4.1. INTRODUCTION

It is observed that light signals can travel along very fine flexible glass rods roughly the same diameter as a human hair known as optical fibre. Optical fibres, as they are called, are replacing the copper cables previously used for communication means. The typical diameters of optical fibre ranges from 0.05 mm to 0.25 mm. The glass or silica used, has to be highly pure to minimize attenuation. In principle, there is no limit on the length and in fact it can be several kilometers as fibre joining techniques have reached a very high level of perfectness. We know that the propagation of light along a waveguide can be described in terms of a set of guided electromagnetic waves known as modes of the waveguide. These modes are also referred to as trapped modes. Each guided mode is a pattern of electric and magnetic field lines that is repeated along the fibre at intervals equal to the wavelength. The propagation of light in fibre is similar to that in a waveguide (see article 1.27). Reflection in case of waveguides was obtained by the waveguide walls which were made of conducting material, whereas here the reflection is obtained by total internal reflection at the glass boundary, even if the fibre is bent or twisted.

The light waves used, lie in the infrared region with typical wavelength of the order of 0.9 μm. At this wavelength, fibre losses are very low, besides lasers, photodiodes are ready for operation on this wavelength 0.9 μm corresponds to frequency of 330 THz. Just imagine the splended broadband system that can be designed using this frequency. In a typical fibre optic communication system, it is possible to send more than 140 megabytes per second through a 250 km link of a single optical fibre, which corresponds to approximately 450000 voice channel, a fantastic achievement.

4.1.1. Fibre Types

There are many different types of solid optical fibres so far but the most widely accepted structures is the single solid dielectric cylinder of radius ‘a’ and index of refraction $n_1$ shown in Fig. 4.1. This cylinder is known as the core of the fibre. The core is surrounded by a similar material but of lower refractive index $n_2$ (i.e., $n_2 < n_1$), known as cladding. Although in principle, a cladding is not necessary for light to propagate along the core of the fibre, it serves several purposes:

(a) The cladding reduces scattering loss resulting from dielectric discontinuities at the core surface,

In 1870, a British physicist John Tyndall demonstrated the phenomenon of transmission of light through glass fiber.
(b) it adds mechanical strength to the fibre, and
(c) it protects the core from absorbing surface contaminants with which it could come in contact.

The whole assembly is encapsulating in a plastic buffer known as buffer coating. This adds further strength to the fibre and mechanically isolates the fibres from small geometrical irregularities, distortions or roughnesses of adjacent surfaces. These perturbations could otherwise cause scattering losses induced by random microscopic bends that can arise when the fibres are incorporated into cables or supported by other structures.

![Fiber Cross Section and Ray Paths]

**Fig. 4.2.** Comparison of single-mode and multi-mode optical fibers.

On the basis of variations in material composition of the core, the fibres are classified into two main types as shown in Fig. 4.2.

(i) The monomode fibre has a very narrow core of diameter about 8 – 12 μm or less, so the cladding is relatively big ~125 μm. As the name implies, monomode fibre sustains only one mode of propagation, that is why it is also known as single mode fibre.

(ii) The multimode fibre has a core of relatively large diameter such as 50–200 μm. In one form of multimode fibre the core has a uniform refractive index $n_1$ from its centre to the boundary with the cladding. The refractive index then undergoes an abrupt change to a lower value $n_2$ which remains constant throughout the cladding. This is called a step index fibre in the sense that refractive index ‘steps’ from $n_1$ to $n_2$ at the boundary with the cladding. In single mode fibre, the refractive index of core and cladding also
varies in the step manner, so these are also known as single mode step index fibre. In the second form of multimode fibre, the core refractive index is made to vary as a function of the radial distance from the centre of the fibre. This type is a graded-index fibre.

As the name suggests the multimode fibres contain many modes of propagation. The larger core radii of multimode fibres make it easier to launch optical power into the fibre and facilitate the connecting together of similar fibres. Also, light can be launched into a multimode fibre using a light emitting diode (LED) source, whereas single-mode must generally be excited with laser diodes.

4.1.2. Fibre Structure: Index Difference

In practical step-index fibres, the core of radius ‘a’ has a refractive index $n_1$, which is typically equal to 1.48. This is surrounded by a cladding of a lightly lower index $n_2$, with $n_2 = n_1 (1 - \Delta)$; where $\Delta = \frac{n_1 - n_2}{n_1}$ is called the core-cladding index difference or index difference. Values of $n_2$ are chosen such that $\Delta$ is nominally 0.01. Since the core refractive index is larger than the cladding index, electromagnetic energy at optical frequencies is made to propagate along the fibre waveguide through internal reflection at the core-cladding interface.

