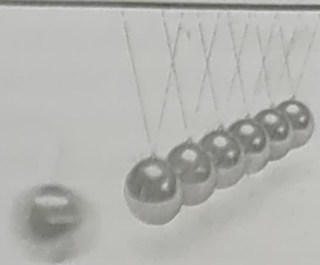
Unit-V

Section A



FIBRE OPTICS

Introduction

The advent of lasers sowed the seeds for the growth of entirely new crop of communication engineering the fibre optics or fibre communication optics. Prior to the introduction of fibre optics, in the conventional telecommunication systems the informations were transmitted through the electromagnetic waves which were propagated through transmission lines or waveguide structures having appropriate dimensions.

All our communications depend on the transmission of signals through carrier waves. When we make a telephone call to a friend at a distant place, a sound wave carries the message from our vocal cords to the telephone. There, an electrical signal is generated which propagates along the copper wire. If the distance is too large, the electrical signal generated may be transformed into the electromagnetic waves and transmitted through the atmosphere, possibly by way of a communication satellite.

The invention of optic fibre, as an alternative to electric and electronic, semi-conductor components, has wholly revolutionized the techniques of communication of information, even over very long distances, quite cheaply, but efficiently. The modern eagerness for telecommunications with carrier waves at optical frequencies of the electromagnetic system owes its origin to the discovery of laser. Earlier, before sixties, there were no suitable light sources available which could reliably used as the information carrier. On the other hand, around the same time telecommunication traffics were growing so rapidly that it was conceivable that conventional telecommunication system based on, say, coaxial cables, radio and microwave links could soon reach a saturation point.

Fast development in the field of communication in present time shows that the cost per unit information bandwidth is reduced considerably if a system is used in which each information carrier has a bandwidth capable of carrying simultaneously a large volume of communication traffic. This concept led to the development and introduction of microwave communication links. In fact, the amount of information carried by electromagnetic waves, having a frequency spectrum down to microwave region, is proportional to the frequency of the wave. A wave having a frequency of 100 can have 100 pulses at best, hence can transmit 100 pulse per second. Thus, the microwave communication and other traditional communications are unable to reduce such a heavy communication traffic.

In this fast growing world, electronics and computers are absolutely essential for human beings because they touch every aspect of our daily lives in some way or others. Bar code scanners read the prices of our grocery items, computers dispense money from automatic tellers. We can use personal computer for banking, real estate, accessing news and entertainment, and a hundred and one other functions that are an integral part of our daily life. This increase in electronic methods for manipulating, interpreting, and communicating informations have revealed the limits of traditional communication technologies such as copper wire and radiowaves. Optical fibres have been developed to overcome these disadvantages.

The invention of LASER and **Light Emitting Diodes** (LED) gave birth to the optical communication. A light beam acting as a carrier wave is capable of carrying far more informations than radiowaves and microwaves. In fact with optical communication in which light signals are used instead of electric signals, it is possible to transmit 44.7 million pulse per second. The optical waves provide such a large bandwidth that it becomes difficult to use it fully. Fibre optics is the overlap of applied science and engineering concerned with the design and application. Optical fibres are widely used in fibre optic communication which permits transmission over long distances. Fibres are used instead of metal wires because signal travel along them with low loss.

Fundamental Ideas about Optical Fibres

History

Guiding of light by the method of refraction, the principle that makes fibre optic possible, was first demonstrated by **Daniel Colladon** and **Jacques Babinet** in Paris 1840s, with Irish inventor **John Tyndall.** Fibre optic really developed in 1950s with the work of **Hopkins** and **Narendra Singh Kapany** in **UK** and **Van Heel** in Holland. These workers conducted experiments that led to the invention of optical fibre, based on **Tyndall** earlier studies. Modern optical fibres, where the glass fibre coated with a transparent cladding to offer a more suitable refractive index, appeared later in the decade. Development then focused on fibre bundles. First fibre optic semi-flexible gastroscope was patented by **Basil Hirschowitz, C. Wilbur Peter,** and **Lawrence E Curtiss,** researchers at the University of Michigan in 1956. In the process of developing gastroscope, **Curtiss** produced the first glass-clad fibres. Previous optical fibres had relied on air or impractical oils and waxes as the low index cladding material. In the right sense the actual evolution of fibre technology was taking place in the year 1960, after the successful invention of **semiconductor laser and the light emitting diodes (LEDs).** At that time the existing fibres had a loss even more than 1000 dB/km. In 1965, **Charles K. Kao** and **George A. Hockhman** of the British Company Standard telephones and cables were the first to suggest that the attenuation of contemporary fibres was caused by impurities, which could be removed, rather than fundamental physical effect such as scattering. They speculated that optical fibre could be practical medium for communication, if the attenuation could be reduced below 20 dB/km. This attenuation level was first achieved in 1970 by researcher **Robert D. Maurer et.al.** at Corning Glass Works, America, now Corning Inc. they demonstrated a fibre with 17 dB attenuation per kilometre by doping silica glass with titanium. A few years later they produced a fibre with only 4 dB/km using germanium oxide as the core dopant. Now-a-days, attenuation in optical fibre cables are far less than those in electrical copper cables. The more strong optical fibre commonly used today was invented by **Gerhard Bernsee** in 1973 by Schott Glass in Germany, they utilizes glass for both core and clad and is therefore less prone to aging process. Since then fibre technology has advanced to point of fabricating fibre with a loss less than 0.5 dB/km. Fibre fabricated with recently developed technology are characterised by extremely low losses (~0.2 dB/km) as a consequence of which the distance between two successive repeaters could as large as 250 km. In a recently developed fibre optic system it has been possible to send 140 M bit/sec information through 220 km link of one optical fibre; this is equivalent to about 450000 voice channel-km. Now it is possible for a typical single optical fibre with great bandwidth at infrared wavelengths to carry 200 million telephone channels or twenty thousand TV channels or some combination of both with an attenuation of only below 0.2 dB/km. With this fast and amazing progress in the advancement of optical fibre technology, it has not very long since the cost of the system came down considerably, enabling people throughout the world to seriously begin the switch over from copper cable to optical fibres. Indeed the British Telecom stopped laying copper wires on its long distance routes where communication traffic is very high and started using optical fibres. Optical fibres are also being extensively used for local area networks that wire up telephones, televisions, computers or robots in office and cities.

In 1991 the emerging field of photonic crystals led to the development of photonic crystals fibre, which guide light by means of diffraction from a periodic structure, rather than total internal reflection. The first photonic crystal fibre and their wavelength dependent properties can be manipulated to improve their performance in certain applications.

Optical Fibre

Optical fibres serve as cables to carry huge amount of informations in the form of optical signals from one place to another over a wide bandwidth with negligible loss. **An optical fibre is a hair-thin flexible transparent medium of cylindrical shape usually made of glass through which light can be propagated.** The optical fibre has three principal sections, such as (i) the core, (ii) the cladding, and (iii) the jacket.

The core is the innermost section of the fibre (Fig. 1) and has a remarkable property of conducting an optical beam. It is made of glass or plastic. The core, the actual working structure of the fibre, is covered with another layer of glass with slightly different chemical composition or plastic, called **cladding.** The cladding has optical properties very different from those of the core. The optical fibre may have a abrupt boundary between the core and cladding or there may be a gradual change in the material between the two. The outerm section of the fibre is called, the **jacket** and is made of plastic or special kind of polymer and o

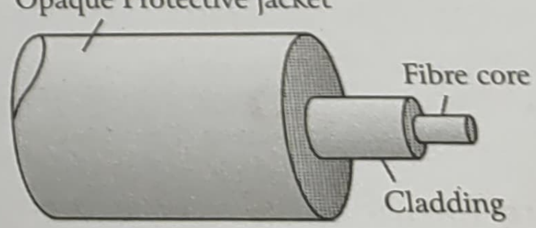
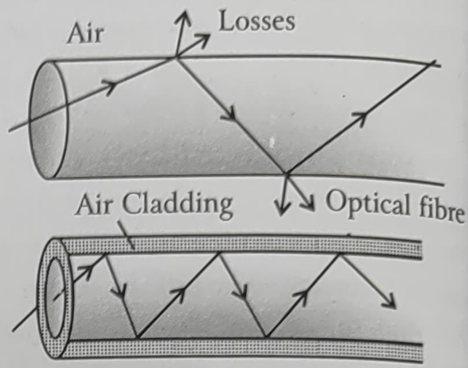


Fig.1

materials. The opaque protective jacket protects the core from abrasion, interaction with environment, moisture, absorption, crushing and other vagaries of the terrestrial atmosphere and thus enhances its tensile strength. In fact the humidity of a normal atmosphere causes micro-cracks on the fibre surface to grow, which eventually degrades inherent high tensile strength of the fibre. The core acts like a continuous layer of two parallel mirrors.



Optical fibre with cladding

Fig. 2

A message which is to be conveyed is first encoded into a light wave and then fed into the fibre, where it is propagated as a result of multiple internal reflections. A modern fibre consists of an optical rod of glass core coated with another type of glass cladding. The refractive index of the core is higher than the refractive index of cladding material in order to utilize the phenomenon of total internal reflection for the propagation of light through the fibre. A bare fibre (without cladding) and a cladded fibre are shown in Fig. 2.

