Engineering Physics

Second Edition

Fibre Optics

LEARNING OBJECTIVES

After reading this chapter you will be able to

LO1 Understand the concept of optical fibre

LO2 Know about types of optical fibres

LO3 Learn about acceptance angle, numerical aperture, skip distance and relative refractive index

LO4 Explain fibre optic communication

LO5 Illustrate optical fibre sensors, connectors, and couplers

LO6 Discuss the applications of optical fibre couplers

Introduction

In communication systems, there has been a frequent use of either the radiowaves or the microwaves in the form of carrier waves for sending the information. However, the advent of the laser in 1960 revolutionised the telecommunication and networking areas with an immediate appreciation of the potential benefits of sending information from one place to the other using light, as the laser is a coherent source of light waves. It is worth mentioning that at higher optical frequencies ($\sim 10^{15}$ Hz), one hundred thousand times more information can be carried compared to microwaves. However, the energy of light waves gets dissipated in open atmosphere. So it cannot travel long distances and hence a guiding channel is required to guide them just like a metal wire is required to guide electrical currents. This purpose is solved with the use of optical fibre. Optical fibre is a very thin glass or plastic conduit designed to guide light waves along the length of the fibre. As long as the refractive index of this fibre is greater than that of its surrounding medium, the light shall suffer a large number of total internal reflections and hence much of the light launched into one end will emerge from the other end due to small losses.

Fibre optics is a technology that uses glass, plastic, threads or fibres to transit data. A fibre optic cable consists of a bundle of glass threads (Fig. 5.1) which are protected by the cable's outer covering of treated paper, PVC or metal, called a jacket. Optical fibre has a number of advantages over the copper wire used to make connections electrically. For example, optical fibre, being made of glass or sometimes plastic, is protected from electromagnetic interference such as is caused by thunderstorms. A single optical fibre has its parts as core, cladding and sheath (protecting layer), as shown in Fig. 5.2. Core is thin glass centre of the fibre where the light travels. Cladding is outer optical material surrounding the core that reflects the light back into the core because cladding has lower refractive index. Sheath is plastic coating that protects the fibre from damage and moisture.

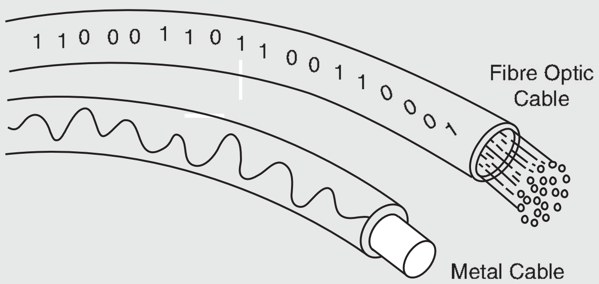

Figure 5.1

In order to understand the advantages of fibre optics, it is necessary to know about the bandwidth in general. Bandwidth is the difference between the upper and lower cutoff frequencies of a filter, a communication channel, or a signal spectrum. It is typically measured in Hertz. In the case of a lowpass filter or baseband signal, the bandwidth is equal to its upper cutoff frequency. In radio communications, bandwidth is the range of frequencies occupied by a modulated carrier wave. For example, an FM radio receiver's tuner spans a limited range of frequencies. In optics, it is the width of an individual spectral line or the entire spectral range.

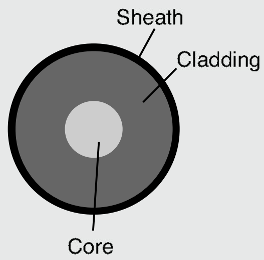

Figure 5.2

Fibre optics has many advantages compared with traditional metal communications lines, which are listed as follows:

(i) Fibre optic cables can carry more data as their bandwidth is greater than metal cables.
(ii) Fibre optic cables are less susceptible than metal cables to interference.
(iii) Fibre optic cables are much thinner and lighter than metal wires.
(iv) Through fibre optic cables the data can be transmitted digitally rather than analogically.
(v) Attenuation through fibre optic cables is very low in transmitting the data over a long distance, so there is so need of repeaters.

5.1 FUNDAMENTAL IDEAS ABOUT OPTICAL FIBRE (LO1)

Optical fibres use light to carry digital signals and as mentioned earlier the base of this technology is the concept of total internal reflection. The digital signal that is carried by the light is reflected inside the optical cable and hence transfers the information. Main concepts of physics that are involved in optical fibres are refraction, refractive indices, critical angle and total internal reflection. In refraction, the light wave bends away from the normal when it propagates from a higher refractive index medium to a lower refractive index medium. The phenomenon of total internal reflection takes place when the angle of refraction becomes 90°. The incident angle at which the angle of refraction (transmitting) is equal to 90° is called *critical angle*. When a light wave propagating from a higher refractive index medium to a lower refractive index medium has a sufficiently large angle, i.e., greater than the critical angle, the light gets reflected back into the same medium. For a particular case of an optical fibre whose core is made of glass which is bounded by a plastic cladding, the critical angle is 82°. Therefore, the light when hits the plastic cladding at an angle more than 82° would be reflected back in the same medium, i.e., back to the glass core. This is shown in Fig. 5.3.

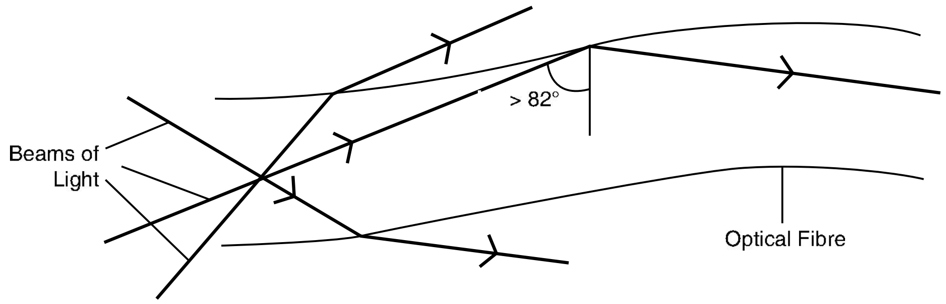

Figure 5.3

5.2 OPTICAL FIBRES AS A DIELECTRIC WAVEGUIDE LO2

An optical fibre is a dielectric waveguide with a very high bandwidth. It guides electromagnetic waves in an optical spectrum, the same way as microwaves are guided by rectangular or cylindrical metallic waveguides. An optical fibre confines the propagating waves inside it by utilizing the property of total internal reflection of light from a dielectric interface (i.e., the interface between two dielectric materials), whereas the waves in waveguides are confined within these structures by the reflection of the waves from the walls of the waveguides. An optical waveguide has a circular cross section, which is made in such a way that the outer dielectric (cladding) has lower refractive index than that of the inner one (core). Due to different refractive indices, the phenomenon of total internal reflection takes place in the optical fibre.

The transmission of light in optical fibres over large distances is possible with minimum loss of data. These fibres occupy less space and are light in weight in comparison with the waveguides or transmission lines. Moreover, the optical fibre has greater tensile strength. However, optical fibres are costly and also, they need more protection than waveguides or transmission lines. The other disadvantage is that attenuation of signals takes place in optical fibres. The attenuation is mainly due to Rayleigh scattering (which is inversely proportional to the fourth power of wavelength), absorption due to impurities and radiation of light due to bending of the core.

5.3 TYPES OF OPTICAL FIBRES LO2

Optical fibres are categorised based on their transmission properties and the structure. These can be classified into two types, one of which is single mode fibre and the second one is multimode fibre. The core size is the basic structural difference in the optical fibres.

