UNIT 12 OPTICAL COMMUNICATION

Structure

12.1 INTRODUCTION

Optical Communications is not new to mankind. In fact, in the early days, light from the fire was used to convey messages over long distances. Towards the end of the sixth century BC, news of the downfall of Troy was transmitted from Asia Minor to Argos, a distance of over 500 kilometres, through a chain of fire signal relay stations.

However, optical communication in the modern sense implies use of techniques to convert electric signals into light waves at one end; transmission of these light waves through thin glass guides called fibres; and then conversion of the light waves back into electric signals at the other end.

In 1960 T.H. Maiman invented the Ruby Laser, which could have been a turning point in optical communications. However, heavy losses in fibre were a big problem. In 1968, the typical fibre losses were above 1000 dB per kilometre and thus not usable for communications. The breakthrough came in 1970 when the scientists at the Corning Glass Works, USA announced the achievement of losses under 20 dB per kilometre over hundreds of metres length. Thereafter, progress in the science and technology of fibre transmission has been continuing all over the world. Recent advances have made fibre optic communications a viable proposition for local, trunk as well as submarine under-sea applications. Present day fibre losses are in the range of 0.18 dB per kilometre.

In this unit we will discuss various elements of a typical optical fibre system and their characteristics. In Sec.12.2 we discuss the basic components of an optical fibre communication system. You will also learn about the advantages of using optical fibre as communication medium. In Sec.12.3 we explain the construction of optical fibre and its types. The losses in signal strength caused by optical fibre are discussed in Sec.12.4. You will learn about different optical sources in Sec.12.5 and optical detectors in Sec.12.6. Joining of optical fibre requires a special process called splicing. You will learn about splicing in Sec.12.7. In Sec.12.8 we discuss the techniques to improve the efficiency of data transmission by using compression techniques.

Objectives

After studying this unit you should be able to:

- explain the basic configuration of an optical fibre communication system;
- enumerate the advantages of optical fibre as a medium of communication;
- define numerical aperture;
- distinguish between different modes of propagation in fibres;
- describe various losses incurred in a fibre;
- discuss the dispersion in fibre;
- explain the working principle of optical sources and detectors;
- describe the method of optical fibre splicing;
- compare the channel capacities of different media; and
- discuss some methods of data compression.

12.2 BASICS OF OPTICAL FIBRE COMMUNICATION SYSTEM

12.2.1 Elements of Optical Fibre System

Basic configuration of a typical optical fibre communication system is indicated in Fig. 12.1. In such a system the communication signals, which basically are electronic signals, are converted into light signals by virtue of an electrical to optic transducer. This light signal is launched into a glass fibre making use of interface connectors. Light travels through the optical fibre cable over distances of 60-70 kilometres. These fibres are available in lengths of 2 kilometres and typically are joined together by fusion of glass called splicing. At the other end, the interface connectors extract these signals and feed them into an optical to electrical transducer, which once again convert them back to electronic signals for various communication applications.

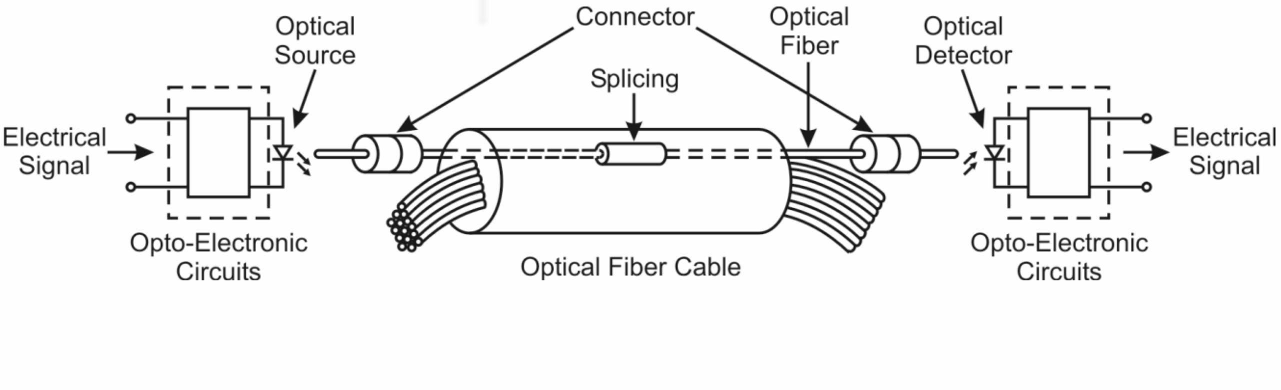

Fig. 12.1: Basic configuration of typical optical fibre system

Thus in a typical fibre optic communication system the light waves are used as carriers, optical fibres as transmission media and light sources, and detectors as opto-electronic transducers.

12.2.2 Advantages of Optical Fibre as Communication Medium

Demand for wide bandwidth has led us to the optical fibre systems. There are other reasons too which have promoted the use of optical fibres:

a. High information capacity of fibre

Optical fibres are inherently digital transmission media. Bit rates up to 2.5 Mbps are already in use in our country.

b. Low attenuation and dispersion

Fibre attenuation is now less than 0.20 dB km^{-1} and can be as low as 0.18 dB km^{-1}. The dispersion can also be kept to very low values. In this case, the repeaters can be spaced much wider apart than in the coaxial cable systems but costs per repeater may be higher.

c. Space saving

Due to extreme thin dimensions of fibre the coefficient of *information capacity* to *cable cross section* is high; therefore efficient use of the duct space is made. This is a very significant advantage in the congested city environments.

d. Low cross-talk

The cross-talk between fibres in a well designed optical fibre cable is very low and it does not generate any interference to other systems.

e. Immunity to EMI

The fibres have excellent immunity to electromagnetic interference (EMI). Thus the communications on the optical fibres are free from EMI pick ups, including the natural sources such as lightening or sparking etc.

f. Higher security

Since there is no radiation of EM waves involved unlike in the cases of microwave or the satellite systems, it is very difficult for an intruder to detect the actual signal being transmitted.

g. Low cost

The major advantage of optical fibre systems is that they are expected to be low cost systems compared with other high capacity transmission systems, due mainly to the expected very low cost of fibres relative to the metallic coaxial cables and wide spacing between the repeaters.

h. Abundance of basic resource

The basic material used in the optical fibre is Silica which is available in plenty along the sea shores in the country. It is not a depleting resource.

i. Easy maintainability

Except in case of places where the possibility of damage due to man-made faults is high, the overall maintenance effort involved is less as compared to the other high capacity systems.

You may now like to attempt an SAQ.

SAQ 1

Spend
2 *Min.*

Give any two disadvantages of an optical fibre usage.

12.2.3 Transmission Windows

You know that in the electromagnetic spectrum in optics refers to the frequencies in the infrared, visible and ultraviolet bands of the spectrum. While there is heavy attenuation in the visible and the ultraviolet portions, efficient optical communication takes place in the infrared band of the spectrum, as the loss is relatively less.

Though the infrared band is the chosen band for optical communications, the complete band is not useful for communications. There are strong absorption losses in the fibre due to the hydroxyl (OH^-) ions dissolved in the glass. The absorption spectrum of silica is shown Fig. 12.2. In this spectrum, you will notice distinct sharp absorption peaks due to OH^- ions. Between these peaks, it is possible to identify narrow windows, which are not affected by the OH^- absorption. Three such windows at 850 nm, 1310 nm and 1550 nm are identified as the best for optical fibre communication. They are called the *first,* the *second* and the *third telecommunication windows* respectively. Maximum number of optical fibre communication circuits work with sources belonging to one of the three windows.

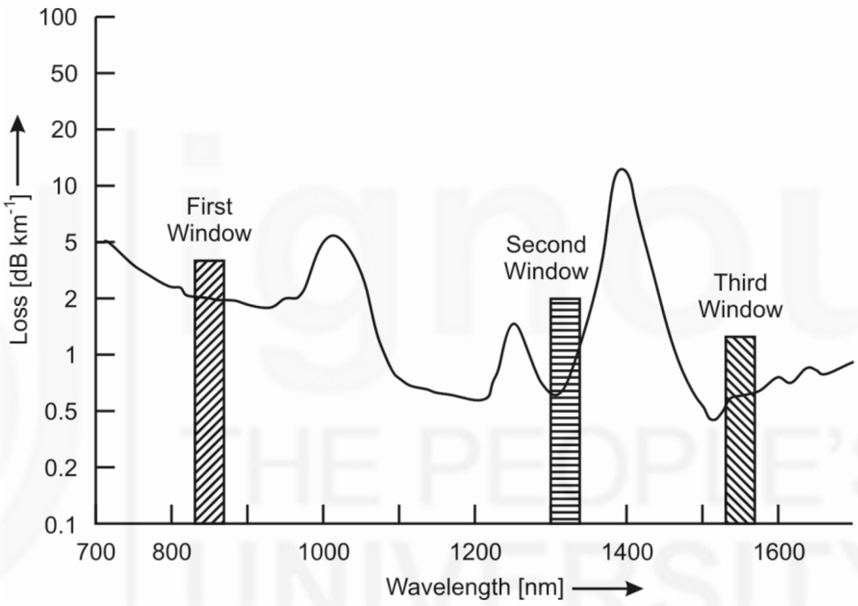

Fig. 12.2: Telecommunication windows in optical fibre

Spend 1 *Min.*

SAQ 2

Choose the proper statement:

Windows in an optical fibre are:

i) air gaps in the fibre
ii) spots where fibre is transparent
iii) spots where losses are minimum
iv) spots where losses are maximum

Let us now understand the light propagation through an optical fibre.

12.3 OPTICAL FIBRE WAVEGUIDE

After taking a broad overview of the optical fibre communication system, let us now discuss the working of an optical fibre as a waveguide. You have already learnt about the basics of optical fibre working in the course on Optics (PHE-09), however we will recapitulate the concepts briefly in this section.

12.3.1 Construction and Working of Optical Fibre

As you have already learnt in the first unit of this course, the optical fibre consists of two concentric glass cylinders with different refractive indices such that the refractive index of the core is larger than that of cladding layer. Hence there is a refraction of light, when it crosses the interface border between the core and cladding as shown in Fig. 12.3a.