The light signal travels through the fibre from the transmitter to the receiver and can be easily detected at the receiving end of the fibre (Fig. 3). The transmitter convert electrical signal to optical signals which is transmitted through the fibre. The information in the form of either voice, data or video is transmitted through the fibre. The receiver receives the optical signals from the fibre and converts the same to its electrical equivalent. Finally electrical signals are decoded to give the original information. The transmitters in optical fibre links are generally laser diode and receivers are semiconductor photodiodes. Infrared light rather than visible light is used more commonly for propagation, because optical fibres transmit infrared wavelengths with less attenuation and dispersion. To protect the fibre from chemical and mechanical attacks (as it routed, underground, overhead, through walls or under the ocean) several fibre cable designs are available. Each design has different properties such as water resistance, flame retardent, crush proof etc., but the components of all type of the fibre cables are roughly the same.

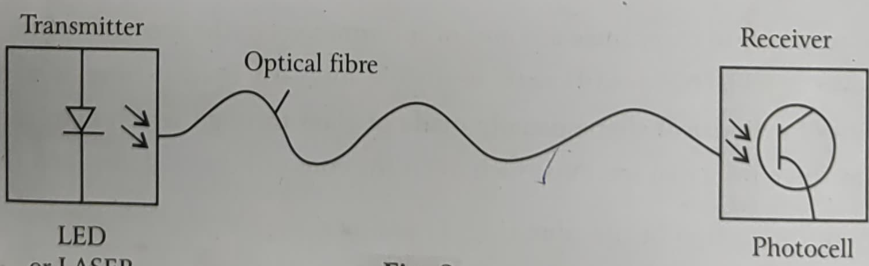


Fig. 3

Fibre Fabrication

Optical fibres are drawn from a furnace containing pure silica in the molted form and a small amount of dopant like GeO_2, B_2O_3 and P_2O_5. The dopant produce the required change in refractive index. Most of the cable bulk is made up of strengthening and buffering materials which protect the fibre against chemical and mechanical attacks.

The dimensions of the fibre (diameters of the core and cladding) vary, depending on the application of the fibre, but these dimensions must be kept within the tight specifications, for a particular type of a fibre. The type of glass used will also vary with the application, but the purity must also be kept very high.

Advances in light sources, detectors and manufacturing techniques have led to new designs. Fibre design has concentrated on reducing the losses in a fibre in two ways. Decreasing attenuation losses is focused on bringing as much of the light originally launched in the fibre out the other end. Reducing dispers.ion limits the amount of distortion in the signal carried by the light through the fibre.

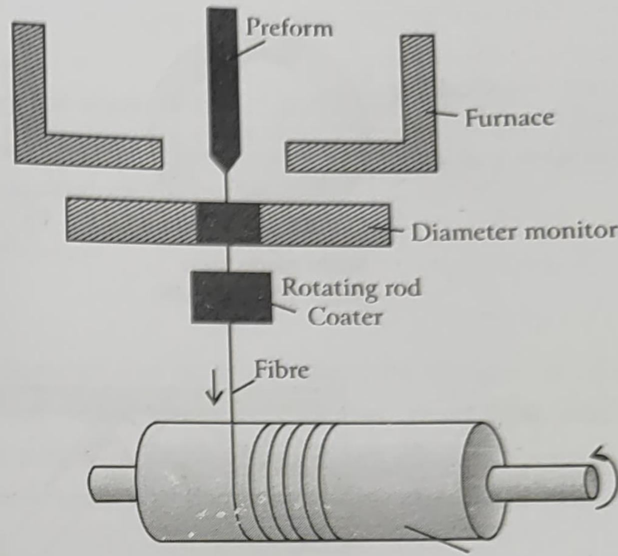


Fig. 4

Principle of Operation of a Fibre

An optical fibre is a cylindrical waveguide that propagates informations, coded in the form of light pulses, along its axis by the process of total internal reflection. Fibre consists of a glass core surrounded by another glass layer, called cladding. To confine the optical signal in the core, the refractive index of the core must be greater than that of the cladding. The boundary between the core and the cladding may either be abrupt or gradual depending upon the use of the fibre.

Types of Fibres

(Optical fibres, which form a passage way for transmitting optical signals, are designed in different ways to meet different requirements. On the basis of refractive index profile of the core and the way in which light signal propagates down the core, the fibres are broadly divided into three categories.

(i) Step index multimode fibres (MMF),

(ii) Step index single mode or monomode fibres (SMF),

(iii) Graded index multimode fibres (GRIN)

(i) Step Index Multimode Fibres (MMF)

In a step index multimode fibre a transparent glass core with a constant index of refraction is surrounded by another coaxial glass or plastic cladding of index of refraction lower than that of the core. The upper and lower interfaces between the core and cladding act as a cylindrical mirror at which the reflection of the transmitted light takes place. The multimode fibre has a larger core diameter of about 20–100 μm and the diameter of cladding is about 100–200 μm. The standard overall diameter of the MMF is 125 μm. These multimode fibres are referred to as step index fibres due to the step discontinuity of the refractive index profile at the core-cladding interface. The difference in the refractive index of the core and cladding materials is relatively large so that the critical angle (the minimum angle for total internal reflection) made by the ray with the line normal to the core-cladding boundary is small ($\theta_c = \frac{\mu_{clad}}{\mu_{core}}$). Hence, there will be

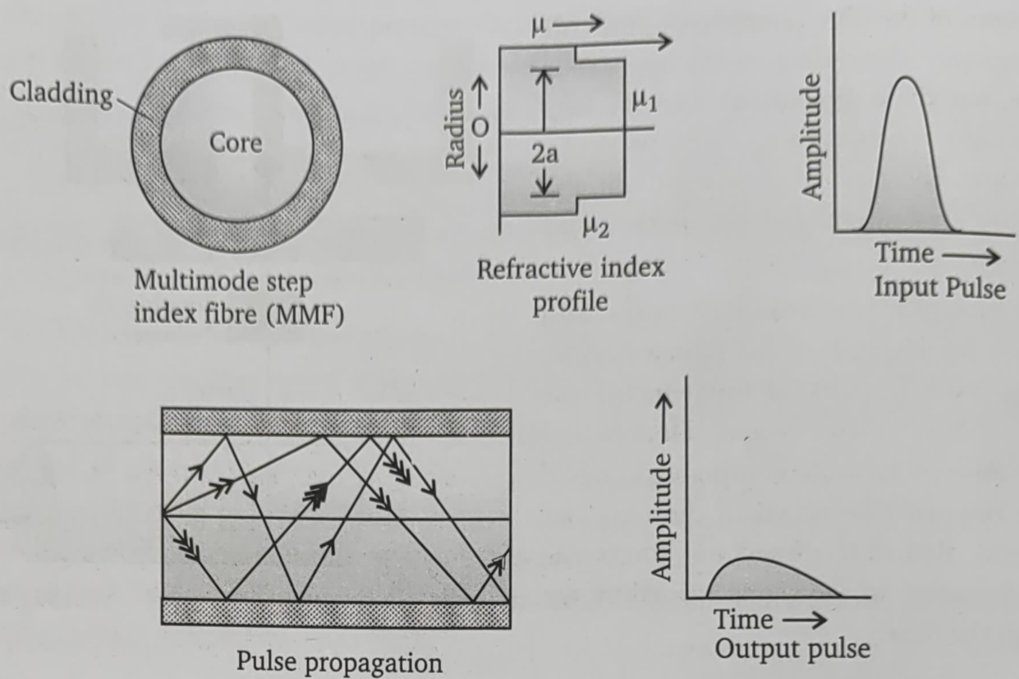


Fig. 5

many paths available for light signals to travel down the fibre. The light signals that meet the core-cladding boundary at high angles, greater or equal to the critical angle for the boundary, are totally reflected into the core. Further, because of the cylindrical symmetry in the fibre structure, these totally reflected rays will further suffer complete reflections at the lower interface and therefore get guided through the core by repeated total internal reflections (Fig. 5).

Rays that meet the interface at low angles (less than critical angle) will pass into and be absorbed by the cladding material. These rays do not convey light signals and hence the information along the fibre.

The critical angle determines acceptance angle of the fibre, often reported as numerical aperture (NA). A high numerical aperture allows light to propagate down the fibre in a set of many rays both close to the axis and at various angles with the axis, allowing efficient coupling of light into the fibre. Since the refractive of the core is constant all the rays making larger angles with the axis (or angles equal or greater than the critical angles with the normal to the core-cladding boundary) travel with same velocity in the core and take different times to reach the output end of the fibre, as their path lengths are different (Fig. 5). This spreading of arrival times of the transmitted rays at the exit end of the fibre cause a distortion or dispersion known as modal dispersion.Thus, **the amount by which a pulse broadens as it passes through a multimode fibre is commonly known as dispersion.** Due to this modal dispersion, a narrow pulse of light energy at the input end of the fibre, after travelling along the core, produces an attenuated output pulse dispersed over a wide period of time. That is, the light pulse containing the data transmitted is elongated or stretched out. If the output pulse spread too much, they begin to overlap on each others and may reach a point where one is not distinguishable from the next. In fact **dispersion in optical fibre reduces the information carrying capacity of the fibre.**

In a stepped index multimode fibre, light propagates in different modes, each with a different path transit-time. If the diameter 'd' of the core satisfies the condition

$$d > \frac{0.766\,\lambda}{(NA)}$$

where λ is the operating wavelength and NA the numerical aperture of the fibre equals to $\sqrt{(\mu_{core}^2 - \mu_{clad}^2)}$. A number of modes existing through the fibre become possible. If the number of modes in a step index fibre is larger than 50, then the number of modes in a multimode fibre is given by

$$N = 2 \,.\, \frac{\pi^2\, a^2\, (NA)^2}{\lambda^2}$$

where a is the radius of the core.