5.3.1 Single Mode Step Index Fibre

A single mode fibre is called single (mono) mode step index fibre because the refractive index of the fibre "steps" up as we move from the cladding to the core and this fibre allows single mode to propagate at a time due to very small diameter of its core (Fig. 5.4a). In this fibre, the refractive indices of the cladding and the core remain constant. The size of its core (diameter) is typically around 10 μm. Single mode fibres have a lower signal loss and a higher information capacity or bandwidth than multimode fibres (introduced later) as the signal loss depends on the operational wavelength. These fibres are capable of transferring higher

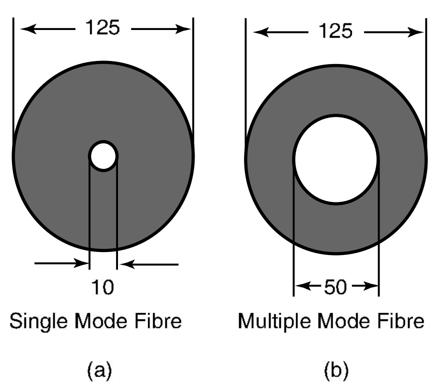

Figure 5.4

amount of data due to low fibre dispersion. In these fibres, the wavelength can increase or decrease the losses caused by fibre bending. In general, single mode fibres are considered to be low loss fibres, which increase system bandwidth and length. So these fibres are most useful for large bandwidth applications. Since these fibres are more resistant to attenuation, they can also be used in significantly longer cable runs.

5.3.2 Multimode Fibres

As the name implies multimode fibres allow more than one mode to propagate. Over 100 modes can propagate through multimode fibres at a time. Multimode fibre is sometimes abbreviated as MMF. The size of its core is typically around 50 μm (Fig. 5.4b). The multimode fibre is of two types, namely step index and graded index fibres.

5.3.2.1 Multimode Step Index Fibres

Multimode step index fibre is shown in Fig. 5.5 along with the refractive indices of its core and cladding. In this type of optical fibre, the number of propagating modes depends on the ratio of core diameter and the wavelength. This ratio is inversely proportional to the numerical aperture (abbreviated as NA and defined later). Typically the core diameter is 50 μm to 100 μm and NA varies from 0.20 to 0.29, respectively. Multimode fibre is used in short lengths, such as those used in Local Area Networks (LANs) and Storage Area Networks (SANs). Because the multimode optical fibre has higher NA and the large core size, fibre connections and launching of light has become very easy. Multimode fibres permit the use of light emitting diodes (LEDs). In such fibres, core-to-core alignment is less critical during fibre splicing. However, due to several modes the effect of dispersion gets increased, i.e., the modes arrive at the fibre end at slightly different times and so spreading of pulses takes place. This dispersion of the modes affects the system bandwidth. Therefore, the core diameter, NA, and index profile properties of multimode fibres are optimized to maximize the system bandwidth.

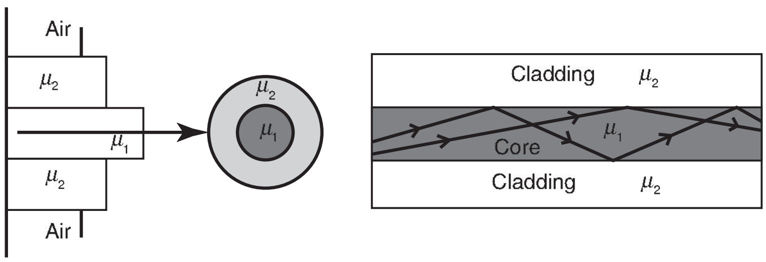

Figure 5.5

5.3.2.2 Multimode Graded Index Fibres

In a multimode graded index optical fibre, the refractive index of the core decreases with increasing radial distance from the fibre axis, which is the imaginary central axis running along the length of the fibre (Fig. 5.6). The value of the refractive index is highest at the centre of the core and decreases to a value at the edge of the core that equals the refractive index of the cladding. Therefore, the light waves in the outer zones of the core

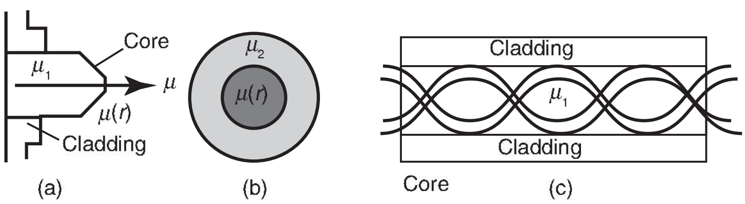

Figure 5.6

travel faster than those in the centre of the core. Thus the dispersion of the modes is compensated by this type of fibre design. Under this situation, the light waves follow sinusoidal paths along the fibre. In such fibres, the most common profile of the refractive index is very nearly parabolic that results in continual refocusing of the rays in the core, and minimizing modal dispersion. Standard graded index fibres typically have a core diameter of 50 μm or 62.5 μm and a cladding diameter of 125 μm. It is typically used for transmitting the information to the distances of a couple of kilometers. The advantage of the graded index fibre in comparison with multimode step index fibre is the considerable decrease in modal dispersion.

5.4 ACCEPTANCE ANGLE AND NUMERICAL APERTURE LO3

In order to propagate or transmit the light wave through the optical fibre, it is necessary to launch the light at angles that fall within certain range. The maximum limit of this angle is decided by the acceptance angle.

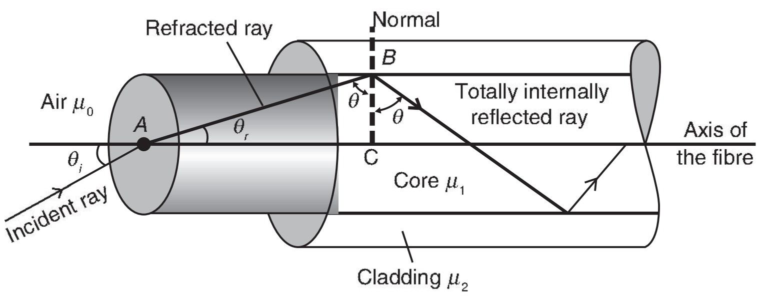

FIGURE 5.7

5.4.1 Acceptance Angle

Let us consider an optical fibre into which the light is incident. In Fig. 5.7, we show a section of cylindrical optical fibre. The refractive index of the core is μ_1 and that of the cladding is μ_2 such that $\mu_1 > \mu_2$. The refractive index of the medium form which the light is incident in the fibre is μ_0. A light wave enters the fibre at an angle θ_i with the axis of the fibre. This wave gets refracted at an angle θ_r and strikes core-cladding interface at an angle θ. If θ is greater than the critical angle θ_c, the wave undergoes total internal reflection at the interface, since $\mu_1 > \mu_2$. As long as the angle θ is greater than θ_c, the light will stay within the core of the fibre.