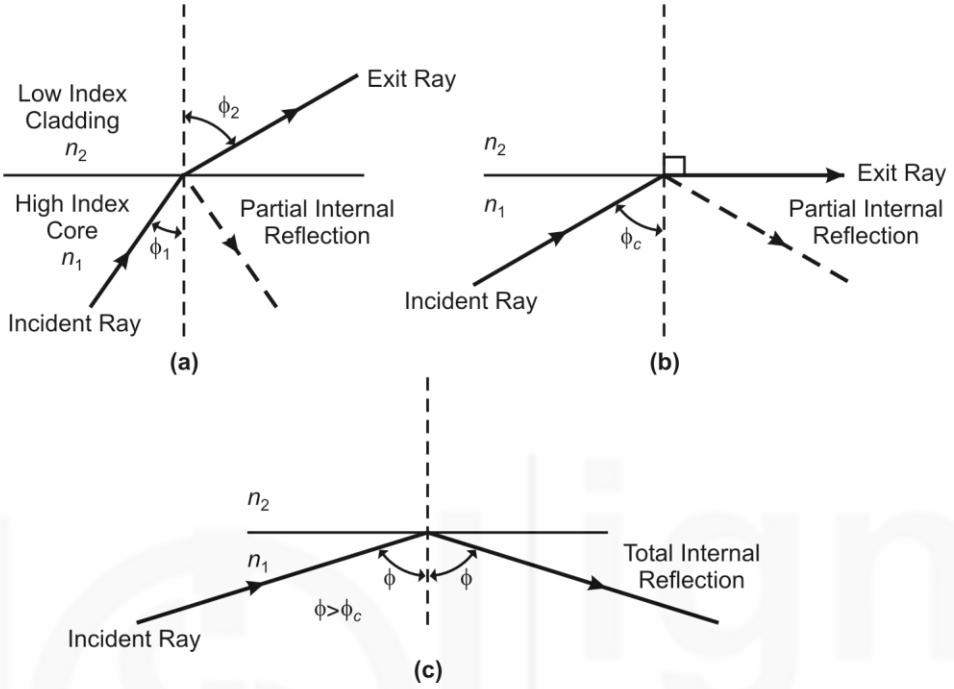

Fig. 12.3: a) Light ray on the boundary of core-cladding interface; b) limiting case of refraction at critical angle; and c) total internal reflection

The ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle ϕ_1 to the normal at the surface of the interface. If the dielectric on the other sides of the interface index (n_2) is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle ϕ_2 to the normal, where ϕ_2 is greater than ϕ_1. The angles of incidence ϕ_1 and refraction ϕ_2 are related to each other and to the refractive indices of the dielectrics by Snell's law of refraction which states that:

$$n_1 \sin \phi_1 = n_2 \sin \phi_2$$

or

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1} \qquad (12.1)$$

You will observe in Fig. 12.3a that a small amount of light is reflected back into the originating dielectric medium (partial internal reflection). As n_1 is greater than n_2, the angle of refraction is always greater than the angle of incidence. As angle ϕ_1 increase, ϕ_2 also increases and at certain values of $\phi_1 = \phi_c$ ($\phi_c < 90°$), the refracted ray is perpendicular to the normal, i.e. it travels parallel to the interface as shown in Fig.12.3b. This is the limiting case of refraction and the angle of incidence is now known as the **critical angle,** ϕ_c.

From Eq. (12.1) the value of the critical angle is given by:

$$\sin \phi_c = \frac{n_2}{n_1} \qquad (12.2)$$

At angle of incidence greater than the critical angle, the light is reflected back into the original dielectric medium with high efficiency (around 99.9%). Hence, it may be observed in Fig. 12.3c that **total internal reflection** occurs at the interface between two dielectrics of differing refractive indices when light is incident on the dielectric of lower index from the dielectric of high index, and the angle of incidence of the ray exceeds the critical value.

By this mechanism of total internal reflection the light at a sufficiently shallow angle ($\phi > \phi_c$) propagates down an optical fibre with low loss. Fig. 12.4 illustrates the transmission of a light ray in an optical fibre via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding.

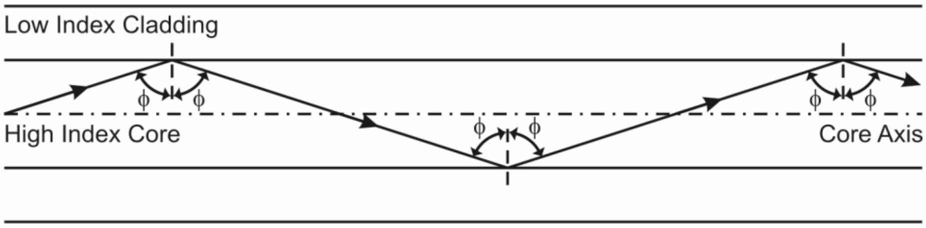

Fig. 12.4: Transmission of light ray in a perfect optical fibre

The light transmission illustrated in this figure assumes a perfect fibre. Any discontinuities or imperfections at the core-cladding interface would probably result in refraction rather than total internal reflection, with a subsequent loss of the light ray into the cladding.

12.3.2 Some Definitions

a. Acceptance angle

As we discussed in the last subsection, in any optical fibre, only the rays with a sufficiently shallow incidence angle (i.e. with an angle greater than ϕ_c) at the core-cladding interface are transmitted by total internal reflection. In other words, not all rays entering the fibre core will continue to propagate down its length.

The geometry concerned with launching a light ray into an optical fibre is shown in Fig. 12.5, which illustrates ray *A* at the critical angle ϕ_c. This ray enters the fibre core at an angle θ_a to the core-axis and is refracted at the air-core interface before transmission to the core-cladding interface at the critical angle. Hence, any ray which is incident on the fibre core at an angle greater than $\theta_{a,}$ will not be transmitted to the core-cladding interface at an angle greater than $\phi_{c,}$ and will not be totally internally reflected. This situation is also illustrated in the figure with incident ray *B* at an angle greater than θ_a. This ray is refracted at the core-cladding interface and eventually lost by radiations.

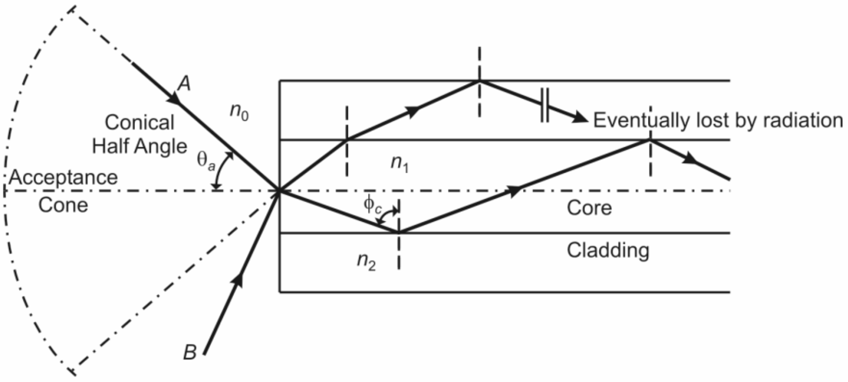

Fig. 12.5: Geometry of ray-launching in fibre

Thus, for rays to be transmitted by total internal reflection within the fibre core, they must be incident on the fibre core within an acceptance cone defined by the conical half angle θ_a. Hence θ_a is the maximum angle to the axis at which light may enter the fibre in order to be propagated, and is often referred to as the **acceptance angle** for the fibre.

b. Numerical aperture

Using the ray propagation geometry, it is possible to obtain a relationship between the acceptance angle and the refractive indices of the three media involved, namely the core, cladding and air. This leads to the definition of a more generally used term, the **numerical aperture (NA)** of the fibre.

Fig. 12.6 shows a light ray incident on the fibre core at an angle θ_1 to the fibre axis which is less than the acceptance angle for the fibre θ_a. The ray enters the fibre from a medium (air) of refractive index n_0, into the fibre core with refractive index n_1, which is slightly greater than the cladding refractive index n_2. Using Snell's law at the air-core interface we get.

$$n_0 \sin\theta_1 = n_1 \sin\theta_2 \tag{12.3}$$

Considering the right-angle triangle *ABC*,

$$\phi = \frac{\pi}{2} - \theta_2 \tag{12.4}$$

where ϕ is greater than the critical angle at the core-cladding interface. Hence Eq. (12.3) becomes

$$n_0 \sin\theta_1 = n_1 \cos\ \phi \tag{12.5}$$

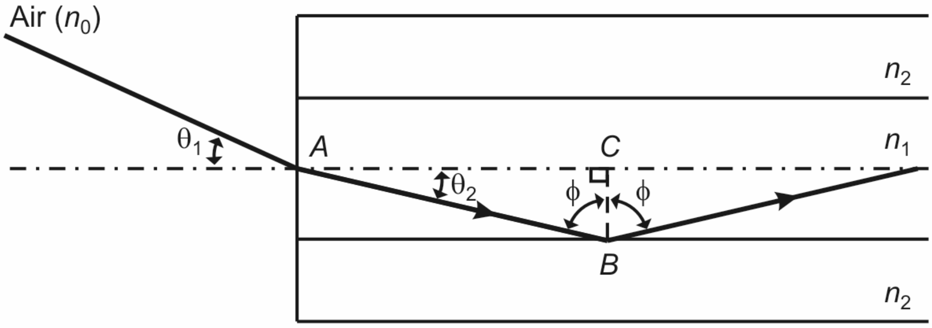

Fig. 12.6: The path for ray launched into an optical fibre in air at an input angle less than the acceptance angle for the fibre

Using the trigonometric relationship $\sin^2 \phi + \cos^2 \phi = 1$ Eq. (12.5) may be written as

$$n_0 \sin \theta_1 = n_1 \sqrt{1 - \sin^2 \phi} \qquad (12.6)$$

When the limiting case for total internal reflection is considered, ϕ equals ϕ_c. Also in the limiting case θ_1 becomes the acceptance angle for the fibre θ_a. Combining these limiting cases into Eq. (12.6) and substituting from Eq. (12.2), we get,

$$n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2} \qquad (12.7)$$

The quantity represented by Eq. (12.7) is called the **numerical aperture** (NA).

Hence the *NA* is defined as:

$$NA = n_0 \sin \theta_a = \sqrt{n_1^2 - n_2^2} \qquad (12.8)$$

Since the *NA* is often used with fibre in air where n_0 is unity, it is simply equal to $\sin \theta_a$. The numerical aperture is a very useful measure of the light-collecting ability of a fibre. It is independent of the fibre core diameter and will hold for diameters as small as 8 μm. The ray-treatment of light we used so far does not hold good for small diameters, as the geometric optics approach is invalid. This is because the ray theory model is only a partial description of the character of light. It describes the direction a plane wave component takes in the fibre but does not take into account interference between such components. When interference phenomena are considered it is found that only rays with certain discrete characteristic propagate in the fibre core. Thus the fibre will only support a discrete number of guided modes.

You may now like to solve one SAQ.

Spend
5 *Min.*

SAQ 3

A silica optical fibre with a core diameter of 30 μm has core refractive index of 1.50 and a cladding refractive index of 1.47. Calculate a) the critical angle at the core-cladding interface; b) the *NA* for the fibre; and c) the acceptance angle in air for the fibre.

12.3.3 Types of Optical Fibres

A **mode** is a stable propagation state in an optical fibre. The number of modes that can be propagated in a fibre depends on

- Refractive index of core and cladding;
- core diameter; and
- wavelength of the propagating light.

For given values of refractive indices of core and cladding and the wavelength of light, the core diameter can be reduced to achieve single mode of operation. Based on the number of modes that can propagate in a fibre, the fibres can be classified as

- Single-mode (SM) fibre; and
- Multi-mode (MM) fibre.

There are three types of optical fibres based on the distribution profile of the refractive index of the core with respect to cladding. These are shown in Fig. 12.7.

a. Step index single mode (SI SM) fibre

It has uniform refractive indices for both core (n_1) and cladding (n_2) with $n_1 > n_2$. The fibre core is very narrow (typically 2 to 10 μm) and supports only a single mode propagation as shown in Fig. 12.7a. This type of fibre has very broad bandwidth.

b. Step index multimode (SI MM) fibre

It has uniform refractive indices for both core n_1 and cladding n_2 with $n_1 > n_2$ as in case of single mode fibre, but the core diameter is above 50 μm and many number of modes are propagated simultaneously, as shown in Fig. 12.7b.