In case of graded-index fibre, the core refractive index decreases continuously with increasing radial distance ‘r’ from the center of the fibre but is generally constant in the cladding. The most commonly used construction for the refractive index variation in the core is the power law

$$n(r) = n_1 \left[1 - 2\Delta \left(\frac{r}{a}\right)^{\alpha_1}\right]^{1/2}$$

for $0 \leq r < a$

$$= n_1(1 - 2\Delta)^{1/2} = n_1(1 - \Delta) = n_2$$

for $r \geq a$

Here ‘r’ is the radial distance from the fibre axis, ‘a’ is the core radius, $n_1$ is the refractive index at the core axis, $n_2$ is the refractive index of the cladding and $\alpha_1$ the dimensionless parameter, defines the shape of the index profile. Above equation is a convenient method of expressing the refractive index profile of the fibre core, as a variation of $\alpha_1$ allows representation of the step index profile when $\alpha_1 = \infty$, a parabolic when $\alpha_1 = 2$ and a triangular profile for $\alpha_1 = 1$. This range of refractive index profiles is illustrated in Fig. 4.3. The index difference $\Delta$ for the graded index fibre is given by

![Fig. 4.3. Fibre refractive index profiles for different values of $\alpha_1$.](image-url)
\[ \Delta = \frac{n_1^2 - n_2^2}{2n_1^2} = \frac{(n_1 - n_2)(n_1 + n_2)}{2n_1^2} = \frac{n_1 - n_2}{n_1} \]

The approximation on the RHS of above equation reduces the expression for \( \Delta \) to that of the step-index fibre. Thus the same symbol is used in both cases.

### 4.1.3. Fibre Materials

In selecting materials for optical fibres, a number of following requirements must be satisfied:

1. It must be possible to make long, thin, flexible fibres from the material.
2. The material must be transparent at a particular optical wavelength in order for the fibre to guide light efficiently.
3. Physically compatible materials having slightly different refractive indices for the core and cladding must be available.

Materials satisfying these requirements are glasses and plastics. Three different combinations of materials are used to construct optical fibres. These are: (a) glass core and glass cladding, (b) glass core and plastic cladding, (c) plastic core and plastic cladding. The majority of fibres are made of glass consisting either of silica or a silicate. The variety of available glass fibres ranges from high loss glass fibres with large cores used for short-transmission distances to very transparent fibres employed in long-haul applications.

#### Fibres based on Silica

To produce two similar materials having slightly different indices of refraction for the core and cladding, either fluorine or various oxides such as \( \text{B}_2\text{O}_3 \), \( \text{GeO}_2 \) or \( \text{P}_2\text{O}_5 \) are added to the silica. It is observed that the addition of \( \text{GeO}_2 \) or \( \text{P}_2\text{O}_5 \) to the silica increases the refractive index whereas doping the silica with fluorine or \( \text{B}_2\text{O}_3 \) decreases it. Since the cladding must have a lower index than the core, examples of glass fibres compositions are:

(i) \( \text{GeO}_2 - \text{SiO}_2 \) core; \( \text{SiO}_2 \) cladding
(ii) \( \text{P}_2\text{O}_5 - \text{SiO}_2 \) core; \( \text{SiO}_2 \) cladding
(iii) \( \text{SiO}_2 \) core; \( \text{B}_2\text{O}_3 - \text{SiO}_2 \) cladding
(iv) \( \text{GeO}_2 - \text{B}_2\text{O}_3 - \text{SiO}_2 \) core; \( \text{B}_2\text{O}_3 - \text{SiO}_2 \) cladding

#### Fibres Based on Polymers

Plastic optical fibre (POF) is a low-cost, easy to use fibre optic solution for short distance applications like local area networks and provides high speed access to internet. These fibres have a diameter of around one millimetre, which is far larger than those of glass fibres (50 \( \mu \text{m} \) – 62 \( \mu \text{m} \)), that makes it easier to connect critical alignments. Plastic optical fibre is more secure than copper cables and allows for multitasking and multimedia applications that can be supported by copper cables at slower and less productive speeds.

1. A polystyrene core \( (n_1 = 1.60) \) and a PMMA \( (n_2 = 1.49) \) cladding,
2. A PMMA core \( (n_1 = 1.49) \) and a cladding made of its copolymer \( (n_2 = 1.40) \).

