UNIT

3

FIBRE OPTICS AND APPLICATIONS

3.1 INTRODUCTION

Fibre optics is a branch of physics which deals with the transmission and reception of light waves using optical fibres. The principle behind the transmission of light waves in an optical fibre is *total internal reflection.* In 1870, John Tyndall gave the demonstration of this principle. Later in 1880, Alexander Graham Bell reported the transmission of speech using light beam.

The development of lasers and optical fibres have brought about a revolution in communication systems. Some experiments were carried out on propagation of information through light waves in open atmosphere. A light beam acting as a carrier wave is capable of carrying information more than that of radio waves and microwaves because of its high frequency.

Radio waves - 10^6 Hz.

Micro waves - 10^{10} Hz.

Light waves - 10^{15} Hz.

The light transmission in the atmosphere is restricted to line of sight and severely affected by disturbances such as rain, snow, fog, dust and atmospheric turbulence. Hence, to have an efficient communication system the light which carries the information requires a guiding mediam known as optical fibres.

3.2 STRUCTURE OF OPTICAL FIBRE

An optical fibre is a very thin, flexible thread of transparent plastic or glass in which light is transmitted based on the principle of total internal reflections. It consists of central cylinder or core surrounded by a layer of material called the cladding which in turn is covered by a polyurethane jacket. Light is transmitted within the core. The cladding keeps the light waves within the core because the refractive index of the cladding material is less than that of the core. The cladding also provides some strength to the core. The additional polyurethane jacket protects the fibre from moisture and abrasion.

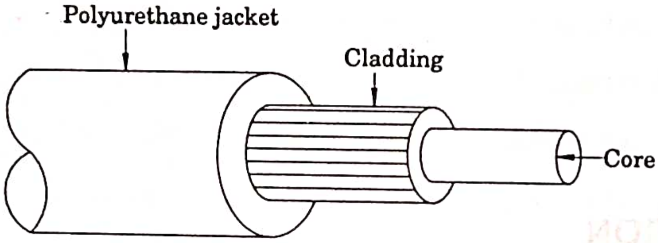


Fig. 3.1 Structure of optical fibre

The core as well as the cladding is made of either glass or plastic. Three major types of fibres are

(i) Plastic core with plastic cladding.

(ii) Glass core with plastic cladding and

(iii) Glass core with glass cladding.

In the case of plastics, the core can be polystryrene or polyether methacrylate. The cladding is generally made of Silicon or Teflon. The glass is made of silica. Small amount of components such as Boron, Germanium or Phosphorus is added to change the refractive index of the fibre. In comparison with glass, plastic fibres are flexible and inexpensive.

The thickness of the core of a typical glass fibre is nearly 50 μm and that of cladding is 100 to 200 μm. The overall thickness of an optical fibre is nearly 125 to 200 μm.

3.3 FEATURES OF OPTICAL FIBRES

1. It is light in weight.
2. It is smaller in size and is flexible, so that it can bend to any position.
3. It is non-conductive, non-radiative and non-inductive.

4. It has high bandwidth and low loss.
5. There is no short circuiting as in metal wires.
6. There is no internal noise (or) cross talks.
7. It can withstand any range of temperatures and moisture conditions.

3.4 PRINCIPLE AND PROPAGATION OF LIGHT IN OPTICAL FIBRES

Principle

The principle behind the transmission of light waves in an optical fibre is *total internal reflection*.

The phenomenon of total internal reflection takes place when it satisfies the following two conditions.

1. Light should travel from denser medium to rarer medium.

   i.e., $n_1 > n_2$

   where, n_1 - refractive index of denser medium (core)

   n_2 - refractive index of rarer medium (cladding)

2. The angle of incidence should be greater than the critical angle.

   i.e., $\theta_i > \theta_c$

   where, θ_i - Angle of incidence

   θ_c - Critical angle.

Let the light ray travel from denser medium to rarer medium. The reflection and refraction at the interface is a result of the difference in the speed of light in two materials having different refractive indices.

Case (i) When $\theta_i < \theta_c$, the ray is refracted into the rarer medium as shown in Fig. (3.2 a).

Case (ii) When $\theta_i = \theta_c$, the ray travels along the interface so that the angle of refraction is 90°. This angle (θ_c) is called as critical angle as shown in Fig. (3.2 b).

Case (iii) When $\theta_i > \theta_c$, the ray is totally reflected back into the denser medium itself as shown in Fig. (3.2 c). This phenomenon is known as total internal reflection.

The angles of incidence θ_i and refraction θ_r are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction which is represented by the following equation.

$$n_1 \text{ Sin } \theta_i = n_2 \text{ Sin } \theta_r$$

$$\frac{\text{Sin } \theta_i}{\text{Sin } \theta_r} = \frac{n_2}{n_1}$$

When $\theta_i = \theta_c$, $\theta_r = 90°$ then by snell's law,

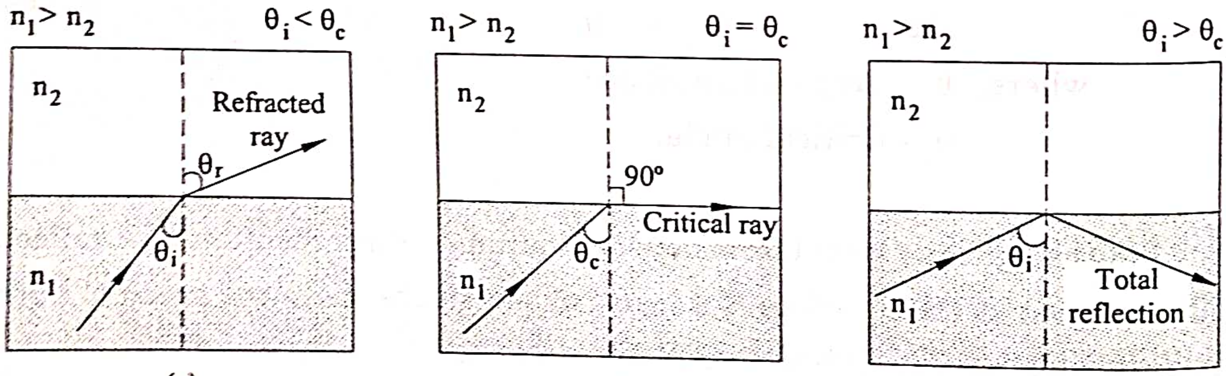
$$n_1 \text{ Sin } \theta_c = n_2 \text{ Sin } 90°$$

$$\frac{\text{Sin } \theta_c}{\text{Sin } 90°} = \frac{n_2}{n_1}$$

$$\therefore \quad \sin \theta_c = \frac{n_2}{n_1} \qquad [\because \sin 90° = 1]$$

$$\therefore \quad \boxed{\theta_c = \text{Sin}^{-1}\left(\frac{n_2}{n_1}\right)}$$

Where θ_c is the critical angle and n_1 and n_2 are the refractive indices of the denser and rarer medium respectively.



(a) (b) (c)

Fig. 3.2 Phenomenon of total internal reflection

Propagation of light in optical fibres

For optical fibres, the process of propagation of light (optical signal) is simple, because the light wave enters at one end of the fibre and strikes the interface of the core and cladding only at large angles of incidence. The light beam undergoes total internal reflection and passes through the length of the cable.

Even for a bent fibre, the light guidance takes place by multiple total internal reflection all over the length of the fibre as shown in Fig. (3.3).

Let us consider an optical fibre into which the light is injected. The light ray travels along AO and enters the core at an angle θ_a to the axis of the fibre.