Step index multimode fibres generally have a large diameter core and are fabricated without sacrificing mechanical strength. **Multimode fibres are used for short distance, shorter than 200 meters, communication links or for application where high power must be transmitted.** Modal dispersion can be minimized by using single mode step or monomode step index fibres or graded index multimode fibres.

(ii) Step Index Single Mode or Monomode Fibres (SMF)

In order to reduce dispersion upto almost zero level and to increase the information carrying capacity, a fibre with a core diameter less than about ten times the wavelength of the propagating light wave is fabricated. In the step index multimode fibres we had considered light propagation in the fibre as a set of many rays meeting at the core-cladding boundary at an angles (making with the normal to the boundary) greater or equal to the critical angle for that boundary. If the diameter of the core is reduced to a value about ten times of the wavelength of the propagating wave or if the refractive index difference between the

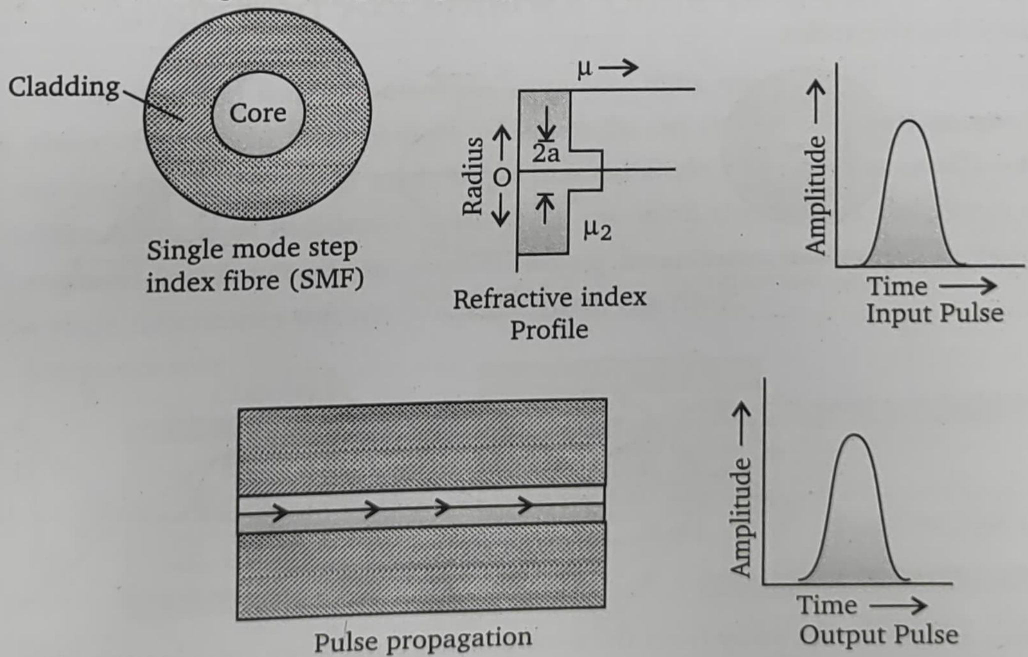


Fig. 6

core and the cladding is made very small, then only a single mode is propagated through the fibre (Fig. 6). Such a fibre is called step index single mode or monomode fibre. The most common type of single mode or monomode fibre has a core diameter of 8 to 10 μm and is designed for use in the infrared region. The mode structure depends on the wavelengths of the light used, so that the fibre actually supports a smaller number of additional modes at visible wavelength. Thus, in a single mode fibre, the transparent glass core is very thin and the refractive index of the cladding material is slightly lower so that the difference between the core and the cladding indices becomes very small. Thus, the single mode fibre is designed to eliminate modal dispersion by reducing the number of modes in the fibre to one. Since only a single ray path, parallel to the axis of the core, is possible in a single mode or monomode fibre, the dispersion caused due to the difference in the arrival times of different rays in multimode fibre would be completely absent. Thus, the information transmission capacity of a single mode fibre is much larger than that of a multimode fibre.

In spite of negligible dispersion, very thin core of a single mode or monomode fibre creates mechanical difficulties in the manufacturing, handling and splicing the fibres. Hence, the fabrication of a single mode fibre is very expensive. **Single mode fibres are used for most communication longer than 200 meters. Single mode fibres are frequently used under sea water.**

In order to get single mode, with all other modes cut-off, the diameter of the core must satisfy the relation

$$d < \frac{0.766\,\lambda}{(NA)}$$

A single mode (or monomode) fibre does require a much more sophisticated light source in order to launch enough light into the tiny core.

(iii) Graded Index Multimode Fibres (GRIN)

The graded index fibre offer a less expensive method of overcoming the modal dispersion or transit time dispersion. In step index fibres the refractive index of the core has a constant value. However, in a graded index multimode fibre, the index of refraction in the core decreases continuously in a nearly parabolic manner from maximum value at the core axis to a minimum constant value at the core-cladding interface (Fig. 7). Since the refractive index

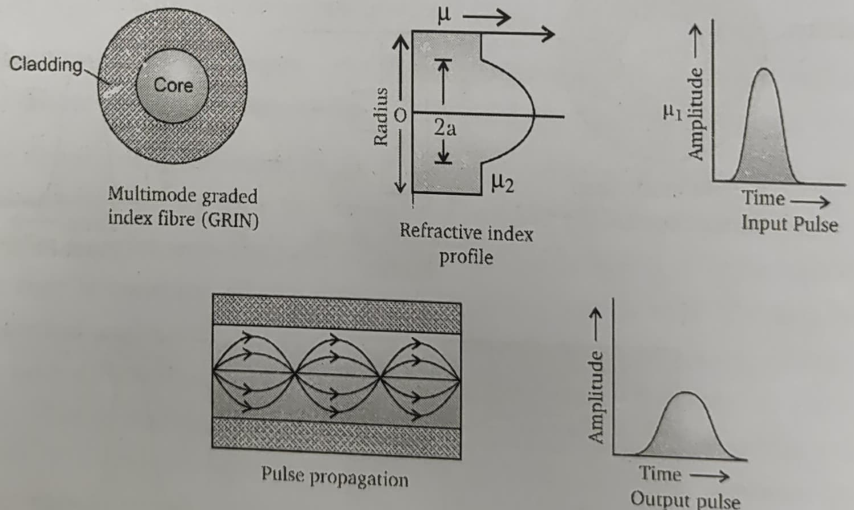


Fig. 7

gradually decreases as one moves away from the centre of the core, a ray entering the fibre is continuously bent towards the axis of the fibre because the ray encounters continuously a medium of lower refractive index and hence bends away from the normal, that is, towards the axis of the fibre. It is because of the fact that the ray moving towards the core-cladding boundary encounters continuously a rarer medium (medium of low refractive index). By gradually decreasing the index of refraction of the optical fibre core as a function of radius, the ray path becomes a smooth undulating curve which does not reach the core-cladding boundary so that the wave propagates as though in an unbounded medium. In such a parabolic index medium rays paths are smooth sinusoidal. The waves propagating at different angles of incidence in the fibre travel different distances from the fibre axis before suffering reflections to recross the axis. Hence, the rays making large angles with the axis pass more through the lower index periphery of the core, rather than high index centre. As we know, higher the refractive index lower the velocity of light ($v = c/\mu$). The light rays travelling near the core axis move slowly than those passing near the core-cladding boundary. Hence, all the rays travelling in the core of the fibre, take same amount of time in traversing the fibre and reaching the receiving end of the fibre, in spite of different path lengths. Thus, the rays travelling in the graded index multimode fibre take equal time to reach the end of the fibre. Thus, the transit-time or modal dispersion is greatly minimized in graded index multimode fibres.

The variation of refractive index of the fibre core of the graded index multimode fibre with radius, a, measured from the centre of the core is expressed as,

$$\mu(x) = \mu_1 \left[1 - 2\Delta\left(\frac{x}{a}\right)^p\right]^2$$

where $\mu(x)$ is the refractive index of the core at a distance x from the centre of the core, μ_1, the refractive index at the centre of the core and p the index profile. Index profile has a typical value of 2.0 for 850 nm.

In the graded index multimode fibre, the number of modes is expressed (provided the number of modes is more than 50) as,

$$N = \left(\frac{p}{p+2}\right)\frac{2\pi^2 a^2 (NA)^2}{\lambda^2}$$

N is doubled to account for the two possible polarisations.

Acceptance Angle and Acceptance Cone of a Fibre

We have seen that in the step index multimode fibre any light wave which is meeting core-cladding boundary at or above the critical angle will be totally reflected in the core and propagated. However, any light-wave meeting the boundary at angle below critical angle will pass into and be absorbed by the cladding. **The external angle of incidence made by a ray with the axis of the fibre, corresponding to the critical angle of incidence at the core-cladding boundary, is termed as acceptance angle.** Thus, the critical angle determines the acceptance angle of the fibre.