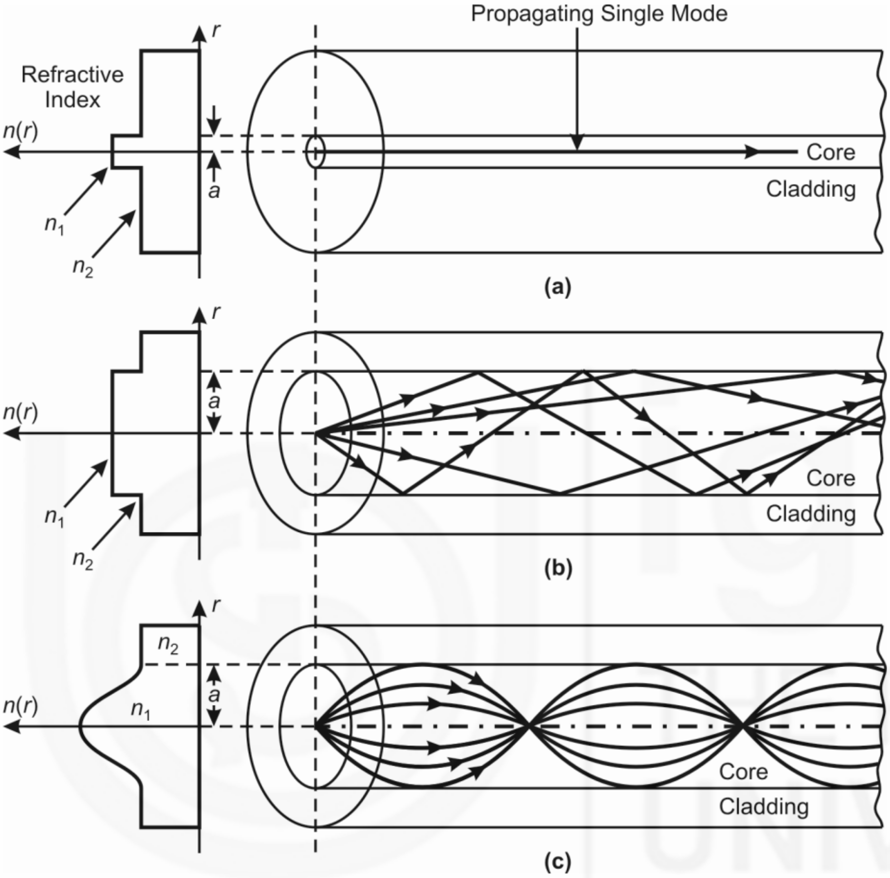

Fig. 12.7: Types of optical fibre: a) step index single mode; b) step index multimode; and c) graded index multimode

c. Graded index multimode (GI MM) fibre

This type of fibre has got a core with refractive index highest at the centre and gradually decreasing till it is the same as that of the cladding at the core-cladding boundary as shown in Fig. 12.7c.

You may now like to attempt one SAQ.

SAQ 4

Spend
3 *Min.*

Choose proper options:

a) The number of modes that can be propagated in a fibre does not depend upon:
  i) refractive index of core and cladding
  ii) cladding diameter
  iii) core diameter

iv) wavelength of light

b) Which of these is not a type of optical fibre?

i) step index multimode fibre

ii) step index single mode fibre

iii) graded index multimode fibre

iv) graded index single mode fibre

After getting the overview of light propagation in fibre, let us now discuss the causes of signal loss and distortion in a fibre.

12.4 ATTENUATION IN OPTICAL FIBRE

When the optical fibre is used for communication applications, the attenuation of signal in the fibre is the most vital parameter, since it decides the maximum length over which the optical communication can be carried out without using a repeater.

You already know that the attenuation is defined as

$$L = 10 \log_{10} (P_{out}/P_{in}). \tag{12.9}$$

Optical power is attenuated while the light traverses through the fibre due to the losses posed by a fibre. Another reason is the dispersion of signal caused during its passage through the fibre. In this section we discuss the reasons of signal attenuation.

12.6.1 Various Losses in Optical Fibre

One of the reasons why optical fibres did not become commercially viable till the seventies has been due to high losses in the fibres. The various types of losses in the fibres are depicted in Fig. 12.8.

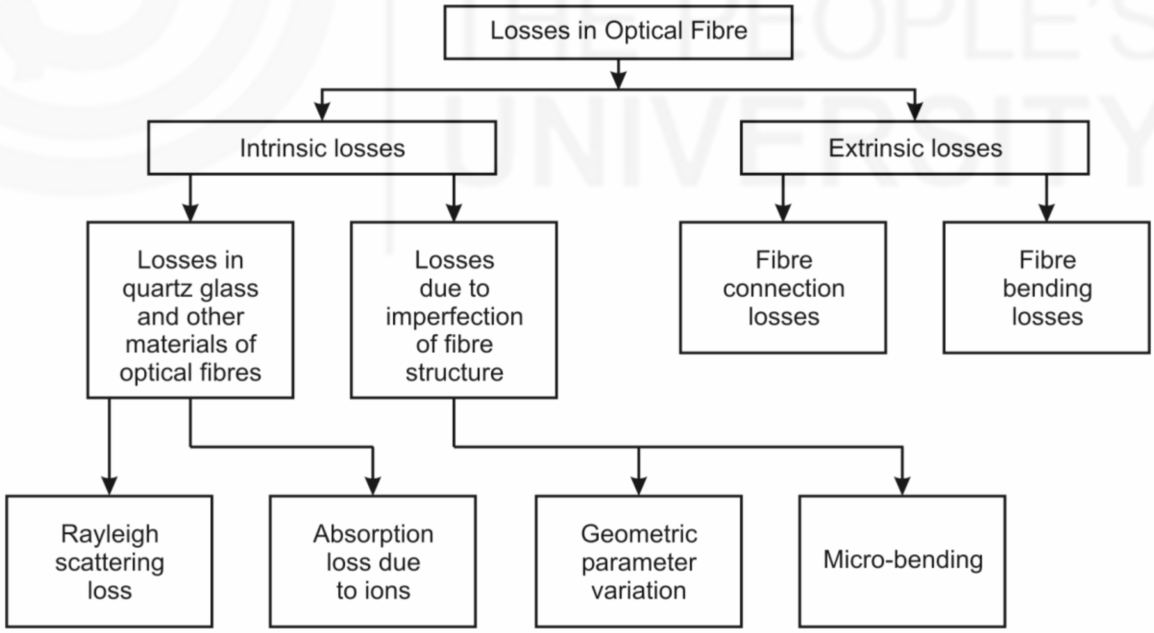

Fig. 12.8: Losses in Optical fibre

The causes of these losses are clear from Fig. 12.9.

- The **absorption losses** are a function of wavelength, as explained in Fig. 12.2. There are some spots where the losses are maximum due to molecular absorption.
- The refractive index inside the glass is not uniform due to the imperfections in the structure introduced during the manufacturing process. These result in random molecular locations which scatter the light passing through the fibre. This type of loss is known as **Rayleigh scattering.**

The Rayleigh scattering loss is approximated by the expression

$$L = 1.7\,(0.85/\lambda)^{4}, \qquad (12.10)$$

where λ is the wavelength in μm and L is the loss in dB km^{-1}.

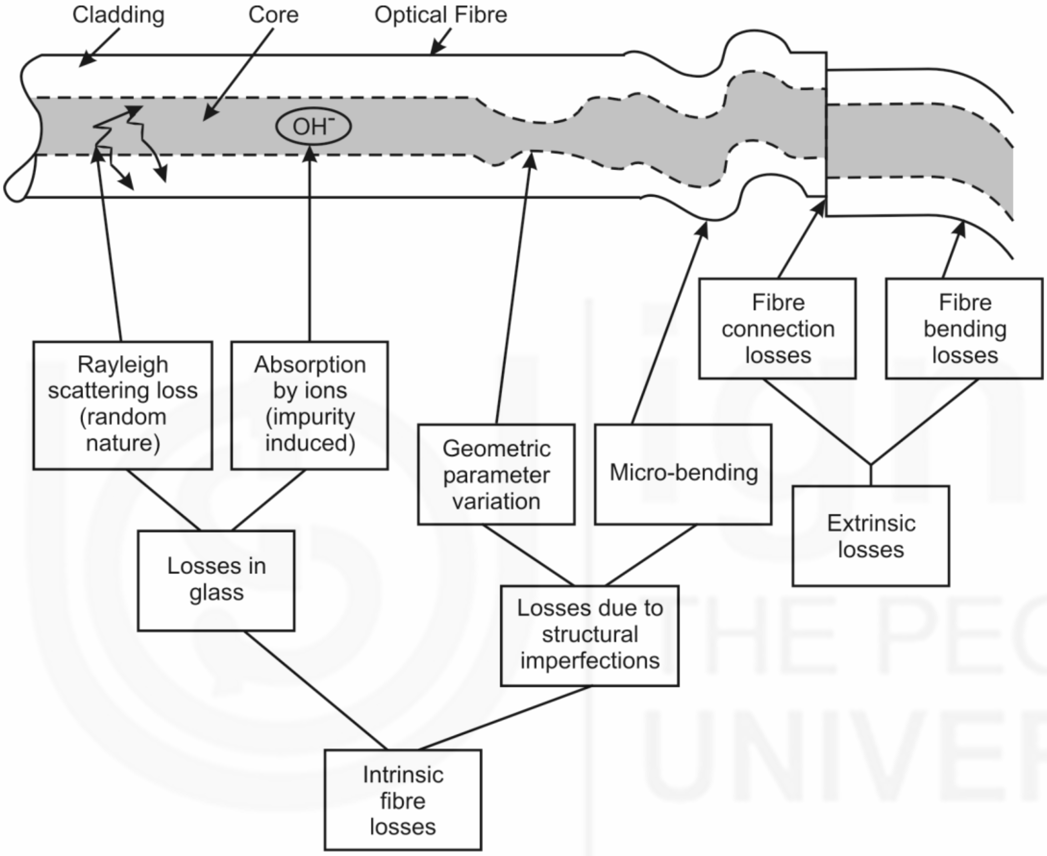

Fig. 12.9: Causes of losses in optical fibre

12.4.2 Dispersion in Fibre

When incident light pulses are applied at one end of the optical fibre, the light pulses emerging from the other end are wider than the incident light pulses as shown in Fig. 12.10. The light pulse waveform spreads in time during its propagation through

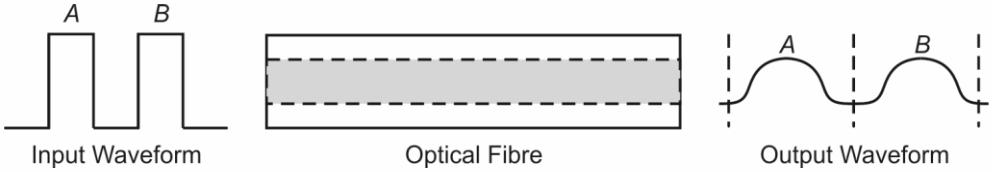

Fig. 12.10: Dispersion in fibre

the fibre. This spreading of waveform is called **dispersion**. It is expressed in terms of time per unit length. Since dispersion causes spreading of a pulse in time scale, it is possible that the output of pulse *A* may overlap with a part of pulse *B*. This is undesirable, since the data transfer in such case becomes unreliable. Dispersion is critical as it limits the bandwidth of information carrying capacity of the fibre.

Dispersion is categorised into two main types:

- Modal dispersion
- Material dispersion

a. Modal dispersion (Multi-path dispersion)

Fig. 12.11 shows the modal dispersion in a multimode fibre. Here we see that, though different modes enter the fibre at the same time instant, the path lengths traversed by each of them inside the fibre are different. Hence a pulse launched in different modes arrives at the end of the fibre at different time instances, thereby stretching the pulse in the time scale. The modal dispersion is prominent in step index multimode fibres. However, if you consider the construction of graded index multimode fibre, you will observe that since the refractive index of the core goes on reducing towards the periphery, the modes deviating away from the centre of the core travel at faster speed and hence the pulse travelling in different modes eventually reaches the end of the fibre at more or less same time, without causing any significant dispersion effect.

