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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT-I -OPTICAL COMMUNICATIONS-SEC1403

I. OPTICAL FIBER COMMUNICATION

Communication may be broadly defined as the transfer of information from one point to another. When the information is to be conveyed over any distance a communication system is usually required. Within a communication system the information transfer is frequently achieved by superimposing or modulating the information onto an electromagnetic wave which acts as a carrier for the information signal. This modulated carrier is then transmitted to the required destination where it is received and the original information signal is obtained by demodulation. Sophisticated techniques have been developed for this process using electromagnetic carrier waves operating at radio frequencies as well as microwave and millimeter wave frequencies. However, ‘communication’ may also be achieved using an electromagnetic carrier which is selected from the optical range of frequencies.

1.1 HISTORICAL DEVELOPMENT

The use of visible optical carrier waves or light for communication has been common for many years. Simple systems such as signal fires, reflecting mirrors and, more recently, signaling lamps have provided successful, if limited, information transfer. Moreover, as early as 1880 Alexander Graham Bell reported the transmission of speech using a light beam [1]. The photophone proposed by Bell just four years after the invention of the telephone modulated sunlight with a diaphragm giving speech transmission over a distance of 200 m. However, although some investigation of optical communication continued in the early part of the twentieth century [2,3] its use was limited to mobile, low-capacity communication links. This was due to both the lack of suitable light sources and the problem that light transmission in the atmosphere is restricted to line of sight and is severely affected by disturbances such as rain, snow, fog, dust and atmospheric turbulence.

Nevertheless lower frequency and hence longer wavelength electromagnetic waves (i.e. radio and microwave) proved suitable carriers for information transfer in the atmosphere, being far less affected by these atmospheric conditions. Depending on their wave- lengths, these electromagnetic carriers can be transmitted over considerable distances but are limited in the amount of information they can convey by their frequencies (i.e. the information-carrying capacity is directly related to the bandwidth or frequency extent of the modulated carrier, which is generally limited to a fixed fraction of the carrier frequency).

In theory, the greater the carrier frequency, the larger the available transmission bandwidth and thus the information-carrying capacity of the communication system. For this reason radio communication was developed to higher frequencies (i.e. VHF and UHF) leading to the introduction of the even higher frequency microwave and, latterly, millimeter wave transmission.

The relative frequencies and wavelengths of these types of electro-magnetic wave can be observed from the electromagnetic spectrum shown in Figure 1. In this context, it may also be noted that communication at optical frequencies offers an increase in the potential usable bandwidth by a factor of around 10^4 over high-frequency microwave transmission. An additional benefit of the use of high carrier frequencies is the general ability of the communication system to concentrate the available power within the transmitted electromagnetic wave, thus giving an improved system performance [4].

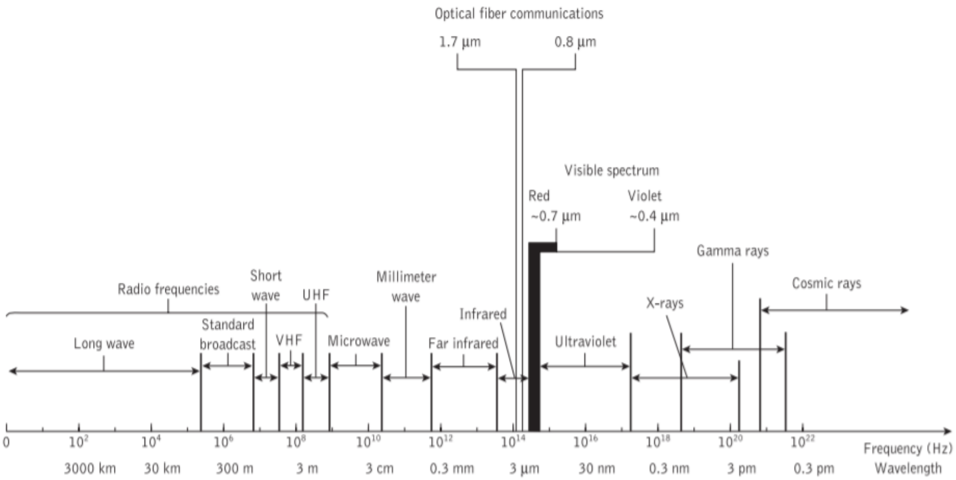

Figure 1: The electromagnetic spectrum showing the region used for optical fiber communications