#### 4.1.4. Optical Fibre Cable [PTU 2007]

Optical fibre cables are fastly replacing existing electrical transmission lines and cables. These cables must be capable of installation and maintenance in all the environment. Therefore, when optical fibres are to be installed in a working environment, their mechanical properties are of importance. Unprotected optical
fibres cannot be used for normal transmission because of their brittle nature and smaller size. Thus it is necessary to cover the fibres to increase tensile strength and protect them against external forces. This is done by covering the fibre with series of protective layers known as cabling. Sometimes, coated and buffered fibre into an optical cable is used to increase its resistance to mechanical strain and environmental conditions. The function of optical cable may be briefed as:

(i) The main function is to protect optical fibre against damage and breakage during installation or service period.

(ii) Optical cables must have mechanical properties comparable to their electrical counterparts so that they can be handled in the same manner. The mechanical properties include tension, compression, bending, squeezing and vibration etc. Cable strength can be improved by using suitable strength member and by giving the cable a thick outer sheath.

(iii) The optical fibre cable must have stable transmission characteristics comparable with uncabled fibre. Optical attenuation due to cabling must be minimized.

(iv) Identification and joining of fibres within a cable should be easier. This is important for cables including a large number of optical fibres. If fibres are arranged in suitable geometry it may be possible to use multiple jointing technique.

In designing optical fibre cables, several types of fibre arrangements are possible and a large variety of components could be included in the construction. The simplest designs are one or two-fibre cable intended for indoor use. In a hypothetical two-fibre design shown in Fig. 4.4, a fibre is first coated with a buffer material and placed loosely in a tough, oriented polymer tube, such as polyethylene. For strength purposes this tube is surrounded by strands of aramid yarn which, in turn, is encapsulated in a polyurethane jacket. A final outer jacket of polyurethane, polyethylene, or nylon binds the two encapsulated fibre units together.

Larger cables can be created by stranding several basic fibre building blocks (as shown in Fig. 4.4) around a central strength member. This is illustrated in Fig. 4.5 for a nine-fibre cable. The fibre units are bound onto the strength member with paper or plastic binding tape, and then surrounded by an outer jacket.

![Diagram of a hypothetical two-fibre cable design.](image)

**Fig. 4.4.** A hypothetical two-fibre cable design. The basic building block on the left is identical to that shown for the right-hand fibre.

If repeaters are required along the route where the cable is to be installed, it may be advantageous to include wires within the cable structure for powering these repeaters. The wires can also be used for fault isolation or as an engineering order wire for voice communications during cable installation.
4.2. BASIC THEORY: LIGHT PROPAGATION IN FIBRES

4.2.1 Total Internal Reflection

The propagation of light signal within an optical fibre can be explained on the basis of ray theory model i.e. total internal reflection. We know that a ray of light travels more slowly in an optically dense medium than in one that is less dense. When a ray is incident on the boundary between two medium of different refractive indices, refraction occurs as shown in (Fig. 4.6(a)). If the medium on the other side of the boundary has refractive index \( n_2 \) which is less than \( n_1 \), then the refraction is such that the ray path in \( n_2 \) medium is at an angle \( \phi_2 \) to normal and \( \phi_2 > \phi_1 \). Using Snell’s law, we have

\[
n_1 \sin \phi_1 = n_2 \sin \phi_2
\]

In above discussion, a small amount of light is reflected back into the incident medium and is known as partial internal reflection. As we increase the angle of incidence \( \phi_1 \) at the boundary, the angle of refraction \( \phi_2 \) also increases. When \( \phi_2 \) becomes 90°, the refracted ray emerges parallel to the boundary (Fig. 4.6(b)). This is the limiting case of refraction and the angle of incidence is known as critical angle \( \phi_c \). Therefore, above equation becomes

\[
n_1 \sin \phi_c = n_2 \sin 90^\circ \quad \text{or} \quad \sin \phi_c = \frac{n_2}{n_1}
\]

At the angle of incidence greater than \( \phi_c \), the light is reflected back into the incident medium \( n_1 \). This type of reflection is known as total internal reflection (Fig. 4.6(c)). Hence, it is observed that the total internal reflection occurs at the boundary between two media of different refractive indices when light is incident on medium of lower refractive index from medium of higher refractive index, and the angle of incidence of the ray exceeds the critical value \( \phi_c \). This is the mechanism by which light ray propagates through the optical fibre.
4.2.2. Total Number of Internal Reflections

We shall now see what happens when a light signal enters one end of an optical fibre. Fig. 4.7 shows a step-index fibre with a large angle of incidence, a ray $AO$ entering one end at $O$ is refracted into the core along $OP$ and then refracted along $PQ$ in the cladding. At $Q$, the fibre surface, the ray passes into the air. In this case only a very small amount of light, due to reflection, passes along the fibre. With a smaller angle of incidence $\alpha$, however, a ray such as $BO$ is refracted in the core along $OD$ and meets the boundary between the core and cladding at an angle $\phi$ greater than critical angle $\phi_c$.