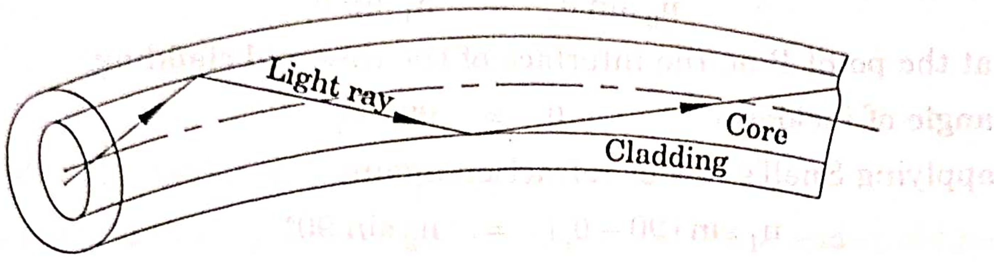


Fig. 3.3. Propagation of light in optical fibre

The light ray is refracted along OB at an angle θ_r in the core. It further proceeds to fall at critical angle of incidence $\theta = (90 - \theta_r)$ on the interface between core and cladding at B as shown in Fig. (3.4).

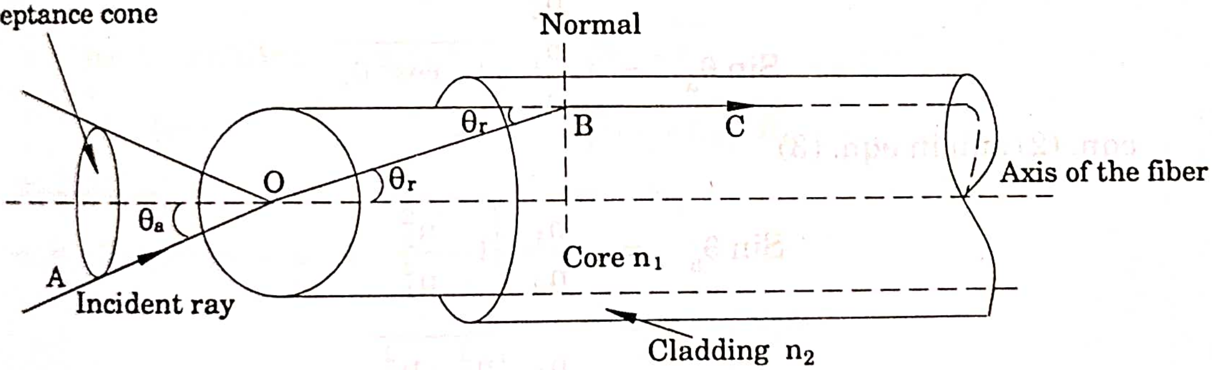


Fig. 3.4 Light propagation in optical fibre

If θ is greater than the critical angle at the core cladding interface, the light ray gets total internally reflected and propagates through the fibre (i.e.,) the light will stay inside the fibre.

Since it is the critical angle of incidence, the ray is refracted at 90° to the normal drawn to the interface (i.e,) it moves along BC.

However, only light wave that enters at an angle of incidence greater than θ_a at O will ultimately be incident at B at an angle less than the critical angle. Due to this, it will be refracted into the cladding region and be absorbed by the cladding and hence it will be lost.

3.5 NUMERICAL APERTURE AND ACCEPTANCE ANGLE

Let n_1 and n_2 be the refractive indices of core and cladding and let n_0 be the refractive index of the medium (air) in which the optical fibre is placed.

Now applying the Snell's law of refraction at the point of entry of the ray AO into the core, we have,

$$n_0 \sin \theta_a = n_1 \sin \theta_r \quad .....(1)$$

at the point B on the interface of the core and cladding,

angle of incidence $\theta = 90 - \theta_r$

applying Snell's law of refraction again,

$$n_1 \sin (90 - \theta_r) = n_2 \sin 90°$$

$$n_1 \cos \theta_r = n_2 \quad [\because \sin 90° = 1]$$

$$\cos \theta_r = \frac{n_2}{n_1} \quad .....(2)$$

Rewriting equation (1), we have

$$\text{Sin } \theta_a = \frac{n_1}{n_0} \sin \theta_r$$

$$\text{Sin } \theta_a = \frac{n_1}{n_0} \sqrt{1 - \cos^2 \theta_r} \quad .....(3)$$

eqn. (2) sub in eqn. (3)

$$\text{Sin } \theta_a = \frac{n_1}{n_0} \sqrt{1 - \frac{n_2^2}{n_1^2}}$$

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

$$\text{Sin } \theta_a = \frac{\sqrt{n_1^2 - n_2^2}}{n_0} \quad .....(4)$$

$\therefore$ Acceptance angle $\theta_a = \text{Sin}^{-1} \frac{\sqrt{n_1^2 - n_2^2}}{n_0}$ .....(5)

If the refractive index of air $(n_0) = 1$

$\therefore$ Acceptance angle $\boxed{\theta_a = \text{Sin}^{-1} \sqrt{n_1^2 - n_2^2}}$ .....(6)

"Thus the maximum angle at (or) below which the light can suffer total internal reflection is called as *acceptance angle*. The cone is referred as acceptance cone".

The sin of the acceptance angle of the fibre is known as *numerical aperture* (NA). It denotes the light collecting efficiency of the fibre and is the measure of the amount of the light rays that can be accepted by the fibre.

$$\therefore \quad NA = \sin\theta_a \qquad .....(7)$$

$$NA = \sin\left[\sin^{-1}\sqrt{n_1^2 - n_2^2}\right]$$

$$\therefore \quad \boxed{NA = \sqrt{n_1^2 - n_2^2}} \qquad .....(8)$$

3.6 FRACTIONAL INDEX CHANGE (Δ)

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

(i.e.,)
$$\boxed{\Delta = \frac{(n_1 - n_2)}{n_1}} \qquad .....(1)$$

Relation between NA and Δ

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

(or)
$$NA = \sqrt{(n_1 + n_2)(n_1 - n_2)} \qquad .....(2)$$

From eqn.(1)
$$n_1\Delta = n_1 - n_2 \qquad .....(3)$$

eqn. (3) sub in eqn. (2)

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

If $n_1 \approx n_2$, then

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

$$\therefore \quad \boxed{NA = n_1\sqrt{2\Delta}} \qquad .....(4)$$

3.7 TYPES OF OPTICAL FIBRES

Optical fibres are classified based on

(i) Material, (ii) Number of modes, (iii) Refractive index profile

Optical Fibre

- **Material**
  - (a) Glass fibres
  - (b) Plastic fibres
- **No.of modes**
  - (a) Single mode fibre
  - (b) Multimode fibre
- **Refractive index profile**
  - (a) Step index fibre
  - (b) Graded index fibre

i. Classification based on material

It can be classified into two types.

a. Glass fibre

b. Plastic fibre

a. Glass fibre

If the optical fibres are made by the fusing mixtures of metal oxides and silica glass, then it is known as glass fibre.

Examples

The glass fibres can be made by any one of the following combinations of core and cladding.

i. GeO_2 - SiO_2 core ; SiO_2 cladding

ii. P_2O_5 - SiO_2 core ; SiO_2 cladding

iii. SiO_2 core ; P_2O_5 - SiO_2 cladding

b. Plastic fibres

The plastic fibres are typically made of plastics, so that they are flexible and also low cost. It exhibits considerably greater signal attenuation than glass fibres. The plastic fibres can be handled without special care due to its toughness and durability.

Examples

1. Polystyrene core – Methylmethacrylate cladding.
2. Polymethylmethacrylate core - Co-polymer cladding.

ii. Classification based on number of modes

Depending on the number of modes of propagation the optical fibres are classified as

a. Single mode fibre

b. Multi mode fibre.

a. Single mode fibre

It has a very small core diameter so that it can allow only one mode of propagation and hence called single mode fibre. The cladding diameter must be large compared to the core diameter. Thus in the case of a single mode fibre, the optical loss is very much reduced. The structure of a single mode fibre is as shown in Fig. (3.5). Generally single mode fibres are called step index fibres.