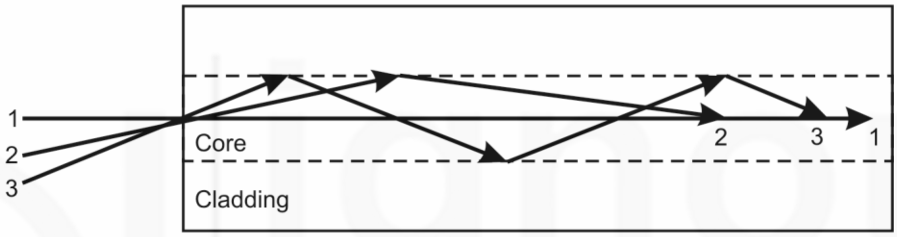

Fig. 12.11: Modal dispersion

b. Material dispersion (Chromatic dispersion)

Waveform spreading is also caused by the fact that the refractive index of glass which is the material of optical fibre, varies depending on the light wavelength. Light emitted from a light source is not a single wavelength but a wavelength spectrum with a certain width. Various components of colours in a given spectrum travel at different speeds through the fibre due to varying refractive index, causing dispersion. This type of dispersion is more prominent in single mode fibre.

Now, here is an SAQ for you.

Spend 2 *Min.*

SAQ 5

Various losses in an optical fibre are:

(a) Scattering loss	(b) Connection loss
(c) Micro bending	(d) Losses due to bends

From the above:

(i) a & b are intrinsic losses and c & d are extrinsic losses.
(ii) a & d are intrinsic losses and b & c are extrinsic losses.
(iii) a & c are intrinsic losses and b & d are extrinsic losses.
(iv) a & c are extrinsic losses and b & d are intrinsic losses.

Every optical fibre communication system has to contain electrical to light and light to electrical transducers. Let us now consider some important optical sources which convert the electrical signal into optical signal.

12.5 OPTICAL SOURCES

The fundamental function of the optical source in a fibre optic system is to convert electrical energy in the form of a current into optical energy (light) in an efficient manner which allows the light output to be effectively launched or coupled into the optical fibre. Three main types of optical light sources are available. These are:

1. wideband continuous spectra sources (incandescent lamps);
2. monochromatic incoherent sources (light emitting diodes, LEDs); and
3. monochromatic coherent source (lasers).

In the early stages of optical fibre communication the most powerful narrowband coherent light sources were necessary in order to counter the attenuation and dispersion in the fibres. Therefore, gas lasers (helium-neon) were utilised initially. However, the development of the semiconductor injection laser and LED, together with substantial improvement in the properties of optical fibres, has given prominence to these two sources.

These two sources fulfil most of the major requirements for an optical fibre emitter as outlined below:

- a size and configuration compatible with launching light into an optical fibre. Ideally, the light output should be highly directional;
- must accurately track the electrical input signal to minimise distortion and noise. Ideally, the source should be linear;
- should emit light at wavelengths where the fibre has low losses and low dispersion and where the detectors are efficient;
- possibility of simple signal modulation over a wide bandwidth extending from audio frequencies to beyond the gigahertz range.
- must couple sufficient optical power to overcome attenuation losses and provide adequate power to drive the detector;
- should have a very narrow spectral bandwidth (line-width) in order to minimise dispersion in the fibre;
- must be capable of maintaining a stable optical output independent of ambient conditions like temperature; and
- the source should be comparatively cheap and highly reliable in order to compete with conventional transmission techniques.

The first generation-optical communication sources were designed to operate between 0.8 and 0.9μm (ideally around 0.85μm) because this wavelength avoided the loss incurred in many fibres near 0.9 μm due to the OH^- ion. The LED being a lower power source generally exhibiting little spatial or temporal coherence was not suitable for long distance wideband transmission; hence laser diodes were used prominently.

However, the role of the LED as a source for optical fibre communications was enhanced following the development of multimode graded index fibre. The substantial reduction in modal dispersion provided by this fibre type over multimode step index fibre allowed incoherent LEDs emitting in the 0.8 to 0.9 μm wavelength band to be utilised for applications requiring wider bandwidths.

The advances in single-mode fibre stimulated the development of single-mode laser sources to take advantage of the extremely low dispersion offered by single-mode fibres. These systems are ideally suited for extra wideband, very long-haul applications and currently active research is being done to examine their suitability for long distance telecommunications.

Let us now discuss the light emission process in solids.

You know that the interaction of light with matter takes place in discrete packets of energy or quanta, called photons. Furthermore, the quantum theory suggests that atoms exist only in certain discrete energy states such that absorption and emission of light causes them to make a transition from one discrete energy state to another. The frequency of the absorbed or emitted radiation ν is related to the difference in energy E between the higher energy state E_2 and the lower energy state E_1 by the expression:

$$E = E_2 - E_1 = h\nu \tag{12.11}$$

where h is the Planck's constant. A single electron transition between two energy levels within the atom will provide a change in energy suitable for the absorption or emission of a photon.

Fig. 12.12a illustrates a two energy state atomic system where an atom is initially in the lower energy state E_1. When a photon with energy $(E_2 - E_1)$ is incident on the atom it may be excited into the higher energy state E_2 through absorption of the photon. This process is sometimes referred to as stimulated absorption. Alternatively, when the atom is initially in the higher energy state E_2 it can make a transition to the lower energy state E_1 providing the emission of a photon at a frequency corresponding to Eq. (12.11).

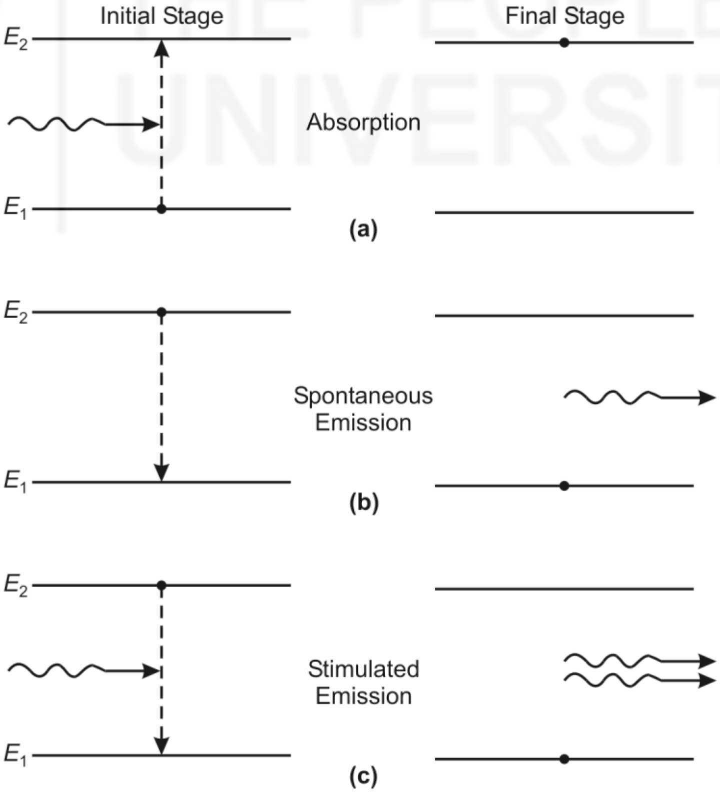

Fig. 12.12: Energy state diagram showing: a) absorption; b) spontaneous emission; and c) stimulated emission

This emission process can occur in two ways:

- by spontaneous emission in which the atom returns to the lower energy state in an entirely random manner as shown in Fig. 12.12b; or
- by stimulated emission when a photon having an energy equal to the energy difference between the two states ($E_2 - E_1$) interacts with the atom in the upper energy state causing it to return to the lower state with the creation of a second photon as shown in Fig. 12.12c.

The random nature of the spontaneous emission process where light is emitted by electronic transitions from a large number of atoms gives incoherent radiation. A similar emission process in semiconductors provides the basic mechanism for light generation within the LED.

However, it is the stimulated emission process which gives the laser its special properties as an optical source. Firstly, the photon produced by stimulated emission is generally of an identical energy to the one which caused it and hence the light associated with them is of the same frequency. Secondly, the light associated with the stimulating and stimulated photon is in phase and has the same polarisation. Furthermore, this means that when an atom is stimulated to emit light energy by an incident wave, the liberated energy can add to the wave in a constructive manner, providing amplification. You will appreciate that in order to obtain stimulated emission, it is necessary to have the electrons already in the higher energy level (excited) before the stimulating photon is incident. This prior condition of excited population of electrons is referred to as *population inversion*. In this case, the number of electrons in the excited state is more than that in the ground state.

12.5.1 Light Emitting Diode (LED)

LED is essentially a forward biased *p*-*n* junction diode. Under forward biasing condition the depletion region width and the resulting potential barrier across the junction are reduced. Electrons from the *n*-type region and holes from the *p*-types region can flow more readily across the junction into the opposite type region. Thus minority carriers are effectively injected across the junction by the application of the external voltage and a current is formed.

The increased concentration of minority carriers in the opposite type region in the forward biased *p*-*n* diode leads to the recombination of carriers across the bandgap. This process is shown in Fig. 12.13 for a direct band gap semiconductor material,

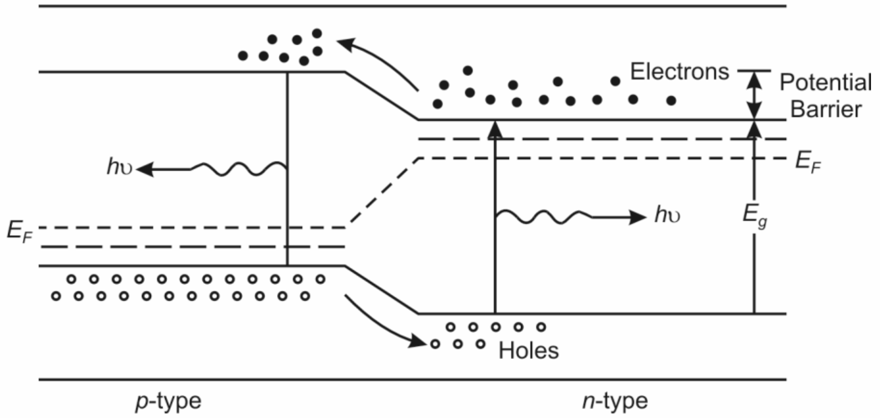

Fig. 12.13: The *p-n* junction with forward bias giving spontaneous emission of photons

where the normally empty electron states in the conduction band of the *p*-type material and the normally empty hole-states in the valence band of the *n*-type material are populated by injected carriers which recombine across the band gap. The energy released by this electron-hole recombination is approximately equal to the band gap energy E_g. Excess carrier population is therefore decreased by recombination which may be radiative or non-radiative.

In non-radiative recombination the released energy is dissipated in the form of lattice vibrations and thus heat. However, in band-to-band radiative recombination the energy is released with the creation of a photon with a frequency following Eq. (12.11) where the energy is approximately equal to the band gap energy E_g and therefore:

$$E_{\mathrm{g}} = h\nu = \frac{hc}{\lambda} \tag{12.12}$$

where c is the velocity of light in a vacuum and λ is the optical wavelength. Substituting the appropriate values of h and c in Eq. (12.12) we get

$$\lambda = \frac{1.24}{E_g} \tag{2.13}$$

where λ is written in μm and E_g in eV.