Let us now compute the incident angle θ_i for which $\theta_i \geq \theta_c$ such that the light refocuses within the core of the fibre. Applying Snell's law to the launching face of the fibre, we get

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{\mu_1}{\mu_0} \tag{i}$$

If θ_i is increased beyond the limit, θ will drop below the critical value θ_c (as $\theta_r + \theta = 90°$, in ΔABC) and the ray escapes from the side walls of the fibre. The largest value of θ_i occurs when $\theta = \theta_c$. This value of θ_i we represent by θ_i max. From the ΔABC, it is seen that

$$\sin\theta_r = \sin(90° - \theta) = \cos\theta, \text{ (as } \theta_r + \theta = 90°) \tag{ii}$$

From Eqs. (i) and (ii), we get

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{\mu_1}{\mu_0} \text{ or } \sin\theta_i = \frac{\mu_1}{\mu_0}\cos\theta$$

when $\theta = \theta_c$, $\sin\theta_i = \dfrac{\mu_1}{\mu_0}\cos\theta_c$ (iii)

At critical angle, $\sin\theta_c = \dfrac{\mu_2}{\mu_1}$ (as $\theta = 90°$)

$$\therefore \quad \cos\theta_c = \sqrt{1-\sin^2\theta_c}$$

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

or $$\cos\theta_c = \sqrt{\frac{\mu_1^2-\mu_2^2}{\mu_1^2}} \qquad \text{(iv)}$$

By putting the value of $\cos\theta_c$ from Eq. (iv) into Eq. (iii), we get

$$\sin\theta_{i\,\max} = \frac{\sqrt{\mu_1^2-\mu_2^2}}{\mu_0} \qquad \text{(v)}$$

If the incident wave of light is launched from air medium (for which $\mu_0 = 1$), then putting $\theta_{i\,\max} = \theta_0$, Eq. (v) may be simplified to

$$\sin\theta_0 = \sqrt{\mu_1^2-\mu_2^2} \text{ or } \theta_0 = \sin^{-1}\left(\sqrt{\mu_1^2-\mu_2^2}\right) \qquad \text{(vi)}$$

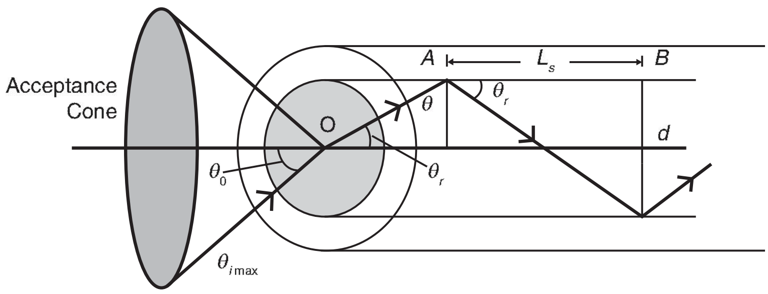

FIGURE 5.8

The angle θ_0 is called the acceptance angle of the fibre, which may be defined as the maximum angle that a light wave can have relative to the axis of the fibre for its propagation through the fibre. The light wave contained within the cone having a full angle $2\theta_0$ are accepted and transmitted along the fibre. Therefore, the cone associated with the angle $2\theta_0$ is called the *acceptance cone* (Fig. 5.8). The light incident at an angle beyond θ_0 refracts through the cladding. As at every internal reflection the light will be lost being incident at an angle less than the critical angle, the corresponding optical energy is lost. It is also obvious that the acceptance angle would be larger if the diameter of the cone is larger.

5.4.2 Numerical Aperture

Numerical aperture (NA) is the most important parameter of an optical fibre. It is a measure of how much light can be collected by an optical system such as an optical fibre or a microscope lens. Based on the refractive indices of core and cladding, we can measure the values of NA. It is defined as the sine of the acceptance angle if the end faces of the fibre are exposed to a medium for which $\mu_0 = 1$ (air). Otherwise, the numerical aperture is defined as $NA = \mu_0 \sin \theta_0$

For $\mu_0 = 1$, $$NA = \sin \theta_0 = \sqrt{\mu_1^2 - \mu_2^2}$$

This relation shows that the light gathering ability of an optical fibre increases with its numerical aperture. Since the maximum value of sin θ_0 can be 1 only, the value of NA cannot exceed 1. It means the largest value of NA is unity. When $\theta_0 \approx 90°$, the fibre totally reflects all the light entering its face. Fibres with a wide variety or numerical apertures running from about 0.2 up to 1.0 and including 1.0 may commercially be obtained.

5.4.3 Skip Distance

It is well known that the light propagates in the optical fibre based on the principle of total internal reflection. The light ray gets reflected from the walls of the fibre. The distance between the two successive reflections of a ray of light propagating in the fibre is called the skip distance L_s. In Fig. 5.8, the distance AB is the skip distance, given by

$$L_s = d \cot \theta_r,$$

where d is the diameter of the core of the fibre and θ_r is the angle of refraction in the core. We can write the above relation in terms of incidence angle θ_i and the refractive indices μ_1 and μ_0 by using Snell's law as $\frac{\sin \theta_i}{\sin \theta_r} = \frac{\mu_1}{\mu_0}$. This gives

$$\sin \theta_r = \frac{\mu_0}{\mu_1} \sin \theta_i \quad \text{or} \quad \cos \theta_r = \sqrt{1 - \frac{\mu_0^2}{\mu_1^2} \sin^2 \theta_i}$$

Hence $$L_s = d \frac{\sqrt{1 - \left(\frac{\mu_0^2 \sin^2 \theta_i}{\mu_1^2} \right)^2}}{\frac{\mu_0 \sin \theta_i}{\mu_1}}$$

or $$L_s = d \sqrt{\left(\frac{\mu_1}{\mu_0 \sin \theta_i} \right)^2 - 1}$$

It is clear that the inverse of the skip distance L_s, i.e., $1/L_s$ will give the total number of reflections made by the light ray in a given length of the fibre. For example, in a fibre of length L, the number of reflections N_r would be

$$N_r = \frac{L}{d \sqrt{\left(\frac{\mu_1}{\mu_0 \sin \theta_i} \right)^2 - 1}}$$

For example, in the case $\mu_1 = 1.60$, $\mu_0 = 1$, $\theta_i = 30°$ and $d = 0.05$ mm, we get the skip distance as 0.152 mm. Therefore, in 1 m of fibre there will be 6580 reflections.

5.4.4 Relative Refractive Index

It has been established that the refractive indices of the core and the cladding of the fibre are different. The difference of these two indices gives a measure of the relative refractive index difference. In this light, it can be obtained that

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

Now $\frac{(\mu_1 + \mu_2)}{2}$ is very nearly equal to μ_1 in view of $\mu_1 >> \mu_2$. Further, we put $\frac{(\mu_1 - \mu_2)}{\mu_1} = \Delta\mu_r$ in the above equation and obtain $\mu_1^2 - \mu_2^2 = 2\mu_1^2\Delta\mu_r$. In term of this relation the numerical aperture *NA* can be written as

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

Here $\Delta\mu_r$ is called the relative refractive index difference or *fractional refractive index*.

5.5 FIBRE OPTICS COMMUNICATION LO4

A general communication system was oftenly used before the development of optical fibre communication. This system employs its essential components as modulator or transmitter, transmission medium and the demodulator or receiver, as shown in Fig. 5.9a. However, optical fibres have replaced copper coaxial cables due to their various advantages as they are very light weight, thin conduit cables which provide greater communications capacity with lower loss.