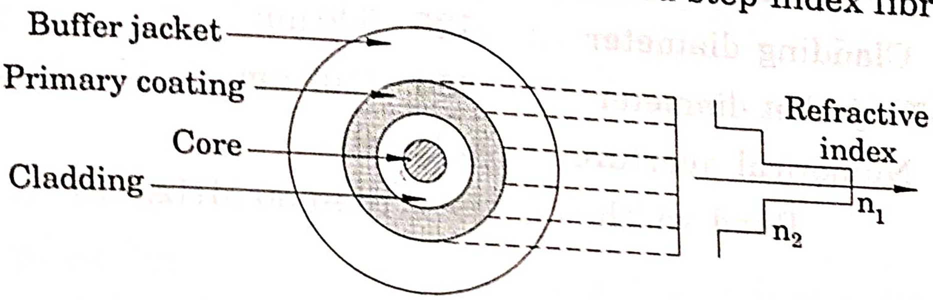


Fig. 3.5. Single mode fibre

Structure

Core diameter	:	5 - 10 μm.
Cladding diameter	:	Generally around 125 μm.
Buffer jacket diameter	:	250 - 1000 μm.
Numerical aperture	:	0.08 to 0.15, usually around 0.10
Band width	:	More than 50 MHz.

Application

Because of it its high band width, they are used in long haul communication systems.

b) Multi mode fibre

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 multimode fibres. The cladding diameter is also larger than the diameter of the single mode fibres as shown in Fig.(3.6). Multimode fibres has several advantages compared to single mode fibres. The large core radii of multimode fibre make it easier to launch optical power into the fibre. The multimode fibres are useful in manufacturing both for the step index and graded index fibres.

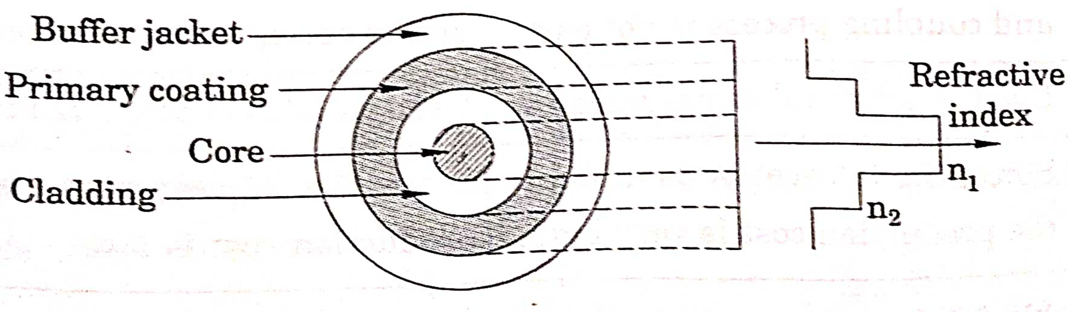


Fig. 3.6. Multi mode fibre

Structure

Core diameter	:	50 - 350 μm.
Cladding diameter	:	125 - 500 μm.
Buffer jacket diameter	:	250 - 1100 μm.
Numerical aperture	:	0.12 - 0.5
Band width	:	Less than 50 MHz.

Application

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

3.8 DIFFERENCE BETWEEN SINGLE MODE FIBRE AND MULTIMODE FIBRE

S.No.	SINGLE MODE FIBRE	MULTIMODE FIBRE
1.	Light can propagate through the fibre in only one mode	Light can propagate through the fibre with multiple number of modes.
2.	The fibre core diameter is very small and the difference between refractive indices of the core and cladding is very small.	The fibre core diameter is large and the difference in refractive indices of the core and cladding is large.
3.	Since light propagates in single mode, no dispersion occurs (i.e., no degradation of light signal takes place during propagation through the fibre).	Due to multimode propagation and material scattering, there is signal degradation.
4.	Launching of light into the fibre and coupling process is not easy.	Launching of light into the fibre and coupling process are easy
5.	Used in longhaul communication.	Used in LAN (Local Area Network).
6.	Since, the fabrication is difficult, the production cost is very high.	Since, the fabrication is easy, the production cost is low.

Table 3.1 Comparison between singlemode and multimode fibre

III. Classification based on the refractive index profile

The optical fibres are classified into two types,

a. Step index fibre

b. Graded index fibre

a. Step index fibre

In step index fibre the variation in refractive indices of air, cladding and core varies by step by step. Hence, it is known as step index fibre. The step index fibre involves both single mode and multimode fibres as shown in Fig.(3.7) and Fig. (3.8) respectively.

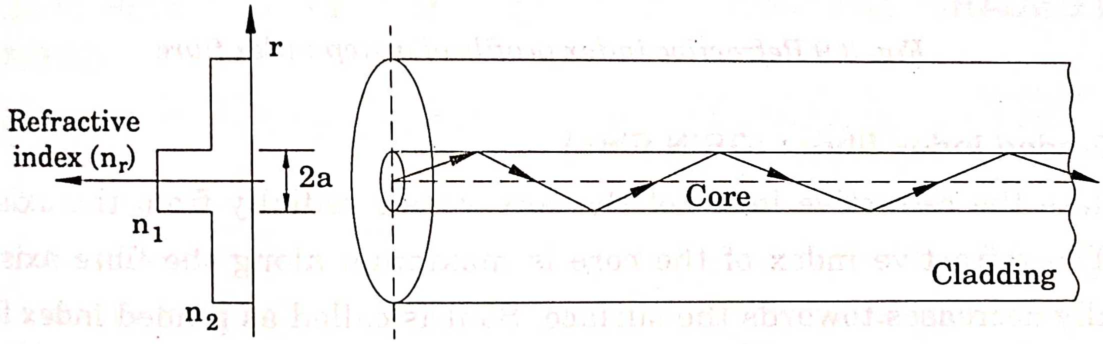


Fig. 3.7 Step index single mode fibre

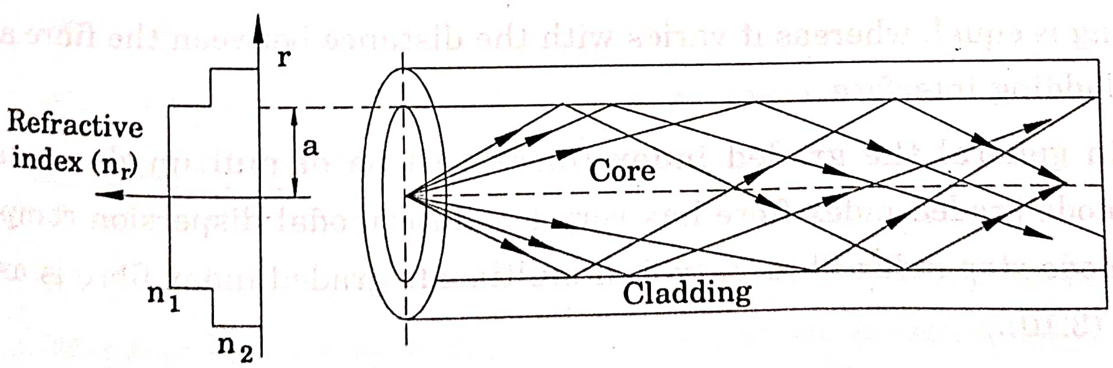


Fig. 3.8 Step index multimode fibre

In both the fibres the variation in refractive indices will be in step by step as shown in Fig. (3.9). Since a single mode fibre has less dispersion than multimode, the single mode step index fibre also has low intermodal dispersion compared to multimode step index fibre.