This spontaneous light emission by carrier recombination is the working principle of LED. Since light is emitted here due to application of electric field, it is sometimes referred as *electroluminescence.*

In order to achieve the light emission, it is necessary to select an appropriate semiconductor material. The most useful materials for this purpose are direct band gap semiconductors in which electrons and holes on either side of the energy gap have the same value of crystal momentum and thus direct recombination is possible. This process is illustrated in Fig. 12.14a with an energy-momentum (E-k) diagram for a direct band gap semiconductor. You will observe that the energy maximum of the valence band occurs at the same (or very nearly the same) value of electron crystal momentum (k) as the energy minimum of the conduction band. Hence when electron-hole recombination occurs, the momentum of the electron remains virtually constant and the energy released, which corresponds to the band gap energy E_g, may be emitted as light. This direct transition of an electron across the energy gap provides an efficient mechanism for photon emission and the average time the minority carrier remains in a free state before recombination is short (10^{-8} to 10^{-10} s). Some common direct band gap semiconductor materials are GaAs, GaSb, InSb etc.

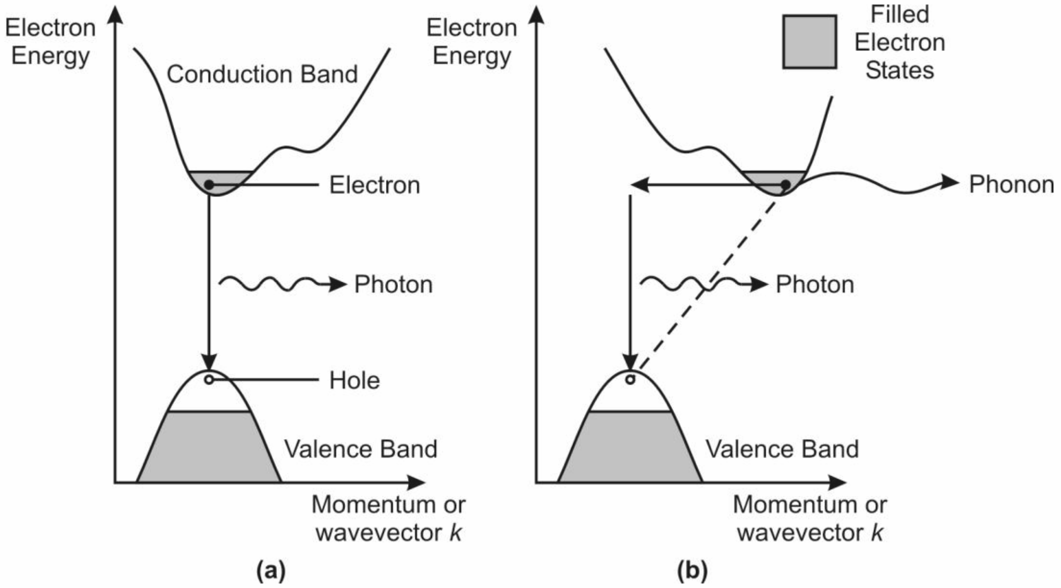

Fig. 12.14: Energy-momentum (*E-k*) diagrams showing a) direct band gap; and b) indirect band gap semiconductors

In indirect band gap semiconductors, however, the maximum and minimum energies occur at different values of crystal momentum (Fig. 12.14b). For electron-hole recombination to take place it is essential that the electron loses momentum such that it has a value of momentum corresponding to the maximum energy of the valence band. The conservation of momentum requires the emission or absorption of a third particle, a phonon. This three particle recombination process is far less probable than the two particle process exhibited by direct band gap semiconductors. Hence, the recombination in indirect band gap semiconductors is relatively slow (10^{-2} to 10^{-4} s). This is reflected by a much longer minority carrier lifetime, resulting in a greater probability of non-radiative transitions.

SAQ 6

Spend
3 *Min.*

How can LED be used practically in communication circuits?

Now we describe the process of lasing in semiconductors briefly.

12.5.2 Laser Diode

You have learnt that for lasing action, it is necessary to achieve population inversion. This carrier population inversion is achieved in an intrinsic (undoped) semiconductor by the injection of electrons into the conduction band of the material. This is illustrated in Fig. 12.15 where the electron energy and the corresponding filled states are shown. Fig. 12.15a shows the ideal situation at absolute zero when the conduction band contains no electrons. Electrons injected into the material fill the lower energy states in the conduction band up to the injection energy level for electrons. Since charge neutrality is conserved within the material, an equal density of holes is created in the top of the valence band by the absence of electrons, as shown in Fig. 12.15b.

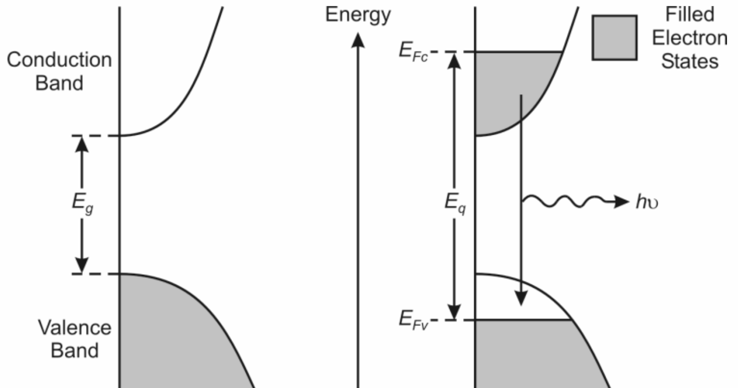

Fig. 12.15: The filled electron states for an intrinsic direct bandgap semiconductor a) at absolute zero in equilibrium; and b) with high carrier injection

Incident photons with energy E_g but less than the separation energy of the quasi-Fermi levels $E_q = E_{F_c} - E_{F_v}$ cannot be absorbed because the necessary conduction band states are occupied. However, these photons can induce a downward transition of an electron from the filled conduction band states into the empty valence band states, thus stimulating the emission of another photon. The basic condition for stimulated emission is therefore dependent on the quasi-Fermi level separation energy as well as the band gap energy and we can write

$$E_q > h\nu > E_g. \qquad (12.14)$$

Population inversion may be obtained at a *p*-*n* junction by heavy doping (degenerative doping) of both the *p*- and *n*-type material. Heavy *p*-type doping with acceptor impurities causes a lowering of the Fermi level into the valence band as shown in Fig. 12.16a. Similarly, degenerative *n*-type doping causes the Fermi level to enter the conduction band of the material. This figure depicts the position of the Fermi level and the electron occupation (shading) with no applied bias. Since in this case the junction is in thermal equilibrium, the Fermi energy has the same value throughout the material.

Fig. 12.16b shows the *p*-*n* junction when a forward bias nearly equal to the bandgap voltage is applied and hence there is direct conduction. In such a degeneratively doped semiconductor junction, there exists an active region near the depletion layer

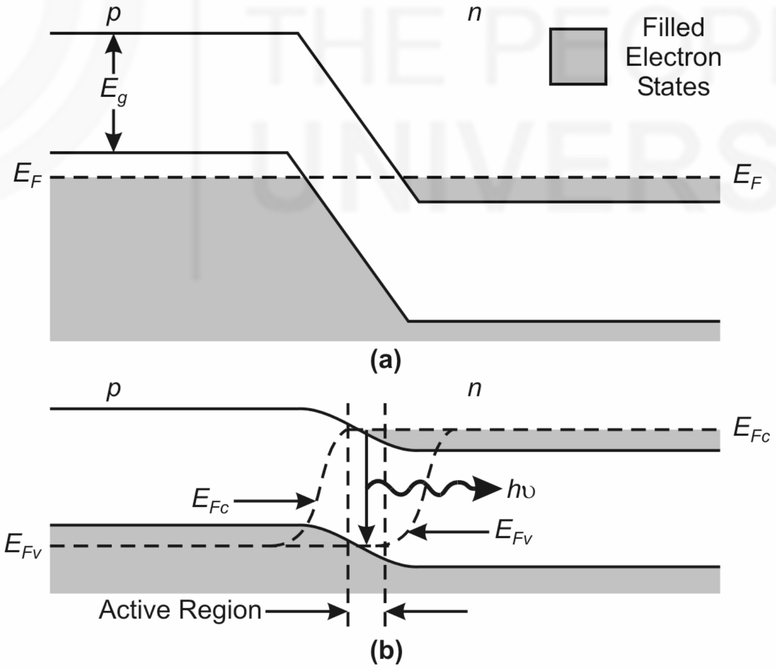

Fig. 12.16: Degenerate *p-n* junction a) with no applied bias; and b) with large forward bias

that contains simultaneously degenerate populations of electrons and holes. For this region the condition for stimulated emission is satisfied for electromagnetic radiation of frequency $E_g/h < \nu < (E_{Fc} - E_{Fv})/h$. Therefore, any radiation of this frequency which is confined to the active region will be amplified. In general, the degenerative doping distinguishes a *p-n* junction which provides stimulated emission from one which gives only spontaneous emission as in the case of the LED.

end
Min.

SAQ 7

On the basis of recombination processes involved in LED and laser diode, comment on their response times.

The following table compares LED and laser diode characteristics.

Table 12.1: A comparison of laser diode and LED performance.

S.No.	Feature	LED	Laser Diode
1	Spectral Width	Line width 20 to 100 nm	Line width 2 to 6 nm
2	Rise Time	high 2 to 250 nm	Low 0.1 to 1 ns
3	Coupling Efficiency	Very Low	Moderate
4	Temperature Sensitivity	Low	High
5	Life Time	10^5 hrs	10^4 to 10^5 hrs
6	Compatible Fibre	SI MM and GI MM	SI SM and GI MM
7	Circuit Complexity	Simple	Complex
8	Cost	Low	High
9	Path Length	Short Haul	Long Haul
10	Output Characteristics	Low Power	High Power

After discussing the optical sources, now we describe some commonly used optical detectors in the next section.

12.6 OPTICAL DETECTORS

Optical detectors work on the principle of photo absorption. The basic detection process of photo absorption is illustrated in Fig.12.17, which shows a *p-n* photodiode operated under reverse bias. The electric field developed across the *p-n* junction sweeps mobile carriers (holes and electrons) to their respective majority sides (*p*- and *n*-type material). A wide depletion layer is therefore created on either side of the junction. This barrier has the effect of stopping the majority carriers crossing the junction in the opposite direction to the field. However, the field accelerates minority carriers across the junction, forming the reverse leakage current of the diode.

A photon incident in or near the depletion region of this device, which has an energy greater than or equal to the band gap energy E_g of the material (i.e. $h\nu \geq E_g$) will excite an electron from the valence band into the conduction band. This process leaves an empty hole in the valence band and is known as the *photogeneration* of an electron-hole (carrier) pair, as shown in Fig. 12.17a. Carrier pairs so generated near the junction are separated and swept (drift) under the influence of the electric field to produce a by-current in excess of any reverse leakage current (Fig. 12.17b). Photogeneration and the separation of a carrier pair in the depletion region of this reverse biased *p-n* junction is illustrated in Fig. 12.17c.