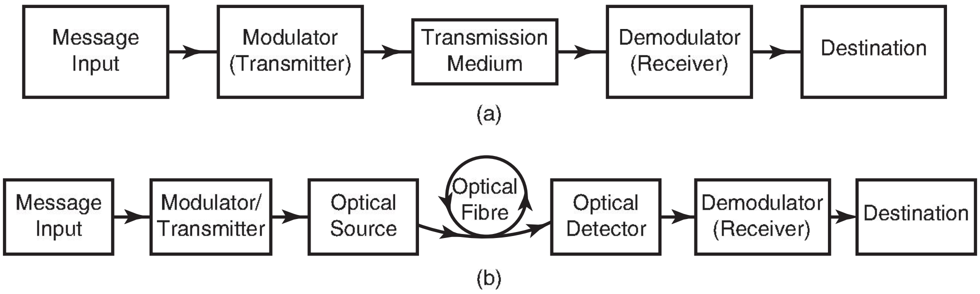

Figure 5.9

A fibre optic communication system from signal source to signal output is shown in Fig. 5.9b. Here, the information that is to be transmitted is first converted into an optical signal from an electrical signal. Then the optical signal is converted to an electrical signal after transmission by an optical fibre. Independent of the original nature of the signal, a fibre provides the choice of format of transmission as analog or digital because these two formats are convertible into one another. So the signal in analog or digital form is impressed onto the carrier wave by using a modulator. The carrier wave is generated from the carrier source which may be either light emitting diode (LED) or laser diode (LD). This carrier wave is modulated using various techniques viz., frequency modulation, amplitude modulation and digital modulation. The carrier source output into the optical fibre is represented by a single pulse. When a pulse is passed through a fibre, then it is attenuated and distorted due to several mechanism for example by intermodal distortion. Therefore, repeaters and regenerators are used to amplify the light signal at several positions of the fibre. And after that the light signal is coupled into a detector that may be a semiconductor device or most commonly a PIN diode at the end of a fibre. This changes the optical signal back into an electrical signal. The response of a detector should be well matched with the optical frequency of the signal received. The output of the detector then passes through the signal processor, which is used to capture the original electrical signal from the carrier by using the process of filtering, amplification and an analog to digital conversion. The signal output is finally communicated by the cathode ray tube (if it is video signal), by loudspeaker (if it is audio signal) or by computer input (if it is digital signal).

5.5.1 High Bit Rate Optical Fibre Communication

A high bit rate signal carried on copper wire transmission line is generally needed to be amplified every 300 m. However, high bit rate signals when carried on optical fibres need such amplification only every 100 km or so. As discussed earlier, a detector changes the optical signal back into an electrical signal, the light signal is coupled to the detector changes the optical signal back into an electrical signal, the light signal is coupled to the detector at the remote end of the fibre. This is done effectively when the response of the detector is well matched with the optical frequency of the signal received. Then a signal processor handles the detector output. The function of the signal processor is to recapture the original electrical signal from the carrier. This process involves filteration and amplification and a digital to analog conversion.

5.5.2 Allowed Modes and Normalised Frequency

It appears from the theory of acceptance cone that every ray shall propagate successfully once it enters the fibre within its acceptance cone. However, this is not the case always and only certain ray directions or modes are allowed to propagate successfully. Actually any ray represents plane waves that move up and down in the fibre. Evidently such waves overlap and interfere with one another. Only those waves will sustain which satisfy a condition of resonance. Keeping in view this point, we can derive a relation for a parameter m_m in terms of the core diameter d, numerical aperture NA and the wavelength λ. This is given by

$$m_m = \frac{1}{2}\left(\pi \frac{d}{\lambda} NA\right)^2$$

The largest integer that is less than the parameter m_m shall give the maximum number of modes that propagate successfully in the fibre. Therefore, it is clear that number of possible modes will be larger for the higher ratio d/λ. So, larger diameter fibres shall allow more number of modes to propagate. For this reason, they are called multimode fibres. However, if d/λ is small such that m_m is less than 2, the fibre will allow only one mode. So this type of fibre is called *single mode fibre* or *monomode fibre*. The condition $m_m < 2$ for a single mode fibre can be achieved if

$$\frac{d}{\lambda} < \frac{2}{\pi\,(NA)}$$

The above condition related to the diameter guarantees the performance of single mode fibre. However, a more careful analysis reveals that the single mode performance can be achieved even if

$$\frac{d}{\lambda} < \frac{2.4}{\pi\,(NA)}$$

As is evident, the parameter m_m decides the number of possible modes. Since this parameter depends on core diameter d and the numerical aperture NA, the number of allowed modes would be different for fibres of different core diameters. The word "number" intuitively adds a concept of normalised frequency, given by

$$v_n = \pi \frac{d}{\lambda} NA = \frac{\pi d}{\lambda}\sqrt{\mu_1^2 - \mu_2^2}$$

A careful look indicates that the normalised frequency is nothing but the factor carried by the parenthesis of the parameter m_m. Therefore, in terms of normalised frequency v_n, the parameter m_m is written as

$$m_m = \frac{v_n^2}{2}$$

5.5.3 Attenuation

When light travels along the fibre, there is a loss of optical power, which is called attenuation. Signal attenuation is defined as the ratio of optical input power (P_i) to the output power (P_0). Optical input power is the power transmitted into the fibre from an optical source. Optical output power is the power received at the fibre end. The following relation defines the signal attenuation or absorption coefficient in terms of length L of the fibre.

$$\alpha = \frac{10}{L}\log_{10}\frac{P_i}{P_0}$$

So signal attenuation is a log relationship. Length L of the fibre is expressed in kilometers. In view of this, the unit of attenuation is decibles/kilometre i.e., dB/km. The causes of attenuation in an optical fibre are absorption, scattering and bending losses. Each mechanism of loss is influenced by the properties of fibre material and fibre structure. However, loss is also present at fibre connections. Absorption losses over a length L of fibre can be described by the usual exponential law for light intensity (or irradiance) I

$$I = I_0 e^{-\alpha L}$$

where I_0 is the initial intensity or the irradiance of the light.

The attenuation profile for a single mode cable is depicted in Fig. 5.10, which shows that the amount of attenuation is also wavelength dependent. In the figure, two absorption peaks at 1.0μm and 1.4 μm are observed which are respectively due to the peculiarities of the single mode fibre and the traces of water remaining in the fibre as an impurity. The wavelengths 1.31 μm and 1.55 μm are the two standard single mode wavelengths that are commonly used due to this water absorption peaks. However, now the wavelength 1.55 μm are used in view of the need to extend the distance between repeaters.

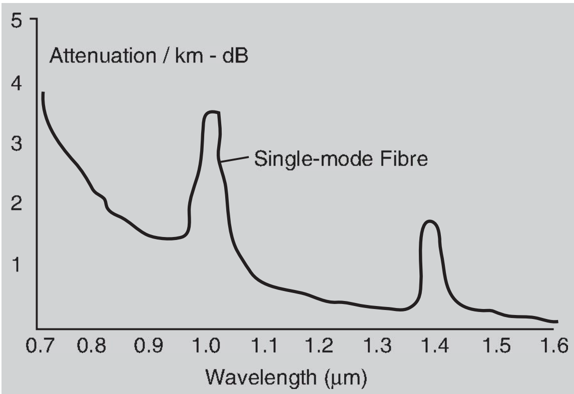

Figure 5.10

5.4.4 Pulse Dispersion in Optical Fibre

The spreading of pulses of light as they propagate along a fibre is called dispersion. In optics, dispersion is the phenomenon in which the phase velocity of a wave depends on its frequency. Such medium is called a *dispersive medium*. The dispersive effects in a single mode fibre are much smaller than a multimode fibre. Due to dispersion, optical pulses in optical fibres spread and hence the signals degrade over long distances. There are several factors that cause dispersion in optical fibres. For example, in multimode fibres, different axial speeds of different transverse modes cause intermodal dispersion that limits the performance of the fibre. In single mode fibres, though intermodal dispersion is eliminated, chromatic dispersion occurs because of the slight variation in the index of the glass with the wavelength of the light. Dispersion limits the bandwidth of the fibre because the spreading optical pulses limit the rate that pulses can follow one another on the fibre and still remain distinguishable at the receiver.