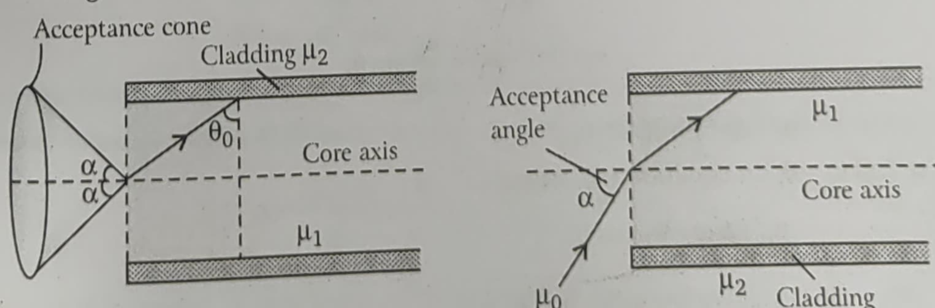


Fig. 8

Hence, the maximum entrance angle (α) subtended by a ray on the fibre axis at the entry point of the fibre for which the ray suffers total internal reflection on striking the core-cladding boundary, is called the acceptance angle (Fig. 8). **Acceptance angle is different for different fibres and depends on the core material and the core diameter.** Only light that enters the fibre a certain range of angles can travel down the fibre without leaking out. The range of angles at entry point which make angles at the interface ≥ the critical angle is called **acceptance cone of the fibre.** Acceptance cone is formed by rotating acceptance angle about the fibre axis and is also defined as the **cone of light described at the entry end of the fibre with semi-angle less than or equal to the acceptance angle of the fibre (or the cone formed with acceptance angle as vertex angle).** The half angle of the cone within which incident light is totally internally reflected is also defined as the acceptance angle. **The size of the acceptance cone is a function of the refractive index difference between the fibre core and cladding materials.** The light which is emerging from the acceptance cone is trapped and guided in the fibre.

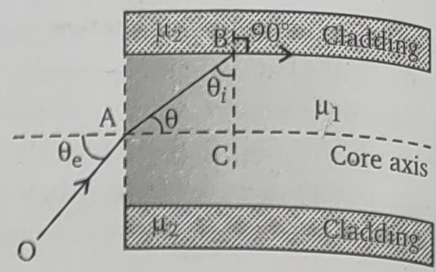


Fig. 9

The concept of acceptance angle and acceptance cone can be best understood with the following mathematical explanation and derivation:

Let a ray of light OA, from an external medium of refractive index μ_0, is incident on entry end of the fibre at an angle θ_e and refracted into the core along AB (Fig. 9). If θ is the angle made by the refracted ray AB with the axis inside the core of refractive index μ_1, then according to Snell's law,

$$\frac{\sin\theta}{\sin\theta_e} = \frac{\mu_0}{\mu_1} \quad \text{or} \quad \sin\theta = \frac{\mu_0}{\mu_1}\sin\theta_e \qquad ...(1)$$

If θ_i is the angle subtended by refracted ray AB on the core-cladding boundary, then from triangle ABC

$$\theta = 90 - \theta_i \qquad ...(2)$$

As θ_e decreases θ also decreases, so that θ_i increases. When θ_e is sufficiently small, θ_i exceeds that of critical angle θ_c (minimum angle for total internal reflection) for core-cladding boundary and the refracted ray AB is totally internally reflected at B and continue to propagate inside the core. The maximum angle of incidence (or entrance angle) subtended by a ray at the entry end of the fibre corresponding to which refracted ray in the core is totally reflected on striking the boundary, is called acceptance angle for that fibre.

If the maximum value of θ_e at which $\theta_i = \theta_c$ (critical angle) or $\theta_i \geq \theta_c$ is α, then

$$\theta_e = \alpha \quad \text{at} \quad \theta_i = \theta_c \qquad ...(3)$$

Substituting the value of θ from equation (2) in equation (1), we get

$$\sin(90 - \theta_i) = \frac{\mu_0}{\mu_1}\sin\theta_e$$

or
$$\mu_1 \cos\theta_i = \mu_0 \sin\theta_e \qquad ...(4)$$

Substituting $\theta_e = \alpha$ and $\theta_i = \theta_c$ in equation (4), we get

$$\mu_0 \sin\alpha = \mu_1 \cos\theta_c$$

or
$$\mu_0 \sin\alpha = \mu_1\sqrt{(1 - \sin^2\theta_c)} \qquad ...(5)$$

Applying Snell's law at a point B on core-cladding boundary

when $\theta_i = \theta_c$
$$\mu_1 \sin\theta_i = \mu_1 \sin\theta_c = \mu_2 \sin 90°$$

or
$$\sin\theta_c = \frac{\mu_2}{\mu_1} \qquad ...(6)$$

where μ_2 is the refractive index of the cladding material.

Substituting the value of $\sin \theta_c$ from equation (6) in equation (5), we get

$$\mu_0 \sin \alpha = \mu_1 \sqrt{1-(\mu_2/\mu_1)^2}$$

or

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

If the external medium around the fibre is air, that is, $\mu_0 = 0$, then

$$\sin \alpha = \sqrt{\mu_1^2 - \mu_2^2}$$

or

$$\alpha = \sin^{-1} \sqrt{\mu_1^2 - \mu_2^2}$$

This is the required expression for acceptance angle of a fibre with core and cladding of refractive indexes μ_1 and μ_2 respectively.

The light rays which are emerging from a cone defined by the acceptance angle would be totally reflected from the core-cladding interface and continue to propagate down the core. On the other hand the rays which are emerging outside the acceptance cone on striking the interface totally absorbed by the cladding material and never propagate.

Numerical Aperture

Another term related with the fibre is the numerical aperture (*NA*). Sometimes it is also called the figure of merit. **Numerical aperture is a number which defines the light acceptance or gathering capacity of a fibre.** In simple terms, there is a maximum angle made with the fibre axis at which the light may enter the fibre so that it is propagate in the core by several internal reflections. **The sine of this maximum angle (acceptance angle) is a numerical aperture (*NA*).** Mathematically numerical aperture (*NA*) is expressed as,

$$NA = \sin \alpha = \frac{1}{\mu_0} \sqrt{(\mu_1^2 - \mu_2^2)}$$

If the external medium surrounding the fibre is air, then

$$\mu_0 = 1$$

$\therefore$

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

where μ_1 is the refractive index of the core and μ_2 that of cladding material.

In terms of relative refractive index difference, $\Delta = (\mu_1 - \mu_2)/\mu_1$ numerical aperture may be evaluated as,

$$\Delta = \frac{\mu_1 - \mu_2}{\mu_1} = \frac{(\mu_1 + \mu_2)(\mu_1 - \mu_2)}{(\mu_1 + \mu_2)\mu_1}$$

Since the difference in μ_1 and μ_2 is very small, therefore we can approximated $\mu_1 + \mu_2 \simeq 2\mu_1$

$\therefore$

$$\Delta = \frac{\mu_1^2 - \mu_2^2}{2\mu_1 \cdot \mu_1} = \frac{\mu_1^2 - \mu_2^2}{2\mu_1^2}$$

or

$$\Delta = \frac{(NA)^2}{2\mu_1^2} \quad \text{or} \quad (NA)^2 = 2\mu_1^2 \Delta$$

or

$$NA = \mu_1 \sqrt{2\Delta}$$

This is the required expression for numerical aperture. Step index single mode fibres has small NA, whereas step index multimode fibre has large numerical aperture NA. A high NA allows light to propagate down the fibre in rays both close to the axis and at various angles with the axis, allowing efficient coupling of light into the fibre. However, this **high numerical aperture increases the amount of dispersion. A low numerical aperture may therefore be desirable.** The variation of numerical aperture (NA) with the acceptance angle α is shown in Fig. 10.

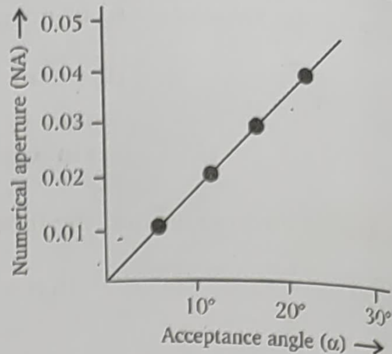


Fig. 10

The numerical apertures for the fibres used in short distance communication are in the range of 0.4 to 0.5, whereas for long distance communications numerical apertures are in the range of 0.1 to 0.3.

Numerical Aperture for Graded Index Fibres

In the graded index fibre, the numerical aperture is a function of position across the core. To get the idea about the numerical aperture for graded index fibre, we are introducing the term local numerical aperture which is a function of radius of the core. From the geometrical optics it is obvious that the light falling on the fibre core at position r will propagate as the guided mode only if it is within the local numerical aperture $NA(r)$ at that point. Local numerical aperture at position r is expressed as,

$$NA(r) = [\mu^2(r) - \mu_2^2]^{1/2} \simeq NA(r=0)\sqrt{1-\left(\frac{r}{a}\right)^x} \quad \text{for } r \le a \qquad ...(1)$$

$$= 0 \text{ for } r > a$$

where μ_2 is the refractive index of the cladding material, a the radius of the core, x is the parameter describing the refractive index profile variation and $NA(r=0)$, numerical aperture at the centre of the fibre core. The axial numerical aperture $NA(0)$ is,

$$NA(0) = \sqrt{(\mu^2(0) - \mu_2^2)} = \sqrt{\mu_1^2 - \mu_2^2}$$

where $\mu(0) = \mu_1$ is the refractive at the centre of the core.

$$NA(0) = \mu_1\sqrt{2\Delta}, \text{ where } \Delta = \frac{\mu_1 - \mu_2}{\mu_1}$$

It is clear from equation (1) that or a graded index fibre numerical aperture decrease from axial numerical aperture $NA(r=0)$ to zero as r increases from zero to core radius 'a'.