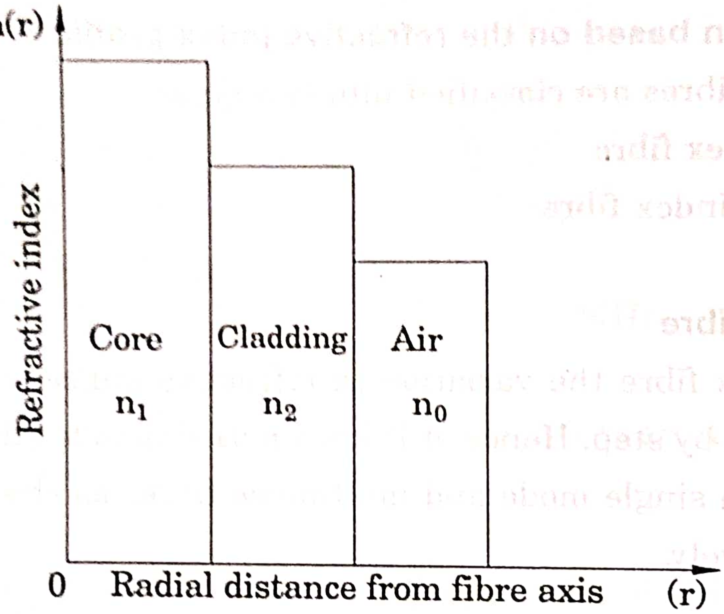


Fig. 3.9 Refractive index profile of a step index fibre

b. Graded index fibre : (GRIN fibre)

Here the refractive index of the core varies radially from the axis of the fibre. The refractive index of the core is maximum along the fibre axis and it gradually decreases towards the surface. So it is called as graded index fibre.

Refractive index is maximum at the fibre axis and minimum at the core-cladding interface. That is at the interface, the refractive index of the core and cladding is equal, whereas it varies with the distance between the fibre axis and core cladding interface.

In general the graded index fibres will be of multimode system.The multimode graded index fibre has very less intermodal dispersion compared to multimode step index fibre. A typical multimode graded index fibre is as shown in Fig. (3.10).

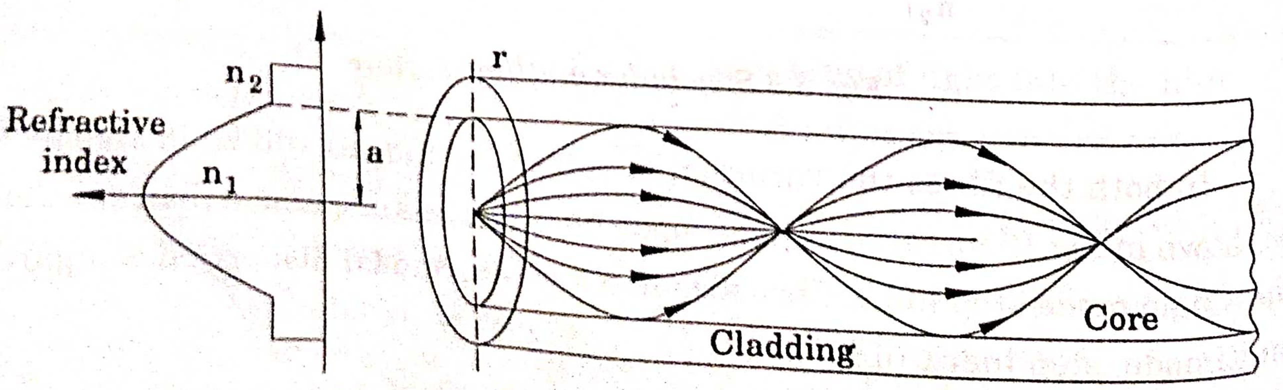


Fig. 3.10 Graded index multimode fibre

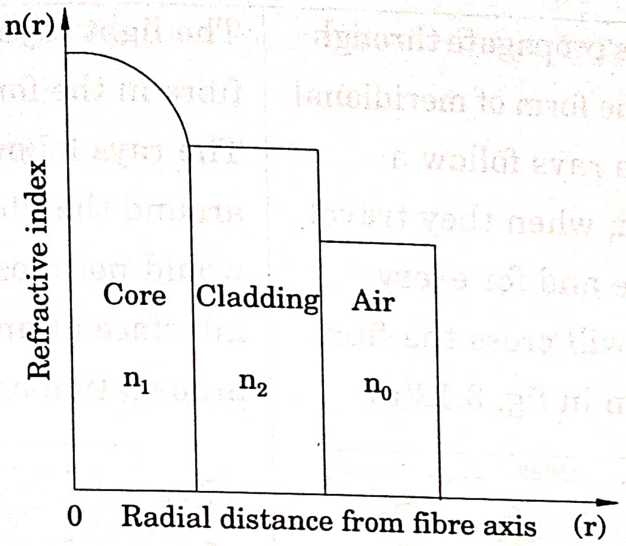


Fig. 3.11 Refractive index profile of a graded index fibre

3.9 DIFFERENCE BETWEEN STEP INDEX FIBRE AND GRADED INDEX FIBRE

S.No.	STEP INDEX FIBRE	GRADED INDEX FIBRE
1.	Since there is an abrupt change in the refractive index at the core and cladding interface, the refractive index profile takes the shape of step. Hence, called step index fibre.	In this fibre, the refractive index of the core is maximum at the centre and decreases gradually (parabolic manner) with distance towards the outer edge. Hence, called graded index fibre.
2.	Attenuation is less for single mode step index fibre and more for multi mode step index fibre.	Attenuation is less.
3.	Number of modes of propagation for a multimode step index fibre is given by $N_{step} = \frac{4.9\,(d \times NA)^2}{(\lambda)^2}$ where d is the diameter of the core, λ is optical wavelength and NA is numerical aperture.	Number of modes of propagation for a multimode graded index fibre is given by $N_{graded} = \frac{4.9 \times (d \times NA)^2/(\lambda)^2}{2}$ i.e., $N_{graded} = \frac{N_{step}}{2}$ Thus, the number of modes is half the number supported by a multimode step index fibre.

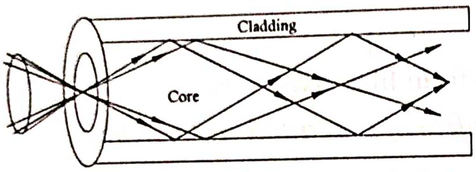
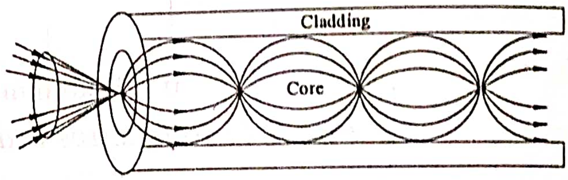
4.	The light rays propagate through the fibre in the form of meridional rays, i.e., the rays follow a zig- zag path, when they travel through fibre and for every reflection it will cross the fibre axis as shown in fig. 3.12(a)  *Fig. 3.12 (a)*	The light rays propagate through fibre in the form of skew rays. i.e., The rays follow a helical path around the fibre axis, and they would not cross the core-cladding interface at any time during their propagation as shown in fig. 3.12(b).  *Fig. 3.12 (b)*
5.	Single mode step index fibres are expensive and difficult to manufacture. But, multimode step index fibres are inexpensive and simple to manufacture.	Graded index fibres are easy to manufacture.
6.	The bandwidth for single mode step index fibre is more than multimode step index fibre.	Multimode graded index fibre has higher band width.
7.	Numerical aperture is very less for singlemode step index fibre but is more for multimode step index fibre.	Numerical aperture is high.