5.6 OPTICAL FIBRE SENSORS LO5

Optical fibre sensors are fibre based devices that are used for sensing some typical quantities like temperature or mechanical strain. These sensors are also sometimes used for several vibrations, pressure, acceleration, or concentrations of chemical species. The general principle of operation of fibre optic sensors is that when a light beam is sent through an optical fibre, then its parameters either in the fibre or in one or several fibre Bragg gratings experience subtle change. Then the light reaches a detector arrangement that measures these changes (Fig. 5.11). The light beam may be changed in five of its optical properties viz. intensity, phase, polarisation, wavelength and spectral distribution.

Optical fibre sensors have a number of advantages over other types of sensors.

(i) They consist of electrically insulating material, which makes possible their use in high voltage environments.

(ii) Since there is no risk of electrical sparks, even in the case of defects, these can be safely used in explosive environments.

(iii) They are immune to electromagnetic interference (EMI).

(iv) Their materials can be chemically inactive.

(v) They can operate over a broad range of temperature.

(vi) They have multiplexing capabilities, i.e., multiple sensors in a single fibre can be interrogated with a single optical source.

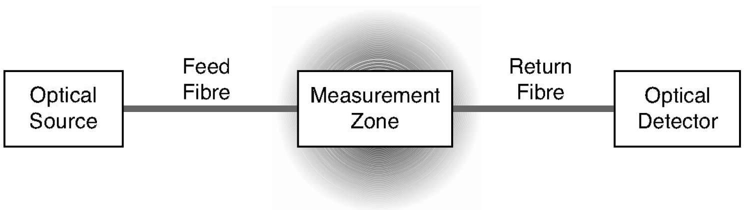

Figure 5.11

There are two types of sensors named intrinsic sensor and extrinsic sensor, which are dicussed below.

5.6.1 Intrinsic Sensors

In these types of sensors, the sensing medium is itself a fibre. It means the propagating light never leaves the fibre and is altered in some way by an external phenomenon. The simplest type of sensor called *intensity based fibre* optic pressure sensor is based on the variation of intensity, as in this case only a simple source and detector are required. A special feature of intrinsic fibre optic sensors is that they can provide distributed sensing over distances of up to one metre.

This type of sensor is useful in measuring the force being exerted between the two objects A and B, shown in Fig. 5.12. The fibre will become slightly deformed when the pressure is increased and it experiences increased microbending losses which results in a decrease in the light intensity received at the detector. A decrease in the pressure relieves stress on the fibre and hence there is an increase in transmitted light detected.

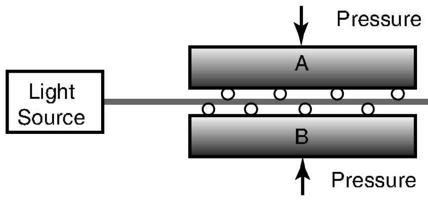

Figure 5.12

5.6.2 Extrinsic Sensors

In extrinsic sensors, the delivery of light and its collection is done by the fibre. Thus the propagating light leaves the fibre, is altered in some way, and is collected by the same or another fibre. These sensors are used to measure vibration, rotation, displacement, velocity, acceleration, torque, and twisting. A major benefit of these sensors is their ability to reach places which are otherwise inaccessible. For example, the temperature inside aircraft jet engines is measured by using a fibre that transmits radiation into a radiation pyrometer located outside the engine. The same way, extrinsic sensors can also be used to measure the internal temperature of electrical transformers, where the extreme electromagnetic fields present make other measurement techniques impossible.

An example of an intensity based extrinsic sensor is shown in Fig. 5.13, which detects any increase or decrease in the length/between the two fibres. The amount of light launched into the return fibre will decrease as the distance between the two fibres is increased. However, if the length is decreased the light intensity collected by the receiver will increase. This way these fibre optic sensors are capable of determining small shifts between objects.

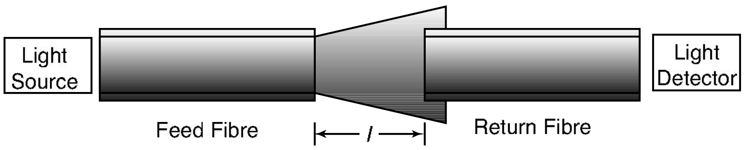

Figure 5.13

5.7 OPTICAL FIBRE CONNECTOR LO5

The end of an optical fibre is terminated by using an optical fibre connector, which enables quicker connection and disconnection than splicing. The coupling and alignment of the cones of fibres is done with the help of connector so that light can pass. Now a days a variety of optical fibre connectors is available. In general, the connectors are differentiated by their dimensions and methods of mechanical coupling. For example, some organisations standardize one kind of connector, depending on what equipment they commonly use, or per type of fibre. Now-a-days, small form factor connectors (for example, LC) and multifibre connectors (for example, MTP) are replacing the traditional connectors (for example, SC) in view of their datacom and telecom applications.

5.8 OPTICAL FIBRE COUPLERS LO5

Optical fibre couplers are fibre devices that are used for coupling light from one or several input fibres to one or several output fibres. Optical fibre couplers can distribute the optical signal (power) from one fibre among two or more fibres. So the light from an input fibre can appear at one or more outputs, with the distribution of power depending on the wavelength and polarisation of light. A two-by-two fibre coupler is shown in Fig. 5.14.

Figure 5.14

Simple point to point connections are required for some fibre optic data links, which need multiport or other types of connections. As the input signal is divided among the output ports, fibre optic couplers attenuate the signal much more than a connector or splice. Fibre optic couplers can be either active or inactive devices. An inactive coupler redistributes the optical signal without optical-to-electrical conversion, whereas the active couplers are electronic devices that split or combine the signal electrically and use fibre optic detectors and sources for input and output.

A basic fibre optic coupler is shown in Fig. 5.15 with N_1 input ports and N_2 output ports, which range from 1 to 64. The number of input ports and output ports vary depending on the intended application for the coupler. Types of fibre optic couplers include optical splitters, optical combiners, X couplers, star couplers, and tree couplers. Fibre couplers are usually directional couplers, which means that essentially no optical power sent into some input port can go back into one of the input ports.

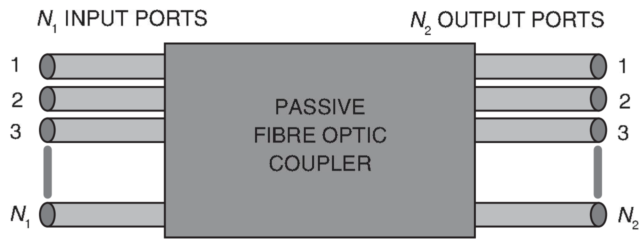

Figure 5.15

5.9 APPLICATIONS OF OPTICAL FIBRE COUPLERS LO6

Below we mention some typical applications of fibre couplers.

(i) Fibre couplers can be used in fibre interferometers.

(ii) In a cable TV system, the powerful signal from one transmitter is sent into a fibre splitter, which distributes the power signal over a large number of output fibres for different customers.

(iii) In fibre ring lasers, there is no resonator ends where light could be injected so a dichroic fibre coupler can be used to inject pump light within resonator. Then another fibre coupler is used as the output coupler.

(iv) For combining the radiation of several laser dioide in high power fibre lasers, we generally use multimode fibre couplers.

SUMMARY

The essence of the topics covered in this chapter is produced below.

- In communication systems, radiowaves or microwaves have been extensively used as the carrier waves for transmitting information. However, invention of laser led to the discovery of optical fibres which can carry hundred thousand times more information.