Number of Modes and Cut-off Parameters of Fibres

The number of modes supported by an optical fibre is obtained by an important parameter associated with the cut-off condition is called, cut-off parameter such as normalized frequency of cut-off, which is referred to V parameter or V–number. Mathematically V–number is expressed as,

$$V = \frac{\pi d}{\lambda_0}\sqrt{\mu_1^2 - \mu_2^2}$$

or

$$V \cong \frac{\pi d}{\lambda_0}(NA)$$

where λ_0 is the wavelength of a monochromatic light beam propagating in a multimode glass fibre of core diameter d, μ_1 and μ_2 are the refractive indices of core and cladding materials respectively, and $NA = \sqrt{\mu_1^2 - \mu_2^2}$ is the numerical aperture, provided the environment of the fibre is air (for which $\mu_0 = 0$).

If the external medium around the fibre has a refractive index μ_0, then

$$V = \frac{\pi d}{\lambda_0} \mu_0 (NA) \qquad \left(\because NA = \frac{\sqrt{\mu_1^2 - \mu_2^2}}{\mu_0} \right)$$

The approximate total number of modes which the fibre will support is expressed as,

$$\text{Number of modes } (N) \cong \frac{1}{2} V^2$$

provided the V number of V–parameter is considerably larger than unity. Each of the mode has a particular value of V–parameter, below that value the mode will cut-off. Out of all the modes only those modes will be propagated for which cut-off frequencies are less than the V–number.

V–number can be reduced either by reducing the numerical aperture or by reducing the diameter of the fibre.

Comparison of Single Mode Index and Multimode Index Fibres

	Single Mode Index Fibre (SMF)		Multimode Index Fibre (MMF)
1.	In a single mode index fibre, the diameter of the core is very small and is of the same order as the wavelength of light to be propagated. It is in the range 5 µm–10 µm. The cladding diameter is about 125 µm.	1.	In a multimode fibre, the diameter of the core is large. It is in the range 30 µm – 100 µm. The cladding diameter is in the range 125 µm–500 µm.
2.	The difference in the refractive indices of the core and the cladding materials is very small.	2.	The difference in the refractive indices of the core and the cladding materials is large.
3.	In SM fibre only a single mode is propagated.	3.	In MM fibre, a large number of modes can be propagated.
4.	SM fibre does require a much more sophisticated light source in order to launch enough light into the tiny core.	4.	MM fibre does not require any sophisticated light source.
5.	SM fibre is more expensive, but more efficient.	5.	MM fibre is less expensive.
6.	Acceptance angle and the size of the acceptance cone of a SM fibre is small.	6.	Acceptance angle and the size of the acceptance cone of a MM fibre is large.
7.	Numerical aperture of SM fibre is small.	7.	Numerical aperture of MM fibre is large.
8.	SM fibre has a very high information carrying capability.	8.	MM fibre has low information carrying capability.
9.	SM fibres are used when short distance communication is required.	9.	It is used for long distance communication.
10.	Modal dispersion in SM fibre is almost nil.	10.	Modal dispersion in MM fibre is the dominant source of dispersion.
11.	Material dispersion in SM fibre is low.	11.	Material dispersion in MM fibre is large.
12.	When a transmission has a very large band-width, a single mode fibre is used *e.g.*, undersea cables.	12.	When the system bandwidth requirement is low, multimode fibres are used *e.g.*, Data link.

Comparison of Step Index and Graded Index Fibres

	Step Index Fibre (SI)		Graded Index Fibre (GRIN)
1.	In a step index fibre, the refractive index of the core has a constant value.	1.	In graded index fibre, the refractive index in the core decreases continuously in a nearly parabolic manner from a maximum value at the centre of the core to a constant value at core-cladding interface.
2.	For a SI fibre, the variation of refractive index is mathematically expressed as, $\mu(r)=\mu_1 \quad 0<r<a$ (core) $\quad =\mu_2 \quad r>a$ (Cladding) where $\mu_1>\mu_2$	2.	Parabolic refractive index variation in GRIN fibre is mathematically expressed as, $\mu^2(r)=\mu_1^2\left[1-\left(\frac{r}{\alpha}\right)^2\right] \quad 0<r<a$ [CORE] $\quad =\mu_2^2 \quad r>a$ [CLADDING]
3.	In SI fibre the propagating light rays reflect abruptly from the core-cladding boundary.	3.	In GRIN fibre propagating light rays bend smoothly as they approach the cladding.
4.	For a given fibre diameter, the numerical aperture (*NA*) of SI fibre is large.	4.	For the same fibre diameter, the numerical aperture (*NA*) of GRIN fibre is small.
5.	In SI fibre, there may be some irregularities at the interface between the core and cladding.	5.	In GRIN fibre, there is no such irregularities at the interface.
6.	SI fibre has higher attenuation.	6.	GRIN fibre has lower attenuation.
7.	For a SI fibre of given physical size, with a loss of power of the order of 12 dB/km, the numerical aperture is of the order of 0.2 to 0.35.	7.	For a GRIN fibre of same physical size, with an attenuation between 5 to 10 dB/km, the numerical aperture tend to run between 0.16 and 0.2.
8.	In SI fibre, the time interval at the output end or pulse dispersion is expressed as, $\Delta\tau=\frac{\mu_1 l}{c}\left(\frac{\mu_1}{\mu_2}-1\right)=\frac{\mu_1 l}{c}\Delta$ where l is the length of the fibre.	8.	In GRIN fibre the time interval at the output end of pulse dispersion is expressed as, $\Delta\tau=\frac{\mu_2 l}{2c}\left(\frac{\mu_1-\mu_2}{\mu_2}\right)^2=\frac{\mu_2 l}{2c}\Delta^2$ where l is the length of the fibre.
9.	Pulse dispersion in multimode step index fibre is large.	9.	Pulse dispersion in a GRIN fibre is small.
10.	A good quality SI f'bre may have a bandwidth of 50 MHz km.	10.	The equivalent GRIN fibre can have 200, 400 or 600 MHz km bandwidth.

Propagation Mechanism in Optical Fibres

Whenever a ray of light travels from one material medium to another, it deviates from its original path. The refracted ray will bend toward the normal while going from a rarer to a denser medium or away from the normal while going from a denser to a rarer medium. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is always constant. That is,

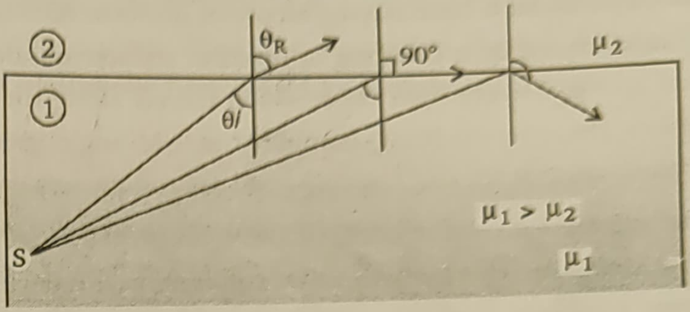


Fig. 11

$$\frac{\sin \theta_i}{\sin \theta_R} = \text{constant} = \mu_{21} \qquad \text{...(1)}$$

This is known as Snell's law. The constant μ_{21} is called refractive index medium 2 with respect to medium 1, when a ray travels from medium 1 to medium 2.

Whenever a light wave travels from one medium to another, the velocity of the wave changes. The velocity of light wave in vacuum is maximum and equal to $c = 3 \times 10^8$ m/sec. The velocity of this wave in another medium will be less than c, say equal to v. The refractive index of the medium is,

$$\mu = c / v$$

Suppose the velocity of light in medium 1 is v_1 and that in medium 2 is v_2. The corresponding refractive indices μ_1 and μ_2 are

$$\mu_1 = c / v_1 \quad \text{and} \quad \mu_2 = c / v_2$$

If we replace μ_{21} by μ_2 / μ_1 in eqn. (1) we get

$$\frac{\sin \theta_i}{\sin \theta_R} = \frac{\mu_2}{\mu_1} \qquad \text{...(2)}$$

The speed of light wave may be different in different media of the fibre, but the frequency υ remains constant as light wave propagates from one medium to another. This means that for the relation, $v = c/\lambda$ to hold good, its wavelength must change.

In the fibre refractive index of the core μ_1 is slightly greater than that of cladding μ_2, that is, $\mu_1 > \mu_2$. From Snell's law, $\mu_1 \sin \theta_i = \mu_2 \sin \theta_R$. It is clear that $\sin \theta_R > \sin \theta_i$. In this case angle of refraction θ_R is always greater than the angle of incidence θ_i. As the angle of incidence increases the angle of refraction also increases. When the angle of refraction is 90°, the refracted ray just grazes (Fig. 11) along the surface, separating the two media. Any further increase in the angle of incidence will turn the refracted ray back into the same medium. This ray is said to be totally internally reflected. When light travelling in a dense medium hits the boundary at steep angle (greater than critical angle for the boundary) the light will be completely reflected. This effect is used in optical fibres to confine light in the core.