Table 3.2 Comparison between step index and graded index fibre

3.10 FABRICATION OF FIBRE

Many techniques are available for the fabrication of optical fibre. They are

i. Crucible-crucible technique (Double crucible technique)

ii. Drying method

iii. Vapour phase oxidation technique

iv. Vapour axial deposition technique

(ii) Fusion splicing

In the fusion splicing method, the fusion splicing is accomplished by applying localized heating techniques such as flame or electric arc at the interface between two butted prealigned fibre ends causing them to soften and fuse. Fibres are aligned using a mechanical fixture equipped with a small microscope. Micropositioners are used to physically move the fibres into position under visual inspection. Once aligned an electric discharge is struck across the two fibre ends, which melt in the heat generated. As they come in contact, surface tension forces help for their self-alignment. An average loss per splice of 0.1 dB or less can be obtained for well-matched fibres. Fusion eliminates reflection at the interface and if done properly results in a strong permanent connection. Fig.(3.15).

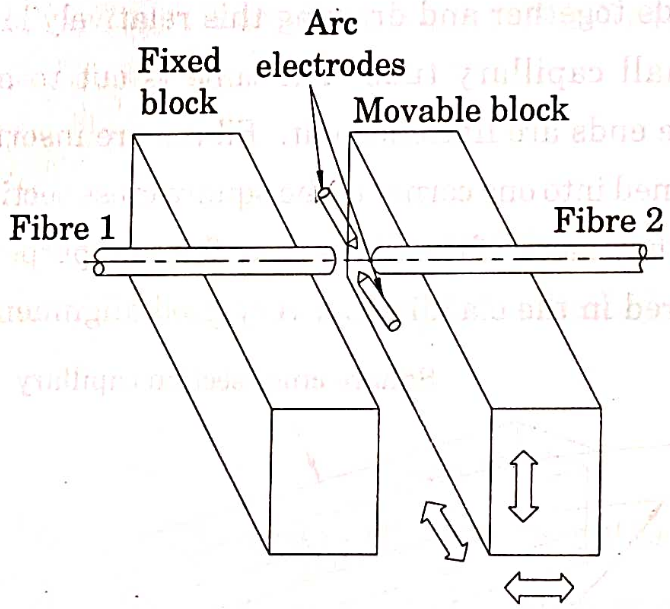


Fig. 3.15 Fusion splicing

3.12 LOSSES IN OPTICAL FIBRE

When light propagates through an optical fibre, a small percentage of light is lost through different mechanisms. Hence the two factors which affect the transmission of light waves in optical fibres are

i. Attenuation

ii. Dispersion

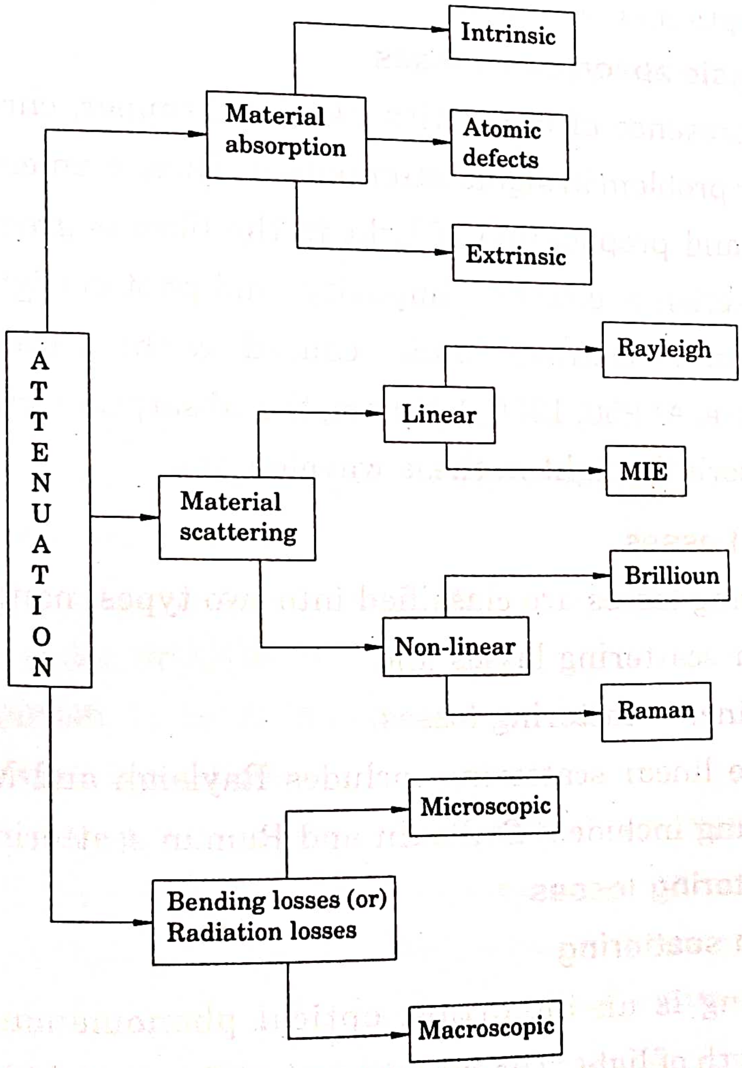
3.12.1 Attenuation

It is defined as the ratio of the optical power output (P_{out}) from a fibre of length "L" to the power input (P_{in}).

$$\text{Attenuation } \alpha = \frac{-10}{L} \log \left[\frac{P_{out}}{P_{in}}\right] \text{ dB/Km}$$

There are three mechanisms that can be attributed to attenuation.

i. Absorption losses
ii. Scattering losses
iii. Radiation or bending losses.



(i) Absorption Losses

Material absorption is a loss mechanism related to material composition. It greatly depends on wavelength of light used. The absorption of light may be of three categories namely,

a. Intrinsic absorption
b. Atomic defect
c. Extrinsic absorption

a. Intrinsic absorption

An absolute pure optical fibre has little intrinsic absorption due to its basic material structure. This absorption cannot be avoided.

b. Absorption by atomic defect

This absorption caused due to inhomogenity of materials like missing molecule, high density clusters of atoms or oxygen defects. This absorption is negligible.

c. Extrinsic absorption losses

The presence of impurities like iron, copper, chromium etc., is the major problem in signal attenuation. These elements contaminate the fibre and propagation of light in the fibre is greatly affected due to interaction of electron (impurity) and photon (light).

Extrinsic loss mechanism is also caused by the presence of hydroxyl or OH^- ions in the fibre. At 950, 1250, 1380 nm, the absorption increases drastically. Hydroxyl ions absorb the light in these wavelengths.

(ii) Scattering Losses

The scattering losses are classified into two types, namely

a. Linear scattering losses and

b. Non-linear scattering losses.

Further, the linear scattering includes Rayleigh and Mie scattering and non-linear scattering includes Brillouin and Raman scattering.

a. Linear scattering losses

i. Rayleigh scattering

Scattering is an important optical phenomenon and depends on wavelength of light. The inhomogenity of material like refractive index fluctuation and compositional variation will cause an attenuation called Rayliegh scattering.

According to Rayleigh scattering, loss is inversely proportional to the fourth power of the wavelength and is given by

$$\text{Attenuation} \;\; \alpha \;\; \frac{1}{\lambda^4}$$

This scattering loss can be reduced by operating at the longest possible wavelength.

ii. **Mie scattering**

The imperfections of fibre such as irregularities in the core-cladding interface, core-cladding refractive index differences, strains and bubbles will cause Mie scattering can cause significant loss.

b. **Non - linear scattering losses**

The Brillouin scattering may be regarded as the modulation of light through thermal molecular vibrations with in fibre. In this scattering process, the incident photon produces a photon of frequency 'v' called acoustic frequency. This produces as optical frequency shift causing loss in transmission.

c. **Stimulated Raman scattering**

Like Brillouin scattering, stimulated Raman scattering produces high frequency optical photon rather than an acoustic photon. The magnitude of loss is greater than Brillioun scattering.