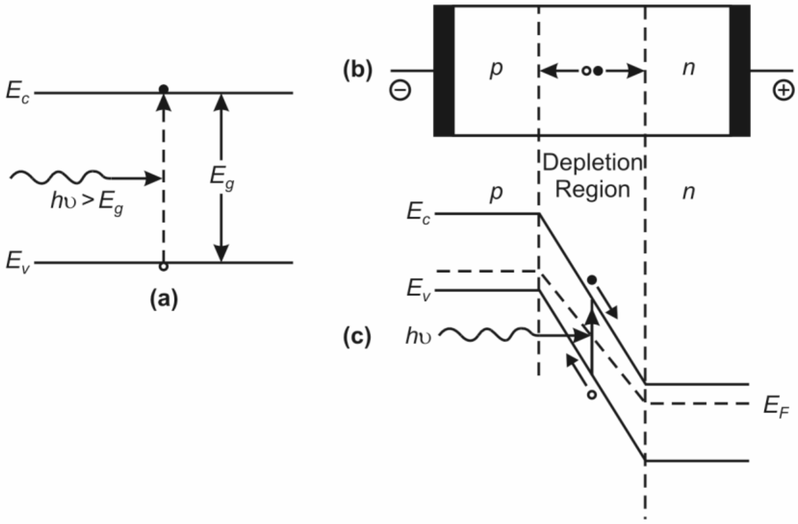

Fig. 12.17: Operation of the *p-n* photodiode: a) photogeneration of an electron-hole pair in an intrinsic semiconductor; b) the structure of the reverse biased *p-n* junction illustrating carrier drift in the depletion region; and c) the energy band diagram of the reverse biased *p-n* junction showing photogeneration and the subsequent separation of an electron-holt pair

The depletion region must be sufficiently thick to allow a large fraction of the incident light to be absorbed in order to achieve maximum carrier-pair generation. However, since long carrier drift times in the depletion region restrict the speed of operation of the photodiode, it is necessary to limit its width. Thus there is a trade-off between the number of photons absorbed (sensitivity) and the speed of response.

The material used for photodiodes are typically Si, Ge, GaAs, InAs, InP, GaSb etc. Here, silicon and germanium absorb light by both direct and indirect optical transitions. Indirect absorption requires the assistance of a phonon so that momentum as well as energy is conserved. This makes the transition probability less likely for indirect absorption than for direct absorption where no phonon is involved.

Ideally, a photodiode material should be chosen with a band gap energy slightly less than the photon energy corresponding to the longest operating wavelength of the system. This gives a sufficiently high absorption coefficient to ensure a good response, and yet limits the number of thermally generated carriers in order to achieve a low dark current (i.e. displacement current generated with no incident light). Germanium photodiodes have relatively large dark currents due to their narrow band gaps in comparison to other semiconductor materials. This is a major disadvantage with the use of germanium photodiodes, especially at shorter wavelengths (below 1.1μm). The III-V compound semiconductor materials are potentially superior to Si or Ge because their band gaps can be tailored by changing the relative concentrations of their constituents, resulting in lower dark currents. They may also be fabricated in heterojunction structures which enhances their speed of operation.

The **quantum efficiency** η of a photodetector is defined as the ratio of number of electrons generated by a photodetector and the total number of photons incident on it.

$$\eta = \frac{\text{number of electrons collected}}{\text{number of incident photons}} = \frac{r_e}{r_p} \qquad (12.15)$$

where r_p is the incident photon rate (photons per second) and r_e is the corresponding electron generation rate (electrons per second).

One of the major factors which determines the quantum efficiency is the absorption coefficient of the semiconductor material used within the photodetector. The quantum efficiency is generally less than unity as not all of the incident photons are absorbed to create electron-hole pairs. The quantum efficiency is often quoted as a percentage. Also remember that the quantum efficiency is a function of the photon wavelength and must therefore only be quoted for a specific wavelength.

12.6.1 *p-n* Photodiode

Fig. 12.18 shows a reverse biased *p*-*n* photodiode with the depletion and diffusion regions. Photons may be absorbed in both the depletion and diffusion regions. Hence electron-hole pairs are generated in both these regions. In the depletion region the carrier pairs separate and drift under the influence of the electric field, whereas outside this region the hole diffuses towards the depletion region in order to be collected. The diffusion process is very slow compared to drift and thus limits the response of the photodiode.

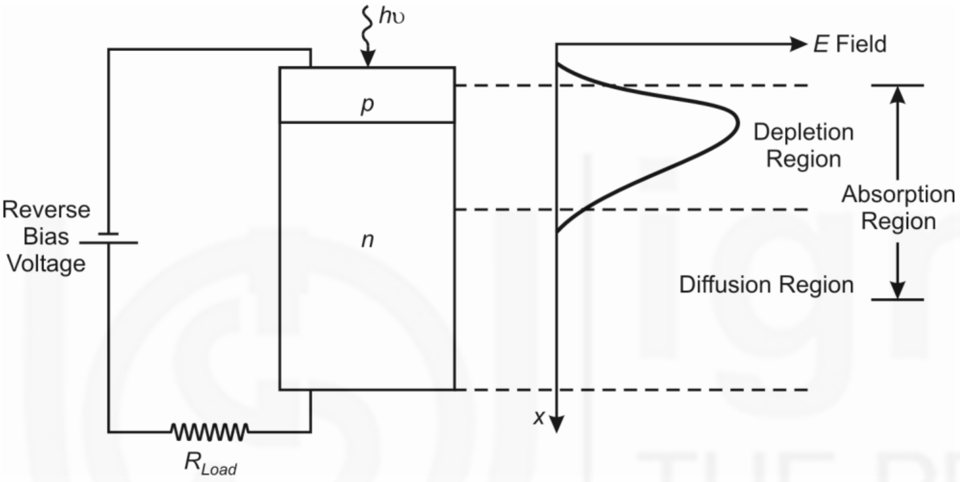

Fig. 12.18: *p-n* photodiode showing depletion and diffusion regions

It is therefore important that the photons are absorbed in the depletion region. Thus it is made as long as possible by decreasing the doping in the *n*-type material. The depletion region width in a *p*-*n* photodiode is normally 1 to 3 μm and is optimised for the efficient detection of light at a given wavelength. For silicon devices this is in the visible spectrum (0.4 to 0.7 μm) and for germanium in the near infrared region (0.7 to 0.9 μm).

12.6.2 *p-i-n* Photodiode

In order to allow operation at longer wavelengths where the light penetrates more deeply into the semiconductor materials a wider depletion region is necessary. To achieve this the *n*-type materials is doped so lightly that it can be considered intrinsic, and to make a low resistance contact a highly doped *n*-type (n^+) layer is added. This creates a *p*-*i*-*n* structure, as may be seen in Fig. 12.19a where all the absorption takes place in the depletion region.

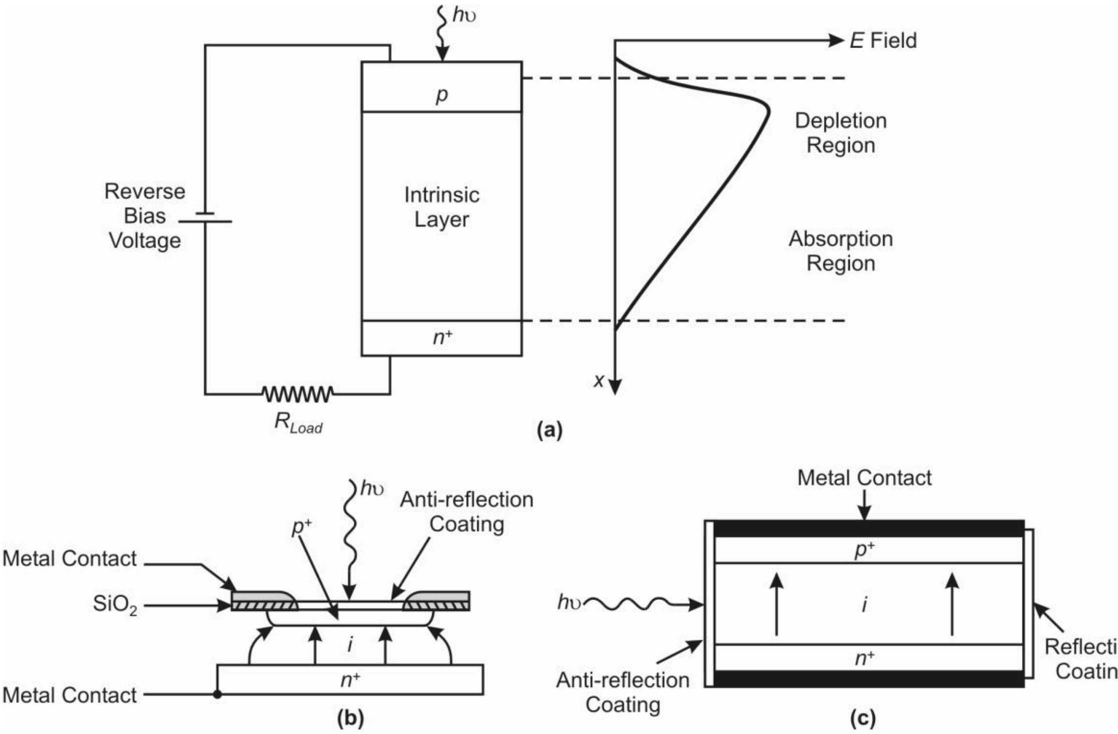

Fig. 12.19: a) *p-i-n* photodiode showing combined absorption and depletion regions; b) front illuminated; and c) side illuminated silicon *p-i-n* photodiode

This figure shows the structures of two types of silicon *p-i-n* photodiode used for operation in the shorter wavelength band below 1.09 μm. The front illuminated photodiode, when operating in the 0.8 to 0.9 μm band (Fig. 12.19b), requires a depletion region of between 20 and 50 μm in order to attain high quantum efficiency (typically 85%) together with fast response (less than 2 ns) and low dark current (1 nA). Dark current arises from surface leakage currents as well as generation-recombination currents in the depletion region in the absence of illumination. The side illuminated structure (Fig. 12.19c), where light is injected parallel to the junction plane, exhibits a large absorption width (≈ 500μm) and hence is particularly sensitive at wavelengths close to the band gap limit (1.09μm) where the absorption coefficient is relatively small.

12.6.3 Avalanche Photodiode

Another major type of optical communications detector is the avalanche photodiode (APD). This has a more complicated structure than *p-i-n* photodiode in order to create an extremely high electric field region (approximately 3×10^5 V cm^{-1}), as shown in Fig. 12.20. Effectively, in the depletion region, where most of the photons are absorbed and the primary carrier pairs generated, there is a high field region in which holes and electrons can acquire sufficient energy to excite new electron-hole pairs. This process is known as *impact ionisation* and is the phenomenon that leads to **avalanche breakdown** in ordinary reverse biased diodes. It often requires high reverse bias voltage (50 to 400 V) in order that the new carriers created by impact ionisation can themselves produce additional carriers by the same mechanism. More recently, however, diodes operating at much lower bias voltage (15 to 25V) have become available. At present both silicon and germanium APDs are available.

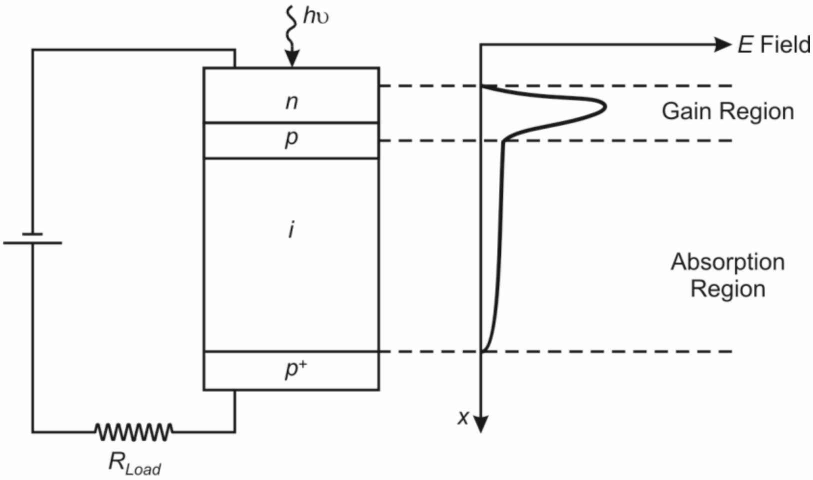

Fig. 12.20: Avalanche photodiode showing high electric field (gain) region

APDs have a distinct advantage over photodiodes without internal gain for the detection of the very low light levels often encountered in optical fibre communications. They generally provide an increase in sensitivity of between 5 and 15 dB over *p-i-n* photodiodes whilst often giving a wider dynamic range as a result of their gain variation with response time and reverse bias.