Communication in Optical Fibre

Let us consider a fibre having a core of uniform refractive index μ_1 surrounded by a cladding of uniform refractive index μ_2 such that $\mu_1 > \mu_2$. Every light wave which travels along the core and strikes the core-cladding boundary at the angle greater than critical angle θ_c $(= \sin^{-1} \mu_2/\mu_1)$ will be totally reflected in the core region. Further, because of the cylindrical symmetry in the fibre structure, this ray will suffer total internal reflection at the lower interface also. Therefore, the light wave is propagated along (or guided through) the fibre core by a series of total internal reflections from the core-cladding boundaries. Even for a bent fibre, light guidance can occur through multiple total internal reflections. Since the refractive index changes abruptly at the core- cladding boundary this is a sort of step index fibre. In Fig. 12 the propagation path of one light wave is shown, it is possible only when a light wave is emitting from a very tiny point-source. In actual practice, several light rays emerge from a point source in different directions and have different colours with different frequencies or wavelengths. These rays strike the core-cladding boundary at different angles of incidence. Out of these, only the rays which are impinging on the interface at an angle greater than the critical angle are trapped inside the core through total internal reflection. Other rays either absorbed in the cladding or scattered.Thus, the multimode propagation is possible in fibre (Fig. 13).

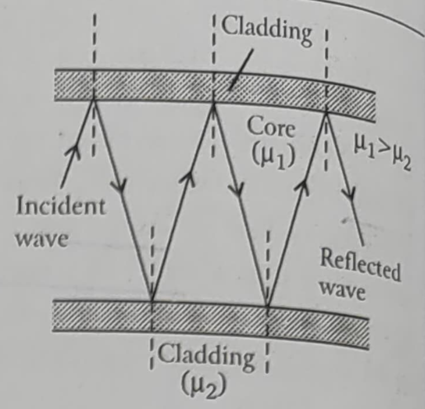
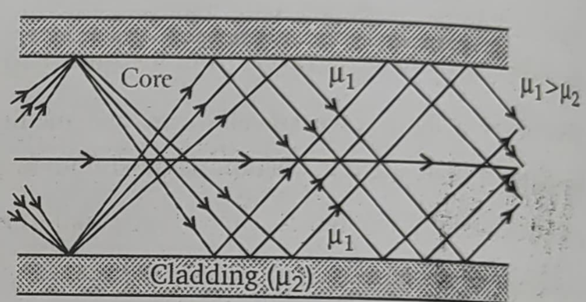


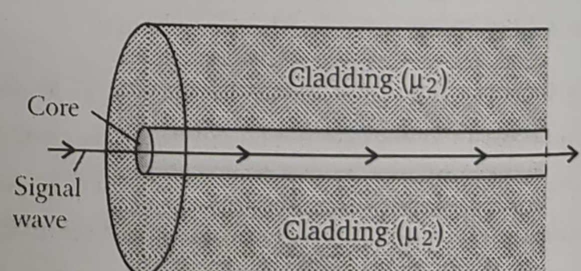
Fig. 12



Step index multimode fibre

Fig. 13

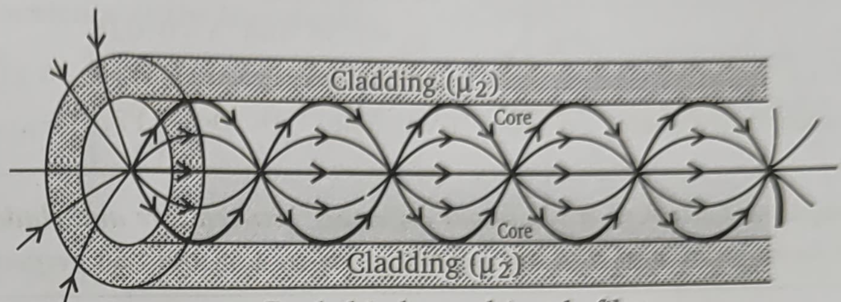
The rays follow zig-zag paths while travelling in an optical fibre by bouncing back and forth at the core–cladding boundaries and hence the rays will travel different total lengths of path and emerge at the far end at slightly different times. Thus, a distortion is produced which is called, transit time dispersion. As a result of this distortion the pulse of light containing the data transmitted is stretched out. If the pulses stretch too much, they begin to overlap each other and there–by cause distortion of the information being carried. This defect can be minimised by greatly reducing the diameter of the core and by reducing the difference in the



Step index single mode fibre

Fig. 14

indices between the core and cladding materials because the number of modes depends on the size of the core in a fibre. A fibre whose core diameter is of the same order as the wavelength of the light wave to be propagated is called monomode or single mode fibre because in such fibre only one mode exists. Since only a single ray path (Fig. 14) is possible in a single mode fibre, the dispersion caused due to the differences in the transit times of different rays in a multimode fibre would be completely absent.



Graded index multimode fibre

Fig. 15

The dispersion in multimode propagation may also be reduced by considering propagation in graded index fibre. Since the refractive index of the core in a graded index fibre decreases continuously as one moves away from the centre of the core towards the interface, a ray of light entering the fibre is continuously bent towards the axis of the fibre (Fig. 15), this follows from Snell's law because the ray encounters continuously a medium of lower refractive index and hence bends away from the normal, that is, it bent towards the axis of the fibre. It is obvious that light waves with large angle of incidence travel longer path than those with smaller angles. As we know ($v = c/\mu$) higher the refractive index slower is the velocity of light travelling through the fibre. Thus, the resulting fibre allows light in longer mode to travel faster than light in shorter modes. Thus, all propagating light waves will reach the end point of the fibre at the same time.

***Example 1:** A silica glass optical fibre has a core refractive index of 1.5 and cladding refractive index of 1.450. Calculate the numerical aperture of the optical fibre.*

[U.P.T.U, B.Tech, I Sem (C.O.) 2010, I Sem 2009]

Solution: We know that the numerical aperture is,

$$NA = \mu_{core}\sqrt{(2\Delta)}, \text{ where } \Delta = \frac{\mu_{core} - \mu_{clad}}{\mu_{core}}$$

$\therefore$ $$\Delta = \frac{1.5 - 1.45}{1.5} = 0.033$$

$\sin^{-1}\sqrt{NA}$ $\quad \frac{\mu_1 - \mu_2}{\mu_1}$

So $$NA = 1.5\sqrt{(2 \times 0.033)} = 1.5 \times 0.257 = 0.385$$

$NA = 2\sqrt{\Delta\mu}$

***Example 2:** Compute the numerical aperture and the acceptance angle of an optical fibre from the following data : μ_1 (core) = 1.48 and μ_2 (cladding) = 1.46.*

Solution: The numerical aperture of the fibre, $NA = \sqrt{(\mu_1^2 - \mu_2^2)}$

or $$NA = \sqrt{[(1.48)^2 - (1.46)^2]} = \sqrt{(2.1904 - 2.1316)} = \sqrt{(0.0588)}$$

or $$NA = 0.2425$$

Acceptance angle, $\alpha = \sin^{-1}\sqrt{(\mu_1^2 - \mu_2^2)} = \sin^{-1}(0.2425) = 14°$

Solution:

$$\text{Number of propagating modes} = \frac{2a^2\pi^2(NA)^2}{\lambda^2} = \frac{2\times(100)^2\times(3.14)^2\times(0.29)^2}{(0.85)^2}$$

$$= \mathbf{22953\ modes}$$

***Example 15:** A graded index fibre has a core diameter 40 μm, NA = 0.21 and index profile = 1.85. Compute the number of modes at operating wavelength of 1.3 μm.*

Solution : Number of modes in a graded index fibre $= \dfrac{2a^2\pi^2(NA)^2}{\lambda^2}\times 2\left[\dfrac{1}{1+\dfrac{2}{p}}\right]$

$$= \frac{2\times(3.14)^2\times(20)^2\times(0.21)^2}{(1.3)^2}\times 2\left[\frac{1}{1+\dfrac{2}{1.85}}\right] = \frac{695.6933}{1.69\times 2.081}$$

$$\simeq 187$$

***Example 16:** Compute the velocity and wavelength of light of frequency $f = 0.5\times 10^{15}$ Hz when travelling through glass having refractive index $\mu_1 = 1.5$ (where $c = 3\times 10^8$ m/s).*

Solution: The velocity of light, $v = \dfrac{c}{\mu_1} = \dfrac{3\times 10^8}{1.5} = 2\times 10^8\ \text{m/s}$

The wavelength of light, $\lambda = \dfrac{v}{f} = \dfrac{2\times 10^8}{0.5\times 10^{15}}$

or $\lambda = 400\text{nm}$

Attenuation and Signal Losses in Optical Fibres

The reduction in amplitude (or power) and intensity of a signal as it is guided through an optical fibre is called attenuation. A fibre with a lower attenuation will allow more power to reach a receiver than with a higher attenuation. The loss of optical power and decrease in signal strength along a fibre are due to the absorption of light energy by the material of the fibre, scattering of light due to impurities and imperfections present in the fibre material. Loss of energy also occurs due to small bumps or variation in the surface of the core.

Additional channel losses are: bending losses, connector loss, splice loss, loss at terminals etc. All these phenomena contribute to the degradation of the fibre transmission.