These non-linear scattering losses can be reduced to minimum by using a optical signal level (less than threshold optical power).

(iii) **Radiation or bending losses**

Radiation loss occurs in fibres due to bending of finite radius of curvature in optical fibres. The radiation losses are two types.

a. Macroscopic bend loss b. Microscopic bend loss

a. **Macroscopic bend loss**

If the radius of core is large compared to fibre diameter, as shown in Fig.(3.16). In this type of bend having 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 losses.

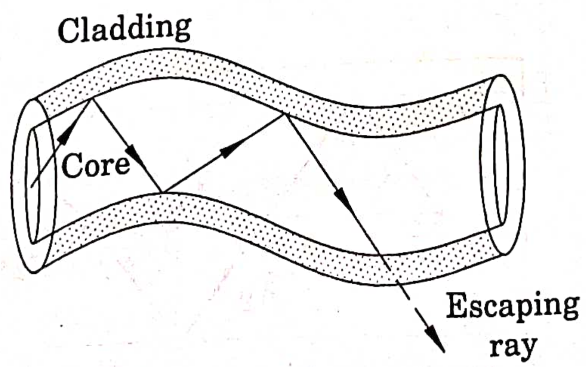


Fig. 3.16. Macroscopic bend

b. Microscopic bend loss

Micro-bend losses are caused due to micro-bends inside the fibre as shown in Fig. (3.17). This micro bends in fibre appears due to non uniform pressures created during the fabrication of the fibre.

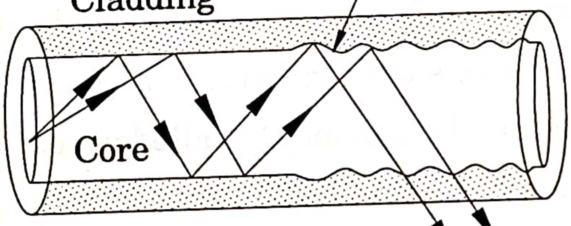


Fig. 3.17. Microscopic bend

Micro-bend losses can be minimised by extruding 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.

3.12.2 Dispersion losses

When an optical signal (or) pulse is sent into the fibre the pulse spreads (or) broaden as it propagates through the fibre. This phenomenon is called dispersion.

The dispersion losses are of three types, namely,

i. Modal dispersion
ii. Material dispersion and
iii. Wave guide dispersion

i. Modal dispersion

Modal dispersion occurs in fibres that have more than one mode of propagation.

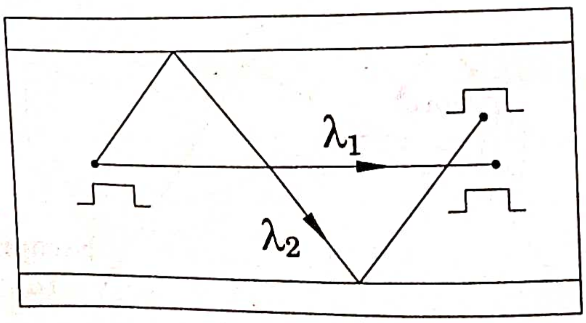


Fig. 3.18 Modal dispersion

When light ray travels through the fibre with all possible modes differing in the path line (i.e) some rays will reach the core end before the another. The information transmitted is stretched out. If the pulse stretch is much, they begin to overlap with each other and may reach a point with a time difference.

ii. Material dispersion

Material dispersion occurs due to the variation of refractive index of the material and wavelength of the light used.

The change in signal is due to the fact that different wavelengths travel at different speeds. Which inturn depends upon the refractive index of the material through which the light is transmitted as shown in Fig. (3.19).

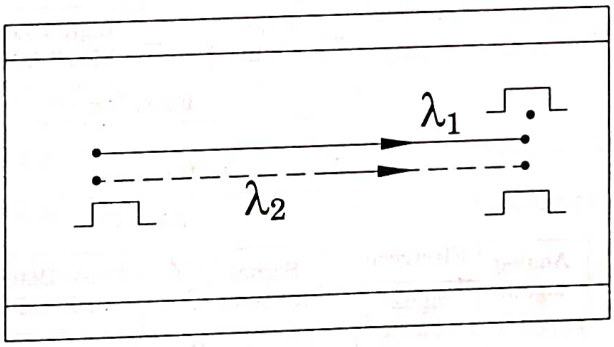


Fig. 3.19. Material dispersion

iii. Wave guide dispersion

Wave guide dispersion occurs only in the fibres with single mode.

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.

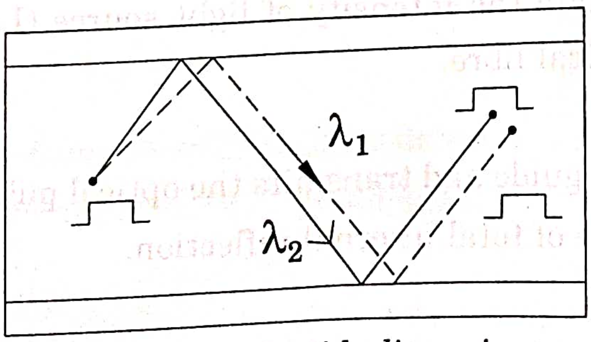


Fig. 3.20 Wave guide dispersions

Among the three dispersions

Intermodal dispersion > Material dispersion > Wave guide dispersion

3.13 FIBRE OPTICAL COMMUNICATION SYSTEM

An optical fibre communication system consists of three important parts

i) Transmitter,

ii) Optical fibre,

iii) Receiver

as shown in Fig. (3.21).

a. Information signal source

The information signal source may be voice, music, video signals etc, which is in the analog form to be transmitted, is converted from Analog signal to electrical signal.

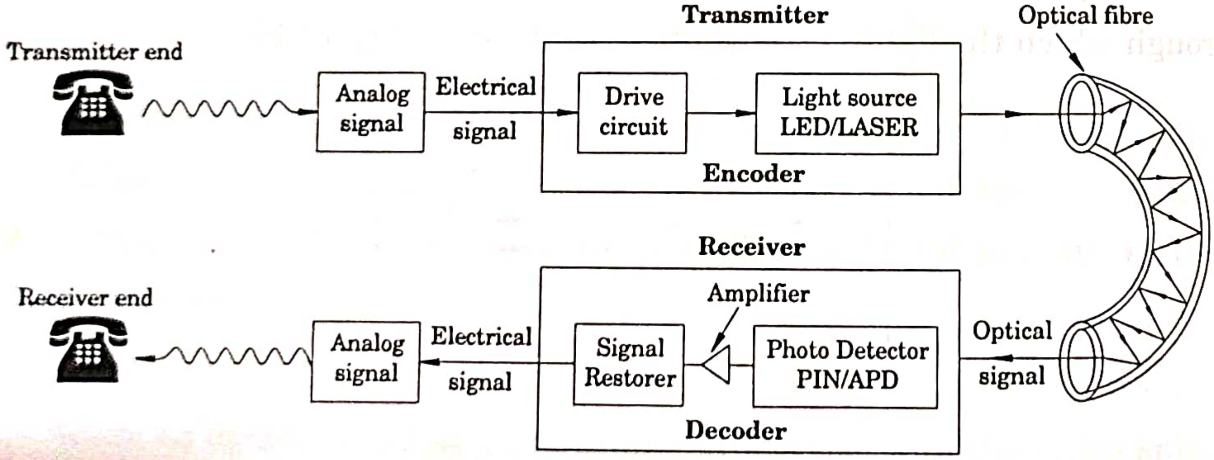


Fig. 3.21 Fibre optical communication system

b. Transmitter

The transmitter consists of a drive circuit and a light source. The drive circuit converts the electric input signal into digital pulses and the light source converts that into optical pulses. The light source usually used is LED. Here the electric pulses modulate the intensity of light source (Laser (or) LED) and are focussed onto the optical fibre.

c. Optical fibre

It acts as a waveguide and transmits the optical pulses towards the receiver based on the principle of total internal reflection.

d. Receiver

The photo detector is a receiver which receives the optical pulses and converts it into electrical pulses. Further the signals are amplified by an amplifier. These electrical signals are decoded (i.e.) converted from digital to analog signals. Thus the original electrical signal is obtained in analog form, with the same information.