Apart from the semiconductor diodes, there are various other types of optical detectors like phototransistors, photoconductive detectors (having light dependence resistance); however we will not go into the details of these at present.

Before proceeding further, you may like to attempt an SAQ.

nd
in.

SAQ 8

Select a proper choice:

Which of these are *not* characteristics of semiconductor optical detectors?

i) low noise
ii) high reliability
iii) narrow-band
iv) high sensitivity

After discussing the optical sources and detectors used in fibre optics systems, let us discuss the method of splicing used for joining two optical fibres.

12.7 SPLICING OF FIBRE

While joining the metal conductors to each other, we can use simple methods like soldering, or sometimes just twisting together two metal wire ends suffices. However since optical fibres are usually made up of glass (and sometimes plastic), it is not possible to use the conventional techniques applicable for metals. Further, the losses in fibres are strongly dependent on the perfection in joining two fibres. Any misalignment results in heavy losses. Hence special techniques are used to join the optical fibres.

They are usually joined by fusion splicing. The two ends are aligned with a gap of several tens of micrometers between two electrodes as shown in Fig. 12.21a. To achieve a splice insertion loss of less than 0.3 dB, the transverse offset (between the two cores) must be less than 3 μm for multimode fibres and less than 1 μm for SM fibres. Preheating by low-energy arc discharge rounds off the fibre ends to prevent bubble formation as shown in Fig. 12.21b. Then the fibres are pressed together and fused with a strong arc (Fig. 12.21c). Then the spliced portion is protected by plastic tubing filled with a silicone compound as shown in Fig. 12.21d.

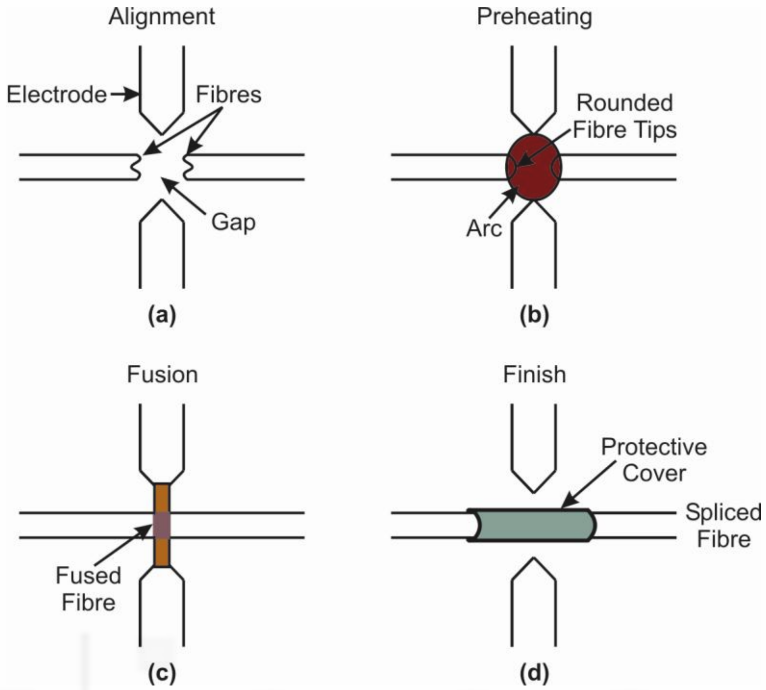

Fig. 12.21: Fusion splicing: a) Alignment; b) preheating; c) fusion; and d) finished splice with protective cover

12.8 EFFECTIVE DATA TRANSFER

12.8.1 Channel Capacity

You have learnt in this course about various media used for transmission. Prominent guided media are two wire (twisted pair) transmission line, co-axial cable and optical fibre. Each medium has its merits and demerits. The main concern in communication is the bandwidth supported by these media, because it in turn decides the data transmission rate of that medium. Table 12.2 compares these media performances.

Table 12.2: Point to point transmission characteristics of guided media

Medium	Total Data Rate	Bandwidth	Repeater Spacing
Twisted Pair	4 Mbps	3 MHz	2 to 10 km
Co-axial cable	500 Mbps	350 MHz	1 to 10 km
Optical Fibre	2 Gbps	2 GHz	10 to 100 km

In case of optical fibre, most of the transmission takes place using digital data format. Hence the bit rate supported by the medium is significant in this case. It is important to understand the correlation between the bandwidth of the medium and the digital bit rate.

If we consider a transmitted signal in the form of a square pulse train (Fig. 12.22a) with pulse repetition frequency f_1, then this signal can be represented by superimposition of various odd harmonics of sine wave of frequency f_1.
i.e.,

$$s(t) = A \sum_{\substack{k=1 \\ (k\,odd)}}^{\infty} \frac{1}{k} \sin(2\pi k f_1 t) \qquad (12.16)$$

As you must have observed, due to a $\frac{1}{k}$ multiplier, the contribution of higher harmonics is quite less. Typically 3rd and 5th harmonics can represent the square wave signal quite satisfactorily as shown in Fig. 12.22b and 12.22c respectively.

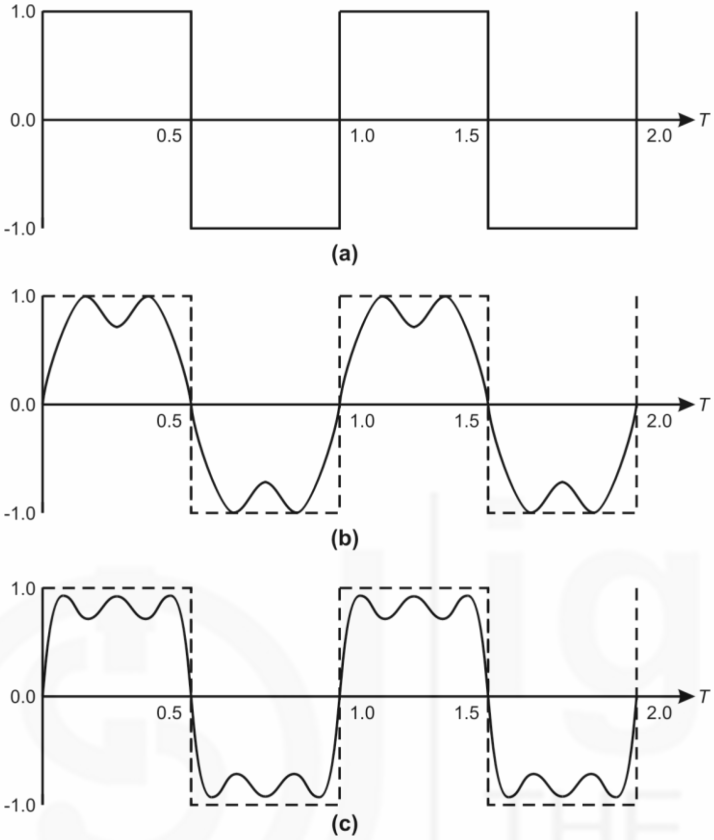

Fig. 12.22: a) Square wave frequency f_1; b) its representation as the sum of first two odd harmonics; and c) as the sum of first three odd harmonics

If we consider f_1 to be 1 MHz (this corresponds to bit rate of 2 Mbps, because alternate low and high in the square wave can be treated as a data sequence of alternate 0101… bits), then the wave shown in 12.22c can be represented as

$$s(t) = \sin((2\pi 10^6)t) + \frac{1}{3}\sin((2\pi \times 3 \times 10^6)t) + \frac{1}{5}\sin((2\pi \times 5 \times 10^6)t) \qquad (12.17)$$

Here the bandwidth of the signal is (5×10^6) Hz – (1×10^6) Hz = 4 MHz.

Hence a medium supporting 4 MHz bandwidth will allow a 2 Mbps bit rate. Similarly you can calculate that a medium having 8 MHz bandwidth can support 4 Mbps data rate.

This limit is set by the need of faithful reproduction (with minimal distortion) of the digital pulse. However, if the signal transmission is error free, it is possible to achieve reliable data transmission at higher bit rates than the bandwidth as shown in Fig. 12.23. Here the 4000 bps data can be reliably reproduced even at 3400 Hz bandwidth. Please remember that this is true for noise-free transmission system only.

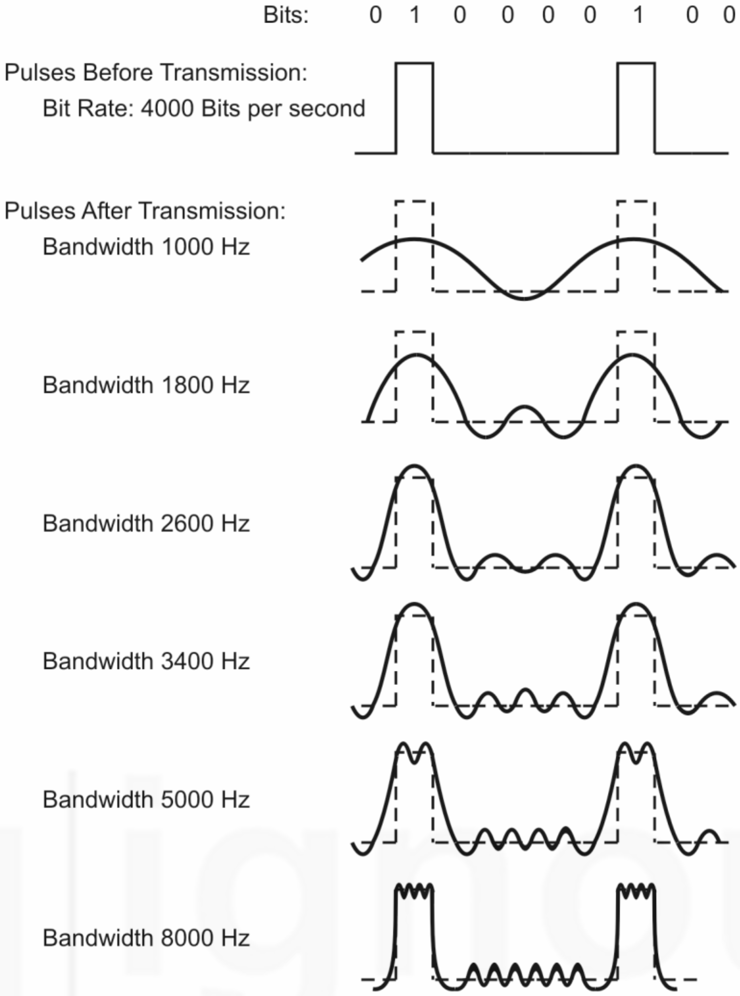

Fig. 12.23: Effect of bandwidth on a digital signal

You will remember from Unit 2 that the channel capacity is directly related to the signal to noise ratio of the transmission system and Shannon Limit of channel capacity is given by Eq. (2.26). It states that if B is the bandwidth of the medium and $\frac{S}{N}$ is the signal to noise ratio, then maximum channel capacity,

$$C = B \log_2 \left(1 + \frac{S}{N} \right) \tag{2.26}$$

This represents theoretical maximum limit of channel capacity that can be achieved.

12.8.2 Data Compression

While making use of limited resources of available information channels (like satellite links, optical fibre cable etc.), it is very important to package the information sent over these channels such that maximum information is exchanged in a reliable manner. Information compression techniques become very vital in this regard. As compared to analog signals the compression of digital data can be done in a more efficient fashion since the mathematical techniques of compression can be used. This is the main reasons for transition from analog to digital communication in recent days.