- Advantages of optical fibres over the traditional metal communication lines were discussed in view of their greater bandwidth, less susceptibility to interference, light weight, smaller thickness, and fast transmission of data.
- Based on transmission properties and the structure, we can categorize optical fibres as single mode fibre or multimode fibre. Typical diameter of core of the single mode fibre is 10 μm and that of multimode fibre ranges from 50 μm to 100 μm.
- Since the refractive index steps up when we move towards core side from the cladding side, these fibres are referred to as step index fibres.
- In order to compensate the mode dispersion, fibre is designed such that the refractive index of core and cladding match at their common boundary. Such type of fibre is called multimode graded index fibre where most commonly parabolic profile of the refractive index is used.
- It is not necessary that all the incident light rays shall transmit through the fibre. In this context, acceptance angle is an important parameter. The rays that fall within the acceptance cone are accepted for the transmission.
- Numerical aperture (NA) is the most important parameter of an optical fibre, which tells us how much light can be collected by an optical fibre.
- It is well known that the propagation of the light is based on its total internal reflection. The light gets reflected from the walls of the fibre. The distance between the two successive reflections of a light ray propagating in the fibre is called the skip distance. Inverse of this distance gives the total number of reflections made by the light in the fibre of a given length.
- Propagation mechanism of the information in optical fibres was discussed in detail along with a difference of components used in the general communication system.
- The acceptance cone only accepts the rays for their transmission in the fibre. It is not that the every ray shall propagate successfully once it enters within the acceptance cone. Only certain ray directions or modes are allowed to propagate successfully. Since ray represents plane waves that move up and down in the fibre, such waves overlap and interfere with one another. Only those waves will sustain which satisfy a condition of resonance. Such waves or modes are called allowed modes. Therefore, the concept of allowed modes and the normalised frequency were given and in support some theoretical relations were talked about.
- When light travels along the fibre, there is a loss of optical power. This is called attenuation. Signal attenuation is defined as the ratio of optical input power (P_i) to the optical output power (P_0) and is given by

$$\alpha = \frac{10}{L}\log_{10}\frac{P_i}{P_0}$$

- The unit of attenuation is decibels/kilometre, i.e., dB/km.
- In addition to the loss of power of the signal (pulse of light) that propagates in the fibre, there is spreading of pulses of light. This is called dispersion. So the dispersion was talked about in the case of optical fibre.
- The wonderful application of the optical fibres is in fibre optic sensors, which are fibre based devices that are used for sensing some typical quantities like temperature or mechanical strain. These sensors

are also sometimes used for sensing vibrations, pressure, acceleration, or concentrations of chemical species.

- The types of optical fibre sensors, namely intrinsic sensors and extrinsic sensors, were discussed. In the intrinsic sensors, the sensing medium is itself a fibre. So the propagating light never leaves the fibre and is altered by an external phenomenon. On the other hand, in the extrinsic sensors, the delivery of light and its collection is done by the fibre. Thus the propagating light leaves the fibre, is altered in some way, and is collected by the same or another fibre. The extrinsic sensors are used to measure vibration, rotation, displacement, velocity, acceleration, torque, and twisting.
- Another application of fibres is in optical fibre connectors and couplers. Optical fibre couplers are fibre devices that are used for coupling light from one or several input fibres to one or several output fibres. Optical fibre couplers can distribute the optical signal (power) from one fibre among two or more fibres. The fibre couplers also have applications in fibre interferometers, cable TV system, fibre ring lasers, etc.

SOLVED EXAMPLES

EXAMPLE 1 The refractive indices for core and cladding for a step index fibre are 1.52 and 1.41 respectively. Calculate (i) critical angle (ii) numerical aperture and (iii) the maximum incidence angle.

SOLUTION Given $\mu_{\text{core}} = \mu_1 = 1.52$, $\mu_{\text{clad}} = \mu_2 = 1.41$

Critical angle $(\theta_c) = \sin^{-1}\left(\dfrac{\mu_2}{\mu_1}\right)$

Numerical aperture (NA) $= \sqrt{(\mu_1^2 - \mu_2^2)}$ and

Maximum incidence angle $(\theta_0) = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}]$

(i) $$\theta_c = \sin^{-1}\left[\frac{1.41}{1.52}\right] = 68.06°$$

or $$\theta_c = \mathbf{68.1°}$$

(ii) $$NA = \sqrt{(\mu_1^2 - \mu_2^2)} = \sqrt{(1.52)^2 - (1.41)^2} = 0.5677$$
$$= \mathbf{0.568}$$

(iii) $$\theta_0 = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}] = \sin^{-1}\sqrt{(1.52)^2 - (1.41)^2}$$
$$= \mathbf{\sin^{-1}\ [0.568]}$$
$$\theta_0 = 34.59° = \mathbf{34.6°}$$

EXAMPLE 2 Find out the numerical aperture and acceptance angle of an optical fibre, if the refractive indices for core and cladding are 1.6 and 1.5, respectively.

SOLUTION Given $\mu_{\text{core}} = \mu_1 = 1.6$, $\mu_{\text{clad}} = \mu_2 = 1.5$

Numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

Acceptance angle $(\theta_0) = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}]$

$$NA = \sqrt{(1.6)^2 - (1.5)^2} = \sqrt{0.31} = 0.556$$

or $NA = \mathbf{0.556}$

$$\theta_0 = \sin^{-1}(0.556) = \mathbf{33.78°}$$

Example 3 A light ray enters from air to a fibre. The refractive index of air is 1.0. The fibre has refractive index of core is equal to 1.5 and that of cladding is 1.48. Find the critical angle, the fractional refractive index, the acceptance angle and numerical aperture.

Solution Given $\mu_{air} = \mu_0 = 1.0$, $\mu_{core} = \mu_1 = 1.5$, $\mu_{clad} = \mu_2 = 1.48$

Critical angle $(\theta_c) = \sin^{-1}\left(\frac{\mu_2}{\mu_1}\right)$

Fractional refractive index $(\Delta\mu_r) = \frac{\mu_1 - \mu_2}{\mu_1}$

Acceptance angle $(\theta_0) = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}]$

Numercial aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

$$\theta_c = \sin^{-1}\left(\frac{\mu_2}{\mu_1}\right) = \sin^{-1}\left(\frac{1.48}{1.50}\right) = 80.63°$$

or $\theta_c = \mathbf{80.63°}$

$$\Delta\mu_r = \frac{\mu_1 - \mu_2}{\mu_1} = \frac{1.50 - 1.48}{1.48} = 0.0133$$

or $\Delta\mu_r =$ **1.33% of light.**

$$NA = \sqrt{(\mu_1^2 - \mu_2^2)} = \sqrt{(1.50)^2 - (1.48)^2} = \mathbf{0.244}$$

$$\theta_0 = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}] = \sin^{-1}[0.244]$$

$\therefore$ $\theta_0 = \mathbf{14.13°}$

Example 4 Calculate the numerical aperture and acceptance angle of optical fibre of refractive indices for core and cladding as 1.62 and 1.52, respectively.

Solution Given $\mu_{core} = \mu_1 = 1.62$ and $\mu_{clad} = \mu_2 = 1.52$

Numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$ and

Acceptance angle $(\theta_0) = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}]$

$$NA = \sqrt{(1.62)^2 - (1.52)^2} = [\sqrt{0.314}]$$

$$NA = \mathbf{0.56}$$

$$\theta_0 = \sin^{-1}(NA) = \sin^{-1}(0.56) = \mathbf{34.06°}$$

$$\theta_0 = \mathbf{34.1°}$$

Example 5 Calculate the refractive indices of the core and cladding material of a fibre from the following data: $NA = 0.22$, $\Delta\mu_r = 0.012$, where NA is numerical aperture,

$$\Delta\mu_r = \frac{\mu_{core} - \mu_{clad}}{\mu_{core}}$$

μ_{core} and μ_{clad} have usual meanings.