* *Light rays propagate through the fibre either as meridional rays or skew rays.*
* *Double - crucible technique is used to produce step index optical fibre.*
* *LED and laser diode are commonly used as light sources for fibre optics.*
* *Photodetector is a device used to convert the light signals to electrical signals at the receiver end of the fibre link.*
* *The light signal transmitting through the fibre is degraded by two mechanisms namely attenuation and dispersion.*
* *Fibre optic sensors have high accuracy, high sensitivity and small size.*
* *Fibre endoscope is used to study the interior parts of the human body.*

SOLVED PROBLEMS

1. **A Silica optical fiber has a core refractive index of 1.50 and a cladding refractive index of 1.47. Determine (a) the critical angle at the core cladding interface (b)the N.A. of the fiber and (c) the acceptance angle in the air for the fiber.**

Given data

Refractive index of the core $n_1 = 1.50$ of the cladding $n_2 = 1.47$

Solution

The critical angle, $\theta_c = \sin^{-1} \frac{n_2}{n_1}$

$= \sin^{-1} \frac{1.47}{1.50}$

$= 78.52^o$

The numerical aperture

N.A. $= (n_1^2 - n_2^2)^{1/2}$

$= (1.50^2 - 1.47^2)^{1/2} = 0.30$

The acceptance angle in air,

$\theta_a = \sin^{-1}$ N.A.

$= 17.45^o$

2. **Calculate the total number of guided modes propagating in a multi mode step index fiber having a diameter of 50μm and numerical aperture of 0.2 and operating at the wavelength of 1 μm.**

Given data

Diameter of the fiber d = 50 μm = 50×10^{-6} m

Numerical aperture = 0.2

Wavelength of operation λ = 1 μm = 1×10^{-6} m.

Solution

$$N = 4.9\frac{(d \times N.A.)^2}{(\lambda)^2} = 4.9\frac{(50 \times 10^{-6} \times 0.2)^2}{(1 \times 10^{-6})^2} = 490$$

Hence the fiber can support approximately 490 guided modes. In this case of graded index fiber, the number of modes propagated inside the fiber = $(N_{step}/2)$ = 245 only.

3. **An optical fiber has an acceptance angle of 30° and a core refractive index of 1.4. Calculate the refractive index of cladding.**

Given data

Refractive index of the core n_1 = 1.4.

Acceptance angle θ_a = 30°

Refractive index of the cladding n_2 = ?

Solution

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

$$\sin^2\theta_a = n_1^2 - n_2^2$$

$$\text{(or)} \quad n_2^2 = n_1^2 - \sin^2\theta_a$$

$$= (1.4)^2 - \sin^2 30°$$

$$= 1.96 - 0.25$$

$$n_2^2 = 1.71$$

$$n_2 = \sqrt{1.71}$$

$$= 1.3$$

4. An optical fiber has a NA of 0.20 and cladding refractive index of 1.59. Determine refractive index of the core and the acceptance angle for the fiber in water which has a refractive index of 1.33.

Given data

Numerical Aperture NA = 0.20

Refractive index of the cladding = 1.59

Refractive index of water = 1.33

Solution

$$NA = \frac{\sqrt{n_1^2 - n_2^2}}{n_{air}} = (0.20)$$

$$= n_1^2 - n_2^2 = (0.20)^2$$

or $$n_1^2 = (0.20)^2 + n_2^2$$

$$n_1 = \sqrt{(0.20)^2 + n_2^2}$$

$$= \sqrt{(0.20)^2 + (1.59)^2}$$

$$= \sqrt{0.04 + 2.5281}$$

$$= \sqrt{2.5681}$$

$$n_1 = 1.6025$$

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

$$= \frac{\sqrt{(1.6025)^2 - (1.59)^2}}{1.33} = 0.1502$$

Acceptance angle = $\theta_a = \sin^{-1}(NA) = \sin^{-1}(0.15)$

$$\theta_a = 8.6^\circ$$

5. The core and the cladding of a silica optical fiber have refractive indices of 1.5 and 1.4 respectively. (i) Calculate the critical angle of reflection for the core-cladding interface. (ii) Calculate the acceptance angle of fiber.

Given Data

The refractive index of the silica core $n_1 = 1.5$

The refractive index of the cladding $n_2 = 1.4$

Solution:

Critical angle of core-cladding interface

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

$$= \text{sin-1 } (0.9333)$$

$$\theta_c = 69^\circ 34'$$

(ii) Acceptance angle $\theta_a = \sin^{-1}\left[n_1^2 - n_2^2\right]^{1/2}$

$$= \sin^{-1}\left[(1.5)^2 - (1.4)^2\right]^{1/2}$$

$$= \sin^{-1}[0.538]$$

$$\theta_a = 32.5^o$$

6. **A fiber has a diameter of 6μm and its core refractive index is 1.47 and for cladding it is 1.43. How many modes can propagate into the fiber, if the wave length of the laser source is 1.5 μm?**

Given data

Diameter of the fiber d = 6 μm = 6×10^{-6} m

Refractive index of core n_1 = 1.47

Refractive index of clodding n_2 = 1.43

Wavelength of light λ = 1.5 μm

= 1.5×10^{-6} m

Solution

We know,

$$N_{step} = 4.9\left(\frac{d \times NA}{\lambda}\right)^2$$

$$= 4.9\left(\frac{6 \times 10^{-6} \times NA}{1.5 \times 10^{-6}}\right)^2$$

Where,

$$NA = \sqrt{1.47^2 - 1.43^2}$$

$$= 0.34$$

$$N_{step} = 4.9\left(\frac{6 \times 10^{-6} \times 0.34}{1.5 \times 10^{-6}}\right)^2 = \frac{2.04 \times 10^{-6}}{1.5 \times 10^{-6}} \times 4.9$$

$$= 9.06$$

$$N_{step} = 9 \text{ modes}$$

Therefore no. of total modes = 9

7. **A step - index fiber has a numerical aperture of 0.26, a core refractive index of 1.5 and a core diameter of 100μm calculate,**

   a. The refractive index of the cladding

   b. The acceptance angle θa

   c. The maximum number of modes with a wave length of 1μm that the fiber can carry.

Given data

Numerical aperture NA = 0.26

Refractive index of core n_1 = 1.5

Diameter of the core = 100 μm = 100×10^{-6} m

Wavelength λ = 1 μm = 1×10^{-6} m

Solution

a. Refractive index of cladding

we know
$$NA = \sqrt{n_1^2 - n_2^2}$$
$$0.26 = \sqrt{1.5^2 - n_2^2}$$
$$0.0676 = 1.5^2 - n_2^2$$

Therefore refractive index of cladding
$$n_2 = 1.4772$$

b. The acceptance angle

From
$$\sin\theta_a = \frac{NA}{n_0} = \frac{0.26}{1}$$

Therefore the acceptance angle $\theta_a = 15.07^{o}$

c. The maximum number of modes

For a step index fiber
$$N_{step} = 4.9 \frac{(d \times NA)^2}{(\lambda)^2}$$
$$N = 4.9 \frac{(100 \times 10^{-6} \times 0.26)^2}{(1 \times 10^{-6})^2}$$
$$= 3312.4$$

Therefore, The step index fiber allows 3312 modes to propagate through it.

