOR (EXTRINSIC SENSORS OR PASSIVE SENSORS)

Principle

Light is sent through a transmitting fibre and is made to fall on a moving target. The reflected light from the target is sensed by a detector. With respect to intensity of light reflected from its displacement of the target is measured.

Description

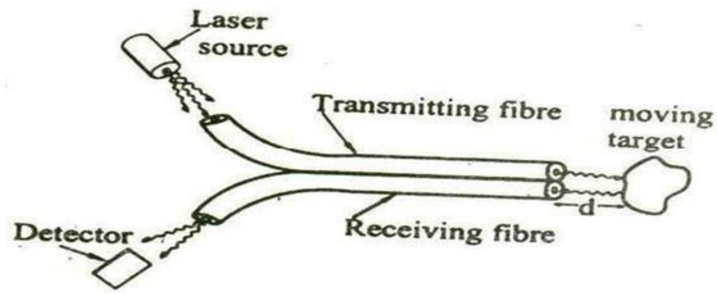
It consists of a bundle of transmitting fibres coupled to the laser source and a bundle of receiving fibres coupled to the detector as shown in the figure.

The axis of the transmitting fibre and the receiving fibre with respect to the moving target can be adjusted to increase the sensitivity of the sensor.

Working

Light from the source is transmitted through the transmitting fibre and is made to fall on the moving target. The light reflected from the target is made to pass through the receiving fibre and the same is detected by the detector.

Based on the intensity of the light received, the displacement of the target can be measured, (i.e.) if the received intensity is more than we can say that the target is moving towards the sensor and if the intensity is less, we can say that the target is moving away from the sensor.



2.30. APPLICATION OF FIBRE OPTICAL SYSTEM

a) It can be used for long distance communication in trunk lines.

b) A large no of telephone signals nearly 15000 can be passed through the optical fibres in a particular time without any interference.

c) It is used in computer networks especially in LAN.

d) It is also used as optical sensor.

e) Fibre optics endoscopes are used in medical diagnosis.

f) It is used to visualize the inner organs of the body.

g) Fibres as endoscopes are used in various medical fields such as cardioscopy, laparoscopy, cryoscopy etc.

2.31. ADVANTAGES OF OPTICAL FIBRE COMMUNICATION OVER RADIO WAVECOMMUNICATION

a) Optical communication can be made even in the absence of electricity.

b) The optical signals are not affected by any electrical signals or lightening.

c) Optical fibre communication is free from electromagnetic interference (EMI).

d) This type of communication is suitable to any environmental conditions.

e) Easy maintenance, longer life, economical and high quality signal transmission are the additional features of optical fibre communication.