Solution Given: $NA = 0.22$, $\Delta\mu_r = 0.012$, $\mu_{core} = \mu_1$ and $\mu_{clad} = \mu_2$

Formula used are

$$\Delta\mu_r = \frac{\mu_1 - \mu_2}{\mu_1} \text{ and } NA = \sqrt{\mu_1^2 - \mu_2^2}$$

$$\Delta\mu_r = 0.012 = \frac{\mu_1 - \mu_2}{\mu_1} = 1 - \frac{\mu_2}{\mu_1}$$

or $\mu_2 = 0.988\,\mu_1$

$$NA = 0.22 = \sqrt{\mu_1^2 - (0.988\mu_1)^2}$$

or $0.0484 = \mu_1^2\,[0.023856]$

or $\mu_1 = \mathbf{1.424} = \mu_{core}$

and $\mu_2 = 0.988\,\mu_1 = \mathbf{1.41}$

$\mu_2 = \mathbf{1.41} = \mu_{clad}$

Example 6 The refractive indices for core and cladding for a step index fibre of diameter 0.064 mm are 1.53 and 1.39, respectively. Calculate (i) numerical aperture of the fibre (ii) acceptance angle (iii) number of reflections in 90 cm of fibre for a ray at the maximum incidence angle and for one at half this angle.

Solution Given $d = 0.064$ mm, $\mu_{core} = \mu_1 = 1.53$ and $\mu_{clad} = \mu_2 = 1.39$

Numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

Acceptance angle $(\theta_0) = \sin^{-1}[\sqrt{(\mu_1^2 - \mu_2^2)}]$

Number of reflections $(N_r) = \dfrac{L}{d\sqrt{\left[\dfrac{\mu_1}{\mu_0 \sin\theta_i}\right]^2 - 1}}$

$$NA = \sqrt{(1.53)^2 - (1.39)^2} = 0.639$$

$NA = \mathbf{0.64}$

$\theta_0 = \sin^{-1}(NA) = \sin^{-1}(0.64) = 39.79°$

$\theta_0 = \mathbf{39.8°}$

N_r at $\theta_i = \theta_0$, then

$$N_r = \frac{90}{0.0064\sqrt{\left(\dfrac{1.53}{1\times 0.64}\right)^2 - 1}}$$

$= \mathbf{6476}$

N_r at $\theta_i = \dfrac{\theta_0}{2}$, then

$$N_r = \frac{90}{0.0064\sqrt{\left(\dfrac{1.53}{1\times \sin 19.9°}\right)^2 - 1}} = \frac{90}{0.0064\sqrt{\left(\dfrac{1.53}{0.34}\right)^2 - 1}}$$

$= 3205.14$

$N_r = \mathbf{3205}$

Example 7 A graded index fibre has a core diameter of 0.05 mm and numerical aperture of 0.22 at a wavelength of 8500 Å. What are the normalised frequency (v_n) and number of modes guided in the core?

Solution Given $d = 0.05$ mm, $NA = 0.22$, $\lambda = 0.00085$ mm

Normalised frequency $(v_n) = \dfrac{\pi d}{\lambda} NA$ and

Maximum number of modes guided or propagated $(m_m) = \dfrac{1}{2}\left[\dfrac{\pi d}{\lambda} NA\right]^2$

$$v_n = \frac{3.14 \times 0.05 \times 10^{-3} \times 0.22}{0.85 \times 10^{-6}}$$

$$= 40.63$$

$$v_n = \mathbf{40.63}$$

and $$m_m = \frac{1}{2}(v_n)^2$$

$$= 825.398$$

$$m_m = \mathbf{825}$$

Example 8 The refractive indices of core and cladding of a fibre are 1.465 and 1.460, respectively, and the light of wavelength 1.25 μm is used. What should be the diameter of core for a single mode propagation? If the core diameter is given as 50 μm, how many modes can propagate through the fibre?

Solution Given $\mu_{core} = \mu_1 = 1.465$, $\mu_{clad} = \mu_2 = 1.460$ and $\lambda = 1.25 \times 10^{-6}$ m, $d = ?$

For single mode propagation, $d < \dfrac{2.4 \times \lambda}{\pi NA}$,

Number of modes propagated $(m_m) = \dfrac{1}{2}\left[\dfrac{\pi d}{\lambda} NA\right]^2$

Numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

So, $$NA = \sqrt{(1.465)^2 - (1.460)^2} = 0.121$$

$$d < \frac{2.4 \times 1.25 \times 10^{-6}}{3.14 \times 0.121} = 7.896 \times 10^{-6}\text{m}$$

$$\mathbf{d < 7.9\ \mu m}$$

$$m_m = \frac{1}{2}\left[\frac{3.14 \times 50 \times 10^{-6} \times 0.121}{1.25 \times 10^{-6}}\right]^2$$

$$= \frac{1}{2}(15.197)^2$$

$$= \frac{230.94}{2}$$

$$= 115.47$$

∴ Number of modes
$= \mathbf{115}$

Example 9 How many modes can propagate in a step-index fibre with a core diameter as 40 μm, if the refractive indices of its core and cladding are 1.461 and 1.456, respectively, and the light of wavelength is 8500 Å?

Solution Given $\mu_{core} = \mu_1 = 1.461$, $\mu_{clad} = \mu_2 = 1.456$, $\lambda = 0.85 \times 10^{-6}$ m and $d = 4.0 \times 10^{-5}$ m.

Maximum mode propagated $(m_m) = \frac{1}{2}\left[\frac{\pi d}{\lambda} NA\right]^2$

and numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

So,

$$NA = \sqrt{(1.461)^2 - (1.456)^2}$$

$$NA = 0.121$$

$$m_m = \frac{1}{2}\left[\frac{3.14 \times 4.0 \times 10^{-5}}{0.85 \times 10^{-6}} \times 0.121\right]^2 = 159.83$$

$$m_m = \mathbf{159}$$

Example 10 Consider a slab waveguide made of Al Ga As having refractive indices for core and cladding as 3.6 and 3.55, respectively. Find how many modes can propagate in this waveguide if
(i) $d = 5\lambda$ and (ii) $d = 50\lambda$?

Solution Given $\mu_{core} = \mu_1 = 3.6$, $\mu_{clad} = \mu_2 = 3.55$

Number of modes propagated $(m_m) = \frac{1}{2}\left[\frac{\pi d}{2} NA\right]^2$

and numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

$$NA = \sqrt{(3.6)^2 - (3.55)^2} = 0.5979$$

(i) $d = 5\lambda$, then

$$m_m = \frac{1}{2}\left[\frac{3.14 \times 5\lambda}{\lambda} \times .5979\right]^2 = 44.06$$

$$m_m = \mathbf{44}$$

(ii) $d = 50\lambda$, then

$$m_m = \frac{1}{2}\left[\frac{3.14 \times 50\lambda}{\lambda} \times 0.5979\right]^2 = 4405.81$$

$$m_m = \mathbf{4405}$$

Example 11 Find out the maximum core diameter of an optical fibre whose core and cladding have refractive indices as 1.460 and 1.457, respectively, and which supports only one mode at 1.25×10^{-6} m wavelength.

Solution Given: $\mu_{core} = \mu_1 = 1.460$, $\mu_{clad} = \mu_2 = 1.457$ and $\lambda = 1.25 \times 10^{-6}$ m.