8. **Calculate the value of fractional index change of an optical fibre of core with refractive index 1.25 and cladding with 1.2.**

Given Data

Refractive index of core $n_1 = 1.25$

Refractive index of cladding $n_2 = 1.2$

Solution

$$\text{Fractional index change } \Delta = \frac{n_1 - n_2}{n_1}$$

$$= \frac{1.25 - 1.2}{1.25}$$

$$\Delta = 0.0392$$

Fractional index change $\Delta = 0.0392$

EXERCISE PROBLEMS

1. Suppose a fiber has a diameter of 5μm and its core refractive index = 1.450 and cladding refractive index = 1.447. If the wavelength of propagation is 1μm, how many modes can be propagated inside the fiber? **(Ans : 1.0646)**

2. The relative refractive index difference for an optical fiber is 0.05. If the entrance end of fiber is facing the air medium and refractive index of core is 1.46, estimate its numerical aperture. **(Ans : 0.4617)**

3. Find the numerical aperture and acceptance angle of an optical fiber with a refractive index of the core 1.546 and the refractive index of cladding 1.40.

   (Ans : NA = 0.6558 ; θ_a = 40.98°)

4. A step-indexed optical fiber has a numerical aperture of 0.16 and a core refractive index of 1.450. Find the refractive index of the cladding. **(Ans : n_2 = 1.441)**

5. Find the numerical aperture of the fiber, if the core index is 1.46 and also calculate the critical angle. Given that the refractive index difference of the optical fiber is 0.02. **(Ans : NA = 0.292 ; θ_c78°52')**

PART – A QUESTIONS & ANSWERS

1. Give four applications of fibre optic sensors.

- Fibre optic sensors are used as optical displacement sensors, which are used to find the displacement of a target along with its position.
- It is used as fluid level detector.
- It is used to sense the pressure, temperature etc., at any environment.
- It is also used to measure the number of rotations of the fibre coil using the instrument called as Gyroscope.

2. Explain the basic principle of fibre optic communication.

Total internal reflection is the principle of fibre optic communication.

Principle : When light travels from a denser to a rarer medium, at a particular angle of incidence called critical angle, the ray emerges along the surface of separation. When the angle of incidence exceeds the critical angle, the incident ray is reflected in the same medium and this phenomenon is called total internal reflection.

3. What are the conditions to be satisfied for total internal reflection?

Light should travel from denser medium to rarer medium.

The angle of incidence (ϕ) on core should be greater than the critical angle (ϕ_c).i.e. $\phi > \phi_c$ The refractive index of the core (n_1) should be greater than the refractive index of the cladding (n_2). i.e. $n_1 > n_2$

4. Define numerical aperture.

Numerical aperture determines the light gathering ability of the fibre. It is a measure of the amount of light that can be accepted by a fibre.

Numerical aperture (NA) can also be defined as the sine of the acceptance angle (θ_a). if n_1 and n_2 are the refractive index of the core and cladding respectively. Then

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

5. Define acceptance angle.

Acceptance angle is the maximum angle to the axis at which light may enter into the fibre so that it can have total internal reflection inside the fibre.

6. **Distinguish between step-index and graded index fibres.**

S.No	Step-index fibre	Graded index fibre
1	The difference in refractive indices between the core and the cladding is obtained in a single step and hence called as step-index fibre.	Due to non-uniform refractive indices between the core and the cladding refractive index garadually increases from centre towards interface and hence called graded -index fibre.
2	The light rays propagate as meridinal rays and pass through fibre axis.	The light rays propagation is in the form of skew rays and does not cross the fibre axis.
3	It follows a Zig-Zag path of light propagation	It follows a Helical path(i.e.spiral manner) of light propagation
4	It has a low bandwidth.	It has a high bandwidth.
5	Distortion is more in multimode step-index fibre.	Distortion is very less and is atmost zero due to self focusing effect.

7. **What is meant by fractional index change? What is the relation between fractional index change and numerical aperture?**

Fractional index change is the ratio of refractive index difference between the core (n_1) and the cladding (n_2) to the refractive index of core.

(i.e.) $$\Delta = \frac{n_1 - n_2}{n_1}$$

The relation between NA and $\Delta$is given by $NA = n_1\sqrt{2\Delta}$

8. **How will you classify optical fibres?**

Optical fibres are classified into three major categories based on

i) Material ii) number of modes iii) refractive index profile.

Based on the material it can be classified into

a) Glass fibre b) Plastic fibre

Based of number of modes they are classified as

a) Single mode fibre b) Multi mode fibre

Based on refractive index profile they can be classified as.

a) Step-index fibre b) Graded index (GRIN) fibre

9. Differentiate between single mode and multimode fiber.

S.No	Single mode fibre	Multimode fibre
1	In single mode fibre only one mode can be propagated.	The fibre in this case allows large number of modes of light to propagate through it.
2	The single mode fibre has a smaller core diameter and difference in refractive index of core and cladding is small.	Here, since the core diameter is large, the core and cladding refractive index difference is also large.

10. Mention the advantages of optical fibre communication over radio wave communication.

- Optical communication can be made even in the absence of electricity.
- The optical signals are not affected by any electrical signals or lightening.
- Optical fibre communication of free from Electromagnetic interference (EMI) and this type of communication is suitable to any environmental conditions.
- Easy maintenance, longer life, economical and high quality signal transmission are the additional features of optical fibre communication.
- Wider bandwidth, so large number of signals can be transmitted simultaneously.

11. What is meant by splicing.

Splicing is the technique used to connect the fibers. In this technique two fibers can be joined with the help of an elastomer (or) four rod splices, using an adhesive (or) matching gel.

12. What are the losses that occurs during optical fiber communication.

During the transmission of light through the optical fiber, three major losses will occur, viz., attenuation, distorsion and dispersion.

Attenuation is mainly caused due to the absorption, scattering and radiation of light inside the fibers.

Distortion and dispersion occurs due to spreading of light and also due to manufacturing defects.

13. What is meant by attenuation ?

It is defined as the ratio of the optical power output (P_{out}) from a fiber of length 'L' to the power input (P_{in}).

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

14. Mention any two fiber optic sources ?

(i) **Light emitting diode (LED)** – In LED's we have two types, viz., (1) Planar and (2) Dome shaped LED

(ii) **Laser diodes (LD)** – In laser diodes we have many types, in which homojunction, heterojunction laser, injection laser diode etc. are widely used a fiber optic sources.

15. What is meant by injection luminescence. Give example.

When the majority carriers are injected from p to n and n to p region, they become excess minority carriers. Then these excess minority carriers diffuses away from the junction and recombines with the majority carriers in p and n regions and emits light. This phenomenon is known as injection luminescence.

Example : Light Emitting Diode (LED).

(ii) Extrinsic sensors - here separate sensing system collects the light from the fibre.

21. Give any two applications of optical fibres in industries.

1. Fibre optic endoscopes are used to find minor cracks, pores etc. in big machinaries.
2. They are used in coagulation in chemical industries and laboratories.
3. It is also used to connect a monitoring station and a remote sensor in industries.

22. State some of the applications of optical fibres in medical field.

1. Fibre optic endoscopes are used in medical diagnosis.
2. It is used to visualize the inner organs of the body.
3. Fibres as endoscopes are used in various medical fields such as cardioscopy, laproscopy, cytoscopy etc.

23. What is meant by endoscope ?

A medical endoscope is a tubular optical instrument, used to inspect (or) view the internal parts of human body which are not visible to the naked eye. The photograph of the internal parts can also be taken using endoscope.

PART - B QUESTIONS

1. Describe the basic phenomenon in an optical fibre. Derive the expression for acceptance angle and numerical aperture.
2. Explain the propagation of light through optical fibre and the applications of optical fibre as wave guide and sensor.
3. What are the different units of fibre optic communication system? Explain their functions.
4. Define total internal reflection? Arrive the condition for total internal reflection in an optical fibre.