A renewed interest in optical communication was stimulated in the early 1960s with the invention of the laser [5]. This device provided a powerful coherent light source, together with the possibility of modulation at high frequency. In addition, the low beam divergence of the laser made enhanced free space optical transmission a practical possibility. However, the previously mentioned constraints of light transmission in the atmosphere tended to restrict these systems to short-distance applications. Nevertheless, despite the problems some modest free space optical communication links have been implemented for applications such as the linking of a television camera to a base vehicle and for data links of a few hundred meters between buildings. There is also some interest in optical communication between satellites in outer space using similar techniques [6].

Although the use of the laser for free space optical communication proved somewhat limited, the invention of the laser instigated a tremendous research effort into the study of optical components to achieve reliable information transfer using a lightwave carrier.

The proposals for optical communication via dielectric waveguides or optical fibers fabricated from glass to avoid degradation of the optical signal by the atmosphere were made almost simultaneously in 1966 by Kao and Hockham [7] and Werts [8]. Such systems were viewed as a replacement for coaxial cable or carrier transmission systems. Initially the optical fibers exhibited very high attenuation (i.e. 1000 dB km^{-1}) and were therefore not comparable with the coaxial cables they were to replace (i.e. 5 to 10 dB km^{-1}). There were also serious problems involved in joining the fiber cables in a satisfactory manner to achieve low loss and to enable the process to be performed relatively easily and repeatedly. Nevertheless, within the space of 10 years optical fiber losses were reduced to below 5 dB km^{-1} and suitable low-loss jointing techniques were perfected.

In parallel with the development of the fiber waveguide, semiconductor optical sources (i.e. injection lasers and light-emitting diodes) and detectors (i.e. photodiodes and to a lesser extent phototransistors) compatible in size with optical fibers were designed and fabricated to enable successful implementation of the optical fiber system. These devices were originally fabricated from alloys of gallium arsenide (AlGaAs) which emitted in the near infrared between 0.8µm and 0.9µm. Subsequently the above wavelength range was extended to include the 1.1µm to 1.6µm region by the use of other semiconductor alloys. To obtain low loss over the entire fiber transmission longer wavelength region from 1.3µm to 1.6µm, or alternatively, very low loss and low dispersion at the same operating wavelength of typically 1.55µm, advanced single-mode fiber structures have been commercially realized: namely, low-water-peak fiber and nonzero dispersion-shifted fiber.

1.2 OPTICAL COMMUNICATION SYSTEM

An optical fiber communication system is similar in basic concept to any type of communication system. A block schematic of a general communication system is shown in Figure 2(a), the function of which is to convey the signal from the information source over the transmission medium to the destination. The communication system therefore consists of a transmitter or modulator linked to the information source, the transmission medium, and a receiver or demodulator at the destination point. In electrical communications the information source provides an electrical signal, usually derived from a message signal which is not electrical (e.g. sound), to a transmitter comprising electrical and electronic components which converts the signal into a suitable form for propagation over the transmission medium. This is often achieved by modulating a carrier, which, as mentioned previously, may be an electromagnetic wave.

The transmission medium can consist of a pair of wires, a coaxial cable or a radio link through free space down which the signal is transmitted to the receiver, where it is transformed into the original electrical information signal (demodulated) before being passed to the destination. However, it must be noted that in any transmission medium the signal is attenuated, or suffers loss, and is subject to degradations due to contamination by random signals and noise, as well as possible distortions imposed by mechanisms within the medium itself.

Therefore, in any communication system there is a maximum permitted distance between the transmitter and the receiver beyond which the system effectively ceases to give intelligible communication. For long-haul applications, these factors necessitate the installation of repeaters or line amplifiers.

For optical fiber communications, the system components are given in Figure 1.2(b). In this case, the information source provides an electrical signal to a transmitter comprising an electrical stage, which drives an optical source to give modulation of the lightwave carrier.