Absorption Losses

The absorption of light by the core and cladding materials of a fibre during wave propagation is the main source of attenuation. There are three main sources for the absorption of light by the glass core and cladding of the fibre : Light is absorbed by the material itself, impurities and imperfection, and the atomic defects present in the glass fibre. Light is absorbed by a glass material of the fibre, when the frequency of the propagating light is in reso... ...'i the natural frequency of that material. Since there is an energy transfer, the atom will mo' to the upper energy state. This type of optical attenuation arises due to the conversion of optical power into heat.

Silicon dioxide of the fibre absor..s light at a specific wavelength value, when light signal is passes through the fibre.This type of intrinsic absorption of light signal is strong in glass. It usually occurs in ultraviolet and in the infrared regions

Atomic defects act like impurities present in the fibre material. Atomic defects are created during the manufacture of the fi..e. These are also be created by the exposure of the fibre to X-rays, γ-rays, neutrons and electrons be. ..s.

In the fabrication of various type of fibres, GeO_2, P_2O_5, B_2O_3 etc., are used as dopants in silica to modify its refractive index. While B_2O_3 produces strong absorption at 3.2 μm and P_2O_5 at 3.8 μm wavelengths. However, in both these cases, absorption tails extend below 1.3 μm. That is why Boron and phosphorous based dopants are not used in the low loss, single mode fibre. Loss is increases considerably when the operating wavelength is beyond 1.55 μm. Introduction of P_2O_5 serves as channel for the gradual build up of hydroxyl (OH^+) ions over the time. The hydroxyl (OH^+) ion can also be penetrated into the glass fibre during or after product formation. Hydroxyl ion absorption in optical fibres is due to the presence of trapped hydroxyl ions remaining from water as a contaminant. Hydroxyl ion absorption produce a significant attenuation of discrete wavelength *e.g.*, centred at 1.383 μm. Impurities like Fe^{+3}, Cr^{+2} and copper are present in the glass it will create unacceptable losses within the useable portion of the spectrum. However, these impurities can be reduced considerably by using good refining techniques for purifying the raw-materials for silica.

Structural defects in the fibre glass are also responsible for the attenuation of optical power by absorption. When the glass molecules of a fibre interact with electrons, neutrons, gamma rays and X-rays, the structure of glass molecules is changed and radiation induced losses occur. These losses increase with the increase of exposure time. In fact ion-resonance absorption, ultraviolet absorption and infrared absorption are the three main mechanisms which contribute to the total absorption losses in glass fibres.

Rayleigh Scattering Losses

Rayleigh scattering is a major cause of the attenuation of radiation in the optical fibre. Rayleigh scattering is the process in which light is scattered by microscopic inhomogeneities, microscopic fluctuation in density of the silica material contents, small spherical volume of variant refractive index, such as particle, bubble etc. Radiative losses take place when a guided light beam is coupled to the radiation propagating in the cladding. Rayleigh scattering produces such a coupling. Attenuation in the light signal due to this scattering effect vary inversely with the fourth power of the wavelength (that is, λ^{-4}) and thus rapidly decreases with increasing wavelength. Light signal is scattered by an obstruction in the fibre. Obstruction refers to density variations in the material of the fibre which produce changes in the refractive index. This index variation behaves like point sources. Light falling on these point sources suffer scattering in all directions. Microscopic inhomogeneities in the glass of the fibre are frozen when the fibre is fabricated and depend on the glass-forming temperature. Lower the glass forming temperature, lower is the density fluctuation and hence scattering. This scattering is most prominent between the wavelength range 500 nm to 1550 nm. At 1000 nm loss is approximately 0.75 dB/km. Fibres with large numerical aperture (NA) exhibit greater scattering losses. Fibre bending, core-cladding interface irregularities etc. are the addition sources of loss of power by scattering.

A portion of a propagating light signal may lost by scattering due to defects in the fibre itself. In cladded fibres, surface defects such as scratches allow light to escape from the fibre. Contaminants on the surface of the fibre may form an area with refractive index different from what is expected and cause the light direction to change. There is always a possibility of developing specks or voids in the fibre material. When light hits these specks it tend to scatter in all directions, causing a loss of power.

Waveguide Scattering Losses

Irregularities in waveguide geometry is the primary source of waveguide scattering or leaky mode losses. These leaky modes have radiative components that result in cladding power losses.These losses can be minimized by putting a third layer of pure silica around the thin cladding layer.The refractive index of third layer should be higher than that of cladding but lower than that of the refractive index of the core.This additional silica coating not only reduces leaky mode losses but also provides extra strength to the fibre.

Bending Losses

These losses occur due to imperfections and deformations present in the fibre structure. Micro- bending and macro-bending losses are two types of bending losses. Microbend losses occur when the core surface has small variations in shape. These variations change the angle at which light strikes the core-cladding interface and can cause the light to refract into the cladding rather than reflect into the core. Macrobend losses depend on the core radius and the bend radius. Larger the core radius and smaller the bend radius, the greater the macrobend losses. In both cases the loss results from scattering of light.

Macrobend loss may occur when wrapping the fibre on a spool or pulling the fibre cable around a corner. If the fibre is sharply bent so that the light travelling down the fibre cannot make the turn and is lost in the cladding. Safe bending distance for most types of fibres is nearly twenty times the total fibre diameters, usually given by the manufacturer.

There is a critical radius of curvature at which or above which large bending losses tend to occur.

Critical radius of a multimode fibre with refractive indices μ_1 and μ_2 of core and cladding respectively, is

$$R_{cm} = \frac{3\mu_1^2\lambda}{4\pi\,(\mu_1^2 - \mu_2^2)^{3/2}}$$

where λ is the operating wavelength.

The critical radius of curvature for a single mode fibre is

$$R_{cs} = \frac{20\,\lambda}{(\mu_1 - \mu_2)^{3/2}}\left[\frac{2.748\,\lambda_c - 0.996\,\lambda}{\lambda_c}\right]^{-3}$$

where λ_c is the cut-off wavelength at which the fibre becomes single mode and is given by

$$\lambda_c = \frac{2\,\pi\,a}{2.405}\,(\mu_1^2 - \mu_2^2)^{1/2} = \frac{2\,\pi\,a\,\mu_1}{2.405}\,\sqrt{2\,\Delta}$$

where a is the core radius.

Attenuation losses in optical fibres are generally measured in terms of the decibel (dB). **A decibel (dB) is a unit used to express relative difference in signal strength. A decibel is expressed as the base 10 logarithm of the ratio of the power at output to the power at input.** Due to attenuation, the power output (P_{out}) at the end of 1 km of optical fibre drops to some fraction (say k) of the input power (P_{in}), that is,

$$P_{out} = k\,P_{in} \text{ where } k < 1$$

Clearly after 2 km of optical fibre, the output power is

$$P_{out} = k.k\,P_{in} = k^2 P_{in}$$

Similarly after L km of optical fibre, the output power is

$$P_{out} = k^L P_{in} \text{ or } \frac{P_{out}}{P_{in}} = k^L$$

Taking log of both sides and then multiply by 10 gives power loss in dB as,

$$\text{Power loss (dB)} = 10 \log_{10} \frac{P_{out}}{P_{in}} = 10 \log k^L = 10\, L \log_{10} k = \alpha\, L$$

where α ($=10 \log_{10} k$) is the attenuation coefficient of the fibre in dB/km.

$$\alpha = \frac{10}{L} \log_{10}\left(\frac{P_{out}}{P_{in}}\right) \text{ dB / km}$$

The number of decibels lost is sometimes indicated by a negative sign to distinguish it from a gain light power which is represented by a positive number.

To indicate loss we are introducing negative sign in the expression as

$$\alpha = -\frac{10}{L} \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Example 17: A signal of 100 mW is injected into a fibre. The outcoming signal from the other end is 40 mW. What is the attenuation loss in dBs ?

Solution: Loss in decibel (dB) is given as

$$dB = -10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

$$dB = -10 \log_{10}\left(\frac{40}{100}\right) = -10\,[\log_{10} 2 - \log_{10} 5]$$

$$= -10\,[0.3010 - 0.6990]$$

or $\quad$ **dB = 3.98 dB**

Example 18: An optical fibre of length 150 m has input power of 10 μW and output power of 9 μW. Compute loss in dB/km.

Solution: Loss of dBs $= -10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$

$$\therefore \quad \lambda_c = \frac{2 \times 3.14 \times 4 \times 10^{-6} \sqrt{(1.5)^2 - (1.46)^2}}{2.405}$$

$$= \frac{2 \times 3.14 \times 4 \times 10^{-6} \times 0.3441}{2.405}$$

or $$\lambda_c = \frac{8.6438}{2.405} \times 10^{-6} = 3.594 \times 10^{-6} \text{m}$$

$$\therefore \quad R_{cs} = \frac{20 \times 1.55 \times 10^{-6}}{(1.5 - 1.46)^{3/2}} \left[\frac{2.748 \times 3.594 \times 10^{-6} - 0.996 \times 1.55 \times 10^{-6}}{3.594 \times 10^{-6}} \right]^{-3}$$

$$= \frac{3.10 \times 10^{-6}}{0.008} \left[\frac{9.8763 \times 10^{-6} - 1.5438 \times 10^{-6}}{3.594 \times 10^{-6}} \right]^{-3}$$

$$= \frac{3.1}{0.008} \times 10^{-6} \times (2.3184)^{-3}$$

$$= \frac{3.1 \times 10^{-6}}{0.008 \times (2.3184)^3} = \frac{3.1 \times 10^{-6}}{0.0997} = 31.0933 \times 10^{-6} \text{ m}$$

or $$R_{cs} = 31.0933 \ \mu\text{m}$$

Example 31: A multimode graded index fibre has a refractive index at the core axis of 1.55 with a cladding refractive index 1.5. The critical radius of curvature which allows large bending losses to occur is 84 μm when the fibre is transmitting light of a particular wavelength. Find the wavelength of transmitted light.