Diameter of core $(d) < \frac{2.4\lambda}{\pi\, NA}$ and numerical aperture $(NA) = \sqrt{(\mu_1^2 - \mu_2^2)}$

So

$$NA = \sqrt{(1.46)^2 - (1.457)^2} = 0.0935$$

$$\therefore \quad d < \frac{2.4 \times 1.25 \times 10^{-6}}{3.14 \times 0.0935}$$

$$d < 10.22\ \mu\text{m}$$

$\therefore$ Maximum core diameter = **10.22 μm**

EXAMPLE 12 A signal of power 5 μW exists just inside the entrance of 0.1 km long fibre. Calculate the absorption coefficient of the fibre if the power inside the fibre be 1 μW.

SOLUTION Given $L = 0.1$ km, $P_i = 5 \times 10^{-6}$ W and $P_0 = 1 \times 10^{-6}$ W.

Absoprtion coefficient $(\alpha) = \dfrac{10}{L}\log\left(\dfrac{P_i}{P_0}\right)$

or $$\alpha = \left(\frac{10}{0.1}\right)\log_{10}\left(\frac{5\times10^{-6}}{1.0\times10^{-6}}\right) = 69.89 \text{ dB/km}$$

or $$\alpha = \mathbf{70\ dB/km}$$

EXAMPLE 13 An optical fibre cable 3.0 km long is made up of three 1.0 km length spliced together. The losses due to each length and splice are respectively 5 dB and 1.0 dB. What would be out put power if the input power is 5 mW?

SOLUTION Given $\alpha = 18/3 = 6$ dB/km, $P_i = 5$ mW.

$\because$ $$\alpha = \left(\frac{10}{L}\right)\log_{10}\left(\frac{P_i}{P_0}\right)$$

$$\frac{\alpha L}{10} = \frac{1}{2.303}\ln\left(\frac{P_i}{P_0}\right)$$

$$\ln\left(\frac{P_i}{P_0}\right) = \frac{6\times3\times2.303}{10} = 4.1454$$

$$\frac{P_i}{P_0} = e^{4.1454}$$

or $$P_0 = \frac{P_i}{e^{4.1454}} = \frac{5\times10^{-3}}{63.143}$$

or $$P_0 = 0.079 \times 10^{-3} \text{ W}$$

or $$P_0 = \mathbf{0.080\ mW}$$

EXAMPLE 14 A step-index fibre has a core index of refraction of $n_1 = 1.425$. The cut-off angle for light entering the fibre from air is found to be 8.50°. (a) Calculate the numerical aperture of the fibre. (b) Find the index of refraction of the cladding of this fibre (c) What would be the new numerical aperture and cut-off angle if the fibre were submersed in water?

SOLUTION

(a) The index of refraction for air $n_0 = n_{\text{air}} = 1.0003$.
The numerical aperture is found from the formula
$$NA = n_0 \sin\theta_{0\max} = (1.0003)\sin(8.50°) = \mathbf{0.1479}$$

(b) The index of refraction of the cladding can be found from the numerical aperture using the formula
$$n_1^2 - n_2^2 = NA^2$$
This gives $n_2^2 = n_2^1 - NA^2 = (1.425)^2 - (0.1479)^2 = 2.0088$
$$n_2 = \mathbf{1.417}$$

(c) The index of refraction for water $n_0 = n_{\text{water}} = 1.33$. Since the numerical aperture is a property of the fibre and only depends upon n_1 and n_2, it will not change when the medium outside the fibre changes.
The cut-off angle will change in case the numerical aperture is to be kept unaffected by a change in n_0. It means $NA = \mathbf{0.1479}$.
Using $\sin\theta_{0\max} = NA/n_0$, we get
$$\theta_{0\max} = \sin^{-1}(NA/n_0) = \sin^{-1}(0.1479/1.33) = \sin^{-1}(0.1112) = \mathbf{6.38°}.$$

Objective Type Questions

Q.1 Optical fibre communication uses carrier wave as
(a) radiowave (b) laser wave (c) ordinary light (d) microwaves.

Q.2 Optical fibre communication is based on the phenomenon of
(a) refraction (b) total internal reflection
(c) polarisation (d) diffraction.

Q.3 The loss in intensity of light in optical fibre is due to
(a) reflection (b) absorption (c) scattering (d) all of these.

Q.4 In single mode fibre the diameter of core is nearly equal to
(a) 10 μm (b) 100 μm (c) 50 μm (d) 125 μm.

Q.5 The inner most part of the optical fibre in known as
(a) core (b) cladding (c) sheath (d) optical fibre axis.

Q.6 The refractive indices of core (μ_1) and cladding (μ_2) of an optical fibre satisfy the relation
(a) $\mu_1 > \mu_2$ (b) $\mu_1 < \mu_2$ (c) $\mu_1 = \mu_2$ (d) none of them.

Q.7 By increasing the refractive index of core, the number of modes of propagation in an optical fibre cable
(a) remains unchange (b) increases
(c) decreases (d) none of these.

Q.8 In graded index optical fibre the refractive index of core is
(a) non-uniform (b) increase towards the axis of core
(c) same at core-cladding interface (d) all of these.

Q.9 In multimode step index fibre, the core diameter is of the order of
(a) 10 to 20 μm (b) 20 to 30 μm (c) 300 to 400 μm (d) 50 to 200 μm.

Q.10 The acceptance angle in terms of refractive index of core (μ_1) and cladding (μ_2), when the end face of an optical fibre is exposed by the air is equal to
(a) $\cos^{-1}(\mu_1^2 - \mu_2^2)$ (b) $\sin^{-1}(\mu_1^2 - \mu_2^2)$ (c) $\sin^{-1}\sqrt{(\mu_1^2 - \mu_2^2)}$ (d) $\sin^{-1}\sqrt{(\mu_2^2 - \mu_1^2)}$.

Q.11 If μ_1 be the refractive index of core, μ_2 that of cladding and μ_0 of the medium meeting end face of fibre, the value of numerical aperture (*NA*) can exceed 1 when
(a) $\mu_0 = 1$ (b) $\mu_0 > 1$ (c) $\mu_2 < \mu_1$ () $\mu_2 > \mu_1$.

Q.12 In intrinsic optical fibre sensor, the sensing medium is
(a) fibre (b) laser light (c) light detector (d) none of these.

Short-Answer Questions

Q.1 What is fibre optics?
Q.2 What do you mean by numerical aperture?
Q.3 What do you understand by core and cladding?
Q.4 Give name of various types of fibres.
Q.5 Why optical fibre communications are so important?
Q.6 Can more than one signal be propagated in single mode fibre?

PRACTICE PROBLEMS

General Questions

Q.1 What is an optical fibre? Define and explain the terms

(a) Acceptance angle
(b) Acceptance cone
(c) Numerical aperture
(d) Relative refractive index difference
(e) Propagating modes and
(f) Normalised frequency.

Q.2 What are single mode, multimode and graded index fibres? Also explain in detail the difference in structures of single mode step index and multimode graded index fibre.

Q.3 Discuss the physical significance of numerical aperture. How does it depend on refractive indices of core and cladding?

Q.4 Explain the allowed modes in an optical fibre. How are they related to normalized frequency?

Q.5 Discuss the propagation mechanisms of light waves in optical fibre.

Q.6 Describe schematically the basic elements of optical fibre communication system.

Q.7 Explain why does fraction of power of a signal get lost due to bending of fibre.

Q.8 Discuss the attenuation and dispersion of signals in optical fibre.

Q.9 What do you understand by optical fibre sensors. How many types of optical fibre sensors are commonly used?

Q.10 How are optical fibre connectors and couplers needed in communication?

Q.11 What are the advantages of using optical fibre communication systems?

Q.12 Enumerate some applications of optical fibre communication system.

Q.13 Write a note on

(a) Fibre optics
(b) Application of optical fibre
(c) Numerical aperture and its physical significance
(d) Optical fibre sensors and couplers.