The ray $OD$ is now totally reflected at $D$ along $DE$, where it again meets the core-cladding boundary at the critical angle. At $E$, therefore, it is totally reflected along $EF$.

Now we will calculate the number of total internal reflections that a ray will occur in propagating through a length $L$ of the fibre with refracted ray making an angle $\theta$ with the fibre axis. Let us suppose that core radius of the fibre be ‘$a$’

\[
\frac{2a}{DE} = \sin \theta
\]

and

\[
\frac{2a}{EF} = \sin \theta
\]

(where $\theta = 90 - \phi$)
Which gives, \( DE + EF = \frac{4a}{\sin \theta} \) \hspace{1cm} \ldots(1)

Also \( DE = EF \)

and \( DE = \frac{DF}{2 \cos \theta} \) \hspace{1cm} \ldots(2)

From eqns. (1) and (2), we have

\[
\frac{DF}{2 \cos \theta} + \frac{DF}{2 \cos \theta} = \frac{4a}{\sin \theta}
\]

or

\[
\frac{DF}{\cos \theta} = \frac{4a}{\sin \theta}
\]

or

\[ L \tan \theta = 4a \] \hspace{1cm} \ldots(3)

In above derivation, we have seen that a ray suffers three reflections while traversing path DF through E. If we will consider number of reflections \( n \) when a ray propagate through a fibre of length \( L \), then we have from above relation

\[ L \tan \theta = (n + 1)a \]

or

\[ (n + 1) = \frac{L \tan \theta}{a} \] \hspace{1cm} \ldots(4)

4.2.3. Acceptance Angle

We know that only rays with an angle greater than critical angle \( \phi_c \) at the core-cladding interface are transmitted by total internal reflection. Thus, it is clear that not all rays entering the fibre core will continue to be propagated down its length. It may be observed that the ray enters the fibre core at an angle \( \alpha \) to the fibre axis and is refracted at the air-core interface before transmission to the core-cladding interface at the critical angle (Fig. 4.7). Hence, any ray which is incident into the fibre core at angle greater than \( \alpha \) will be transmitted to the core-cladding interface at an angle less than \( \phi_c \) and will not be totally reflected. This situation is illustrated in Fig. 4.7, where the incident ray \( A \) at an angle greater than \( \alpha \) is refracted into the cladding and eventually lost.

Thus, in multimode fibres, one important parameter is the angle over which the fibre will accept the light directed towards it. This angle is called the acceptance angle and is defined as the half angle of the cone within which the light is totally reflected by the fibre core. The acceptance cone of this angle is shown in Fig. 4.8.

The maximum angle of incidence in air for which all the light is totally reflected at the core-cladding fibre can be calculated as

\[ n_0 \sin \alpha = n_1 \sin (90^\circ - \phi_c) \] refraction from air to core

and

\[ n_1 \sin \phi_c = n_2 \sin 90^\circ = n_2 \] refraction from core to cladding

Here \( n_0 = 1 \) for air medium. Therefore, from above two equations, we have

\[ \sin \alpha = n_1 \cos \phi_c \] and \( \sin \phi_c = n_2 / n_1 \)

Since

\[ \sin^2 \phi_c + \cos^2 \phi_c = 1, \]

and we get

\[ \frac{n_2^2}{n_1^2} + \frac{\sin^2 \alpha}{n_1^2} = 1 \]
\[
\sin \alpha = \pm \sqrt{n_1^2 - n_2^2}
\]

or
\[
\alpha = \sin^{-1} \sqrt{n_1^2 - n_2^2}
\]...

(5)

for \(n_1 = 1.52\) and \(n_2 = 1.48\), we have \(\alpha = 20^\circ\). So an incident beam from air making an angle of incidence not more than \(20^\circ\) will be transmitted along the fibre with appreciable intensity for fibre with \(n_1 = 1.52\) and \(n_2 = 1.48\).