The information being transmitted can be live generated (like radio, TV transmission signals) or in the form of digital files containing audio, video or data.

a. Compression strategies

In most of the modern communication systems, the electronic sensors (microphones, cameras etc) catch the signals at much better resolution than needed for practical purposes. Hence the data generated by such sensors could be compressed by bringing the signal to lower resolution without affecting the listening and viewing experience. There are many different approaches and strategies used to squeeze the signal (especially in the form of digital media files) down to manageable size. Here are some of the most common compression strategies:

i. Psychoacoustic audio compression

The word *psychoacoustic* means *the way the brain interprets sound*. All forms of compressed audio use powerful algorithms to discard audio information that we cannot hear. For example, if there is a loud shouting voice and very low whispering sound, then the low sound in all probability will not be audible. Hence it is logical to filter it out. This way the size of the file will get reduced without affecting your listening experience in any way.

ii. Psychovisual video compression

Psychovisual video compression is similar to its audio counterpart. You have learnt about it in Unit 10. Instead of discarding audio that we can't hear, psychovisual models discard data that are not needed to be repeated like immobile background scene. This type of compression - called *statistical data redundancy* - is one of the mathematical tricks that WMV, MPEG, and other video formats use to compress video while retaining good quality.

iii. Loss-less compression

The term **loss-less** means *no loss of data*. When a file is compressed in a loss-less fashion, 100 percent of the data is still there, but the compression simply squeezes that data into a smaller space. Lossless compression saves less space because you can compress data only so much before you have to start discarding information. This type of compression is essentially used in the case of text or financial data files, for example, because it is not acceptable to have any digit or word lost or altered after decompression at the receiver end.

iv. Lossy compression

Lossy compression discards data in order to achieve a lower bit rate. Psychoacoustic compression and psychovisual compression are lossy technologies that result in smaller files that contain less of the original source data. Every time you save your file in a lossy file format, it discards more of the data - even if you're saving it in the same format. A good practice would be to move to a lossy format only at the very final step of information compilation/transmission. Fig. 12.24 shows comparison of lossy and loss-less compression schematically.

b. Compression basics

You learnt in Sec. 2.5 that Claude E. Shannon formulated the theory of data compression. He established that *there is a fundamental limit to lossless data compression*. This limit, called the entropy rate, is denoted by H. The exact value of H depends on the statistical nature of the information source. It is possible to compress the source, in a lossless manner, with compression rate close to H. It is mathematically impossible to do better than H.

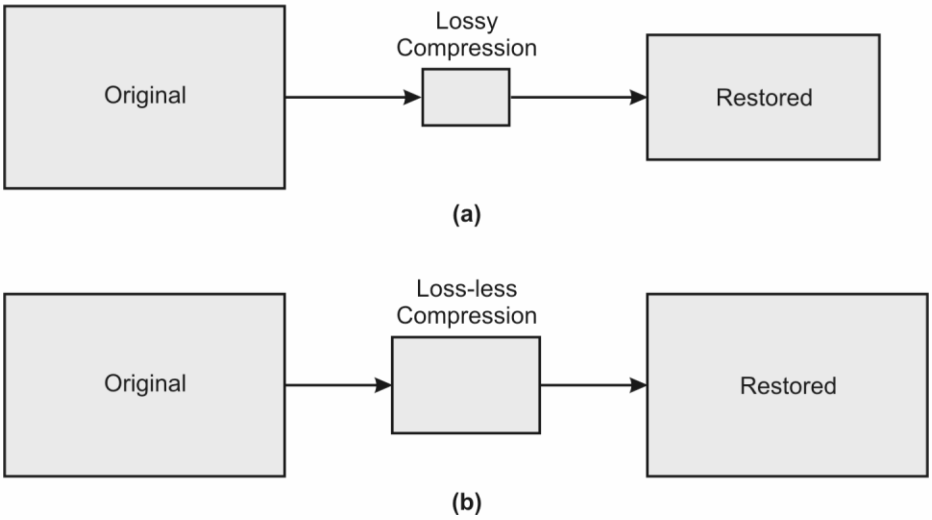

Fig. 12.24: a) Lossy versus b) loss-less compression

c. Compression methods

i. Dictionary method

The widely used dictionary method of compression creates a list of repeatable phrases. For example, GIF images and ZIP and JAR archives are compressed with this method.

These compression techniques use LZW (Lempel-Ziv-Welch) a universal loss-less data compression algorithm created by Abraham Lempel, Jacob Ziv, and Terry Welch. The algorithm is designed to be fast to implement, but not necessarily optimal since it does not perform any analysis on the data. This algorithm builds a string translation table from the text being compressed. The string translation table maps fixed-length codes (usually 12-bit) to strings. The decompressor algorithm only requires the compressed text as an input, since it can build an identical string table from the compressed text as it is recreating the original text. LZW compression provides a better compression ratio, in most applications. It became the first widely used universal data compression method on computers. It would typically compress large English texts to about half of their original sizes.

ZIP
Arc
use
tec

ii. Statistical Method

The statistical method converts characters into variable length strings of bits based on frequency of their use. The most frequently used characters are represented by shorter length codes and those not so often used are assigned longer codes. For example, if a sentence or a word has been repeatedly used in a text, if could be represented by a single letter or symbol; thereby reducing the length of the text. However both the sender and receiver should use the same code for information exchange.

Let us now summarise the points discussed in this Unit.

12.9 SUMMARY

- Optical fibre is used for transmission of light waves. Hence any optical system needs to have an electrical to optical transducer (optical source) and an optical to electrical transducer (optical detector).
- Typical losses in fibre are 0.2 db km^{-1}.
- Optical fibres are connected to each other using splicing techniques.

- Three important frequency windows used in IR range are at 850 nm, 1310 nm and 1550 nm.
- Critical angle ϕ_c is defined as

  $$\phi_c = \sin^{-1}\frac{n_2}{n_1}, \quad (n_1 > n_2)$$

  where n_1 is refractive index of core and n_2 is that of cladding.
- A light ray experiences total internal reflection for an angle more than ϕ_c.
- Numerical aperture of a fibre is defined as

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

  where θ_a is the acceptance angle.
- Fibre optic losses are of two types:
  - Intrinsic losses; and
  - Extrinsic losses.
- Dispersion causes spreading of pulses on time scale. Main causes of dispersion are
  - Modal dispersion; and
  - Chromatic dispersion.
- Depending on refractive index geometry, the optical fibres are classified as
  - Step index single mode (SI SM);
  - Step index multimode (SI MM); and
  - Graded index multimode (GI MM).
- Commonly used optical source are LED and laser diodes.
- Laser diodes have narrow spectral width and fast response.
- Common optical detectors used in fibre optic systems are photodiode, *p-i-n* diode and avalanche photodiode.
- Data can be compressed using mathematical techniques. These techniques may result into lossy or loss-less compression.

12.10 TERMINAL QUESTIONS

Spend 20 *Minutes*

1. What are the remedies to reduce the dispersion in fibre?

2. Velocity of light in the core of a step index fibre is 2.0×10^8 ms^{-1} and critical angle is 80°. Calculate the numerical aperture and acceptance angle for the fibre in air. Consider velocity of light in air to be 3×10^8 ms^{-1}.

3. When a mean optical power launched into 10 km long fibre is 100 μW, the mean optical power output is 2 μW. Calculate the attenuation in dB per kilometre for the fibre.

4. What should be the band gap of the semiconductor material to detect the signal in the second telecommunication window?

12.11 SOLUTIONS AND ANSWERS

Self Assessment Questions

1. i) Optical fibre needs special technique of splicing to connect to other fibre.
   ii) Due to small dimensions the fibre coupling needs great accuracy in alignment (of few μm)
   iii) Every time the signal needs amplification, it needs to be first converted to electrical signal, then amplified using electronic amplifiers and then again converted back into optical signal. Hence at every repeater, extra cost of light sources and detectors is involved.

2. (iii)

3. a) The critical angle ϕ_c at the core-cladding interface is given by Eq. (12.2) where:

$$\phi_c = \sin^{-1}\frac{n_2}{n_1} = \sin^{-1}\frac{1.47}{1.50} = 78.5°$$

   b) From Eq. (12.8) the numerical aperture is:

$$NA = \sqrt{n_1^2 - n_2^2} = \sqrt{\left(1.50^2 - 1.47^2\right)} = 0.30.$$

   c) Considering Eq. (12.8) the acceptance angle in air, $\theta_{a,}$ is given by:

$$\theta_a = \sin^{-1} NA = \sin^{-1} 0.30 = 17.4°$$

4. a) (ii); b) (iv)

5. (iii)

6. LED emits light proportional to the forward current flowing through it. Hence it is possible to generate the light intensity proportional to amplitude of input signal. This intensity modulation can be used in analog communication.

   However, most of the optical fibre communication takes place using digital communication. Here the signal pulses are used to switch the LED on and off.

7. As is evident from Fig. 12.13 for spontaneous emission in *p*-*n* junction diode, the recombination in case of LED takes place in the *p*- and *n*- regions of the diode. (Since there are no free carriers in the depletion layer, there is no possibility of any recombination in that layer). Hence any electron (majority carrier in *n*-region) has to get in to *p*-region, after crossing the depletion layer, in order to find a hole to recombine. The response time of LED depends on this recombination time, which is quite considerable.

   In contrast, if you look at Fig. 12.16 depicting stimulated radiation, it takes place in the narrow active region within the depletion layer. As you must have noticed, here both, electrons and holes, are simultaneously present in the depletion layer region. Hence, the response time of a laser diode is very fast.

   You can check this from the Table 12.1, where comparison of LED and laser diode is listed.

8. (iii)

Terminal Question

1 The modal dispersion can be reduced by using single mode or graded index fibre. The material dispersion can be reduced by using highly monochromatic light source (with narrow spectral width.)

2. Refractive index of core

$$n_1 = \frac{c}{v} = \frac{3 \times 10^8 \, \text{ms}^{-1}}{2 \times 10^8 \, \text{ms}^{-1}} = 1.5$$

$\phi_c = 80°$.

$\therefore$ Refractive index of cladding

$n_2 = n_1 \sin \phi_c = 1.5 \sin 80° = 1.48$

Numerical aperture = $NA = \sqrt{n_1^2 - n_2^2} = \sqrt{(1.5)^2 - (1.48)^2} = 0.24$.

Acceptance angle $\theta_a = \sin^{-1} (NA) = 14.1°$.

3. Signal attenuation = $10 \log_{10} \frac{P_i}{P_o} = 10 \log \frac{100 \times 10^{-6}}{2 \times 10^{-6}} = 17 \text{dB}$.

Assuming uniform attenuation over the fibre length, per km attenuation is

$$\frac{17 \, \text{dB}}{10 \, \text{km}} = 1.7 \text{dB km}^{-1}$$

4. For efficient detection of optical signal, with low noise, it is advisable to have the band gap of detector material just below the energy of radiation to be detected.

The second optical window corresponds to λ = 1310 nm. Hence its energy is

$$E = \frac{hc}{\lambda} = \frac{6.62 \times 10^{-34} \, \text{Js} \times 3 \times 10^8 \, \text{ms}^{-1}}{1310 \times 10^{-9} \, \text{m} \times 1.6 \times 10^{-19}}$$

$$= \frac{1.986 \times 10^{-25}}{2.096 \times 10^{-25}} = 0.95 \text{ eV}.$$

Hence a material with bandgap little smaller than 0.95 eV is appropriate.

Reference Material:

1. *Optical Fiber Communication,Principles and Practice* by Senior, J.M.; (II Edition) (Prentice-Hall of India)
2. *Data and Computer Communications* by Stallings, William; (V Edition) (Prentice-Hall of India)