Solution: The critical radius of curvature for multimode fibres is

$$R_{cm} = \frac{3 \mu_1^2 \lambda}{4\pi (\mu_1^2 - \mu_2^2)^{3/2}} \quad \text{or} \quad \lambda = \frac{4 \pi R_{cm} (\mu_1^2 - \mu_2^2)^{3/2}}{3 \mu_1^2}$$

$$\therefore \quad \lambda = \frac{84 \times 10^{-6} \times 4 \times 3.14 [(1.55)^2 - (1.5)^2]^{3/2}}{3 \times (1.55)^2}$$

$$\lambda = \frac{84 \times 10^{-6} \times 4 \times 3.14 \times 0.05955}{3 \times 2.4025} = \frac{628.2763 \times 10^{-7}}{7.2075}$$

$$\lambda = 8.717 \times 10^{-6} \text{ m or } 8.717 \ \mu\text{m}$$

Optical Cables

A cable containing one or more fibre is called optical fibre cable. A fibre needs protection. The amount of protection depends on its utility and installation conditions. For laboratory work, only a thin buffer coating is sufficient whereas for use in strenuous environments fibre would need a higher protection. But in every circumstances the components of cable are roughly the same.

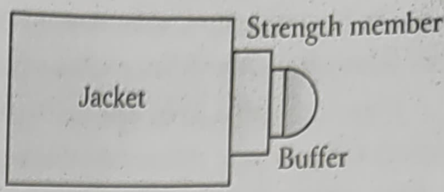


Fig. 23

In practical fibre, the cladding is usually coated with resin buffer layer of plastic, which is further surrounded by a jacket layer (Fig. 23). These layers are use to increase only the strength of the fibre. For indoor applications, such as ceilings or crawl spaces, the jacket fibre is generally enclosed, with a bundle of flexible fibrous polymer strength member in a light plastic cover to form a simple cable. For use in more strenuous environment a much more robust cable construction is required. The fibre is laid in a hard plastic tube with a diameter larger than that of the fibre, called **loose buffer,** allowing fibre some movement so that the cable remain protected from any hazard by the expansion and contraction of the cable due to temperature fluctuations. Finally the fibre may be embedded in a heavy polymer jacket commonly called **tight buffer.** Polyvinyl chloride (PVC) or polyethylene are used for cables intended primarily for indoor use. Polypropylene, polyurethane, nylon or teflon offer good resistance to chemicals, heat, weather, and other conditions that may be found in outdoor use. The outside protection provided to an optical fibre gives mechanical strength, abrasion protection, breakage and damage protection, environmental hazards protection, excessive bending protection, moisture and chemical contaminants protection etc. In addition, it permits easy field installation and maintenance.

The protection of an optical cable from contamination by water is very essential because water components like hydrogen (hydronium) and hydroxyle ions can diffuse into the fibre, reducing the fibre's strength and increasing the optical attenuation. Water is kept out of the cable by the use of solid barriers such as copper tubes, water-repellent jelly, or more recently water absorbing powder surrounding the cable.

Recent fibre cables can have upto a thousand fibres in a single cable, so the performance of the networks easily accommodates even today's demands for bandwidth on a point to point basis. Modern cables come in a wide variety of sheathing and armour, designed for applications such as submarine installation, lashing to aerial telephone poles, dual use as power lines etc.. Optical cables can be suspended directly from power line towers or poles if clearance space permits and if the load can be tolerated.

Advantages of Optical Fibre Over a Coaxial Cable

Fibre optic systems offer many advantages and a wide range of benefits as compared to traditional copper wire or coaxial cables, radio and microwave links and that is why telecommunication industries all over the world either switched over or switching over to optic fibre systems.

In fact fibre optic communication system have revolutionized the telecommunication industries and play a role in the advent of the information.

1. Optical frequencies are extremely large ($\sim 10^{15}$ Hz) as compared to the conventional radio frequencies ($\sim 10^{6}$ Hz) and microwave ($\sim 10^{10}$ Hz) frequencies. Because of this high frequency, light beam acting as a carrier wave has a very high information carrying capacity. It has hundreds and even thousands of times more information carrying capacity than a coaxial cable or copper wire.

2. In the fibre communication system, since the signals are carried by light, the speed of transmission of information is very fast than a metallic transmission media.
3. A fibre optic cable, even one that contains many fibre is usually much smaller and light in weight than a copper wire or coaxial cable with similar information carrying capacity.
4. Fibre cables are cheaper to transport and easier to handle and install, and use less duct space than metallic cables. No physical electrical connection is required between the sender and the receiver.
5. Cost surveys indicate that coaxial cable (copper wire) price will continue to rise due to an almost continuous increase in the price of copper but the prices of fibres will come down as the production volume increases. The optical fibres will be more economical than conventional cables in the long run.
6. Optical fibre can withstand environmental hazards better and have long life than copper cables. Since a fibre can isolate itself from its environments, a large number of fibres can be packed together in a cable to transmit many channels of information along a single patch.
7. The optical fibre has the ability to carry much more information and deliver it with great fidelity than either coaxial cable or twisted pair wire. Fibre optic cable can support much higher data rates, and at a great distances, than coaxial cable.
8. As the fibre is basically fabricated with glass, corrosion due to water or chemicals is quite less as compared to copper cables. It can be buried directly in most kind of soil or exposed to most corrosive atmosphere in chemical plants without significant concern. Glass fibre themselves can stand high temperature before deteriorating.
9. Since the only signal in the fibre is light, there is no possibility of a spark from a broken fibre. Even in the most explosive atmosphere, there is no fire hazard and no danger of any electrical shocks in the repairing of broken fibres.
10. Bandwidth of an optical fibre is higher than that of an equivalent wire transmission line.
11. Since the optical fibres are composed of dielectric materials they are totally protected from external interfering electromagnetic signals. No electric current can flow through it either due to the transmitted signal or due to the external radiation striking it. They do not pick-up line currents, that is why they can be safely used in high voltage environments and can be laid alongside metallic power cables. No light signal can couple into the fibre from out-side. Fibres have excellent rejection power of radio frequency and electromagnetic interferences. Hence, radio, television, radar and other signals cannot introduce any interference in the fibre. Thus, the electrical noise does not interfere with the propagated light signal.
12. Optical fibres have electrical non-conducting photons instead of the electrons in metallic cables, such as wires or coaxial cables. This is attractive for application in which the transmission path traverses environments that are subject to fire and gaseous combustion from electricity.
13. Due to the low signal loss, the error rate for optical fibres is very low.
14. Optical switches are less costly and can accommodate much higher bandwidth.
15. Optical cables are not subject to electrical sparks or interference from electrical components in a building or computer machine room.
16. Attenuation in the fibre due to absorption of light by the material of the fibre, scattering of light due to impurities and imperfection in the fibre and bending loss due to small bumps or variation

in the surface of the core are markedly lower than that of coaxial cables or twisted pair. Therefore, with these optical fibre transmission with wide range of distance is possible without repeater etc .

Hence, due to wide bandwidth, low signal attenuation, no signal leakage, flexibility, high information carrying capacity, possibilities of use in otherwise unaccessible area, use in hazardous environments and compatibility of optical fibres make its advantages over coaxial cables.

Disadvantages of Optical Fibres

In spite of all attractive features, fibre optics has few disadvantages compared with time-tested methods. Unlike radio waves, clouds can block the laser photons and laser beams are narrower than distended radiowaves.

In many situations however, metallic cable communication media continue to provide the economic option *e.g.*,

1. Internal electrical connection within a computer.
2. Subscriber's telephone line.
3. Electrical links within local area networks (LANs).
4. Waveguides for power microwave transmission.
5. Cumulative losses due to fibre couplers are much larger than for their coaxial cable counterparts.

The most significant disadvantage is that optical fibre requires a new set of skills for installation and maintenance by technicians. Technicians who are experienced in splicing, soldering, and installing copper wire will find optical fibre requires additional training and knowledge. Splicing (is a method of connecting two optical fibres permanently through fusion) and connecting optical fibre is a delicate skill that must be carefully learned to produce quality results. The methods and techniques for performing the test and measurements with optical power meters and optical time domain reflectometer required specialized training.

While working with optical fibre, workers may face hazard of glass shards and optical radiation. To protect himself with the hazard of glass shards always wear safety goggles to protect eyes and carefully wash your hands after working in the field or laboratory. Optical radiation hazards can cause damage to the eyes and is especially dangerous when working with invisible infrared light used with fibre. Using specialized protective goggles, shutters, and other systems can limit or deny exposure to hazardous emissions.

Applications of Optical Fibres

1. Optical fibres are widely used primarily in broadcast television and cable T.V., remote monitoring and surveillance. It is also used in high-definition television (HDTV)– a new television system that promise high picture and sound quality.
2. Fibre systems are frequently used for the transmission of digital data such as that generated b computers.