If light rays are entering from medium other than air i.e. \(n_o > 1\), then the above expression will become
\[
n_o \sin \alpha = \sqrt{n_1^2 - n_2^2}
\]

or
\[
\sin \alpha = \sqrt{n_1^2 - n_2^2}
\]

or
\[
\alpha = \sin^{-1} \sqrt{\frac{n_1^2 - n_2^2}{n_o^2}}
\]...

(6)

4.2.4 Numerical Aperture

[PTU 2006]

Step Index Optical Fibre

The light gathering ability of a fibre is related to its acceptance angle and is expressed as the numerical aperture (NA) of the fibre. The numerical aperture of a fibre can be expressed quantitatively as

\[
\text{Fig. 4.8}
\]

\[
\text{NA} = \sin \alpha = \sqrt{n_1^2 - n_2^2} \quad \text{or} \quad \alpha = \sin^{-1} \text{NA}
\]

where \(\alpha\) is the angle of acceptance.

If the optical fibre is placed in medium other than air i.e. \(n_o > 1\), then the above relation can be written as

\[
\text{NA} = \sin \alpha = \sqrt{\frac{n_1^2 - n_2^2}{n_o^2}}
\]...

(7)

Therefore, if \((\text{NA})_{\text{air}}\) is the numerical aperture measured in air for some optical fibre then the value of numerical aperture in any medium of refractive index \(n_o\) will be \(\frac{(\text{NA})_{\text{air}}}{n_o}\).

Now,
\[
n_1^2 - n_2^2 = (n_1 + n_2)(n_1 - n_2) = \left(\frac{n_1 + n_2}{2}\right)\left(\frac{n_1 - n_2}{n_1}\right)2n_1
\]

If we approximate \(\frac{n_1 + n_2}{2} = n_1\), then the above relation becomes
\[ n_1^2 - n_2^2 = 2n_1^2 \Delta \]

\[ \therefore \quad NA = \sqrt{2\Delta} n_1 \quad \ldots \quad (8) \]

Manufacturers do not usually specify the value for numerical aperture for the single mode fibres marketed by them since light in single mode fibres reflected or refracted and therefore, does not exit the fibre at an angle through cladding, is of the order of 0.2 to 0.6. The low value for the NA means a small acceptance angle, which in turn, indicates the use of laser source with single mode fibres.

Graded Index Optical Fiber

The numerical aperture discussed above is for a step index fibre in air. Although above equation for NA may be employed with graded index fibres, the numerical aperture thus defined represents only the local NA of the fibre on its core axis. The graded profile creates a multiple of local NAs as the refractive index changes radially from the core axis. For the general case of a graded index fibre these local numerical apertures \( NA(r) \) at different radial distance \( r \) from the core axis may be defined as

\[ NA(r) = \sin \alpha (r) = \left[ n_2^2 (r) - n_2^2 \right]^{1/2} \]

\[ = \sqrt{n_1^2 \left[ 1 - 2\Delta \left( \frac{r}{a} \right)^{\alpha_1} \right]} - n_2^2 = \sqrt{n_1^2 - n_2^2 - 2\Delta n_1^2 \left( \frac{r}{a} \right)^{\alpha_1}} \]

\[ = \sqrt{n_1^2 - n_2^2 \left[ 1 - \frac{2\Delta n_1^2}{n_1^2 - n_2^2} \left( \frac{r}{a} \right)^{\alpha_1} \right]}^{1/2} \]

\[ = NA(O) \sqrt{1 - \left( \frac{r}{a} \right)^{\alpha_1}} \quad \ldots \quad (9) \]

where the axial numerical aperture is defined as

\[ NA(O) = \sqrt{n_1^2 - n_2^2} = n_1 \sqrt{2\Delta} \]

It is clear that the NA of a graded-index fibre decreases from \( NA(O) \) to zero as \( r \) moves from the fibre axis to the core-cladding boundary.

Therefore, calculations of NA from refractive index data are likely to be less accurate for graded index fibres than for step index fibres unless the complete refractive index profile is considered. It has been observed that for graded index fibre the NA values are relatively small as compared to step index fibres (with large NA values) indicates that about half of the energy can be carried by a graded index fibre than step index fibre with the same core diameter.

4.2.5. Number of Modes (V-parameter or Normalized Frequency)

Since the path that a light wave follows as it propagates the core of an optical fibre is a function of its angle of incidence, the angle at which it strikes the core-cladding boundary, it follows that there are many paths through the core. These paths are called modes. Therefore, a mode is a path that a light wave can follow as it travels down the core of an optical fibre. The number of modes (\( N \)) for a step index fibre ranges from 1 to more than 10,000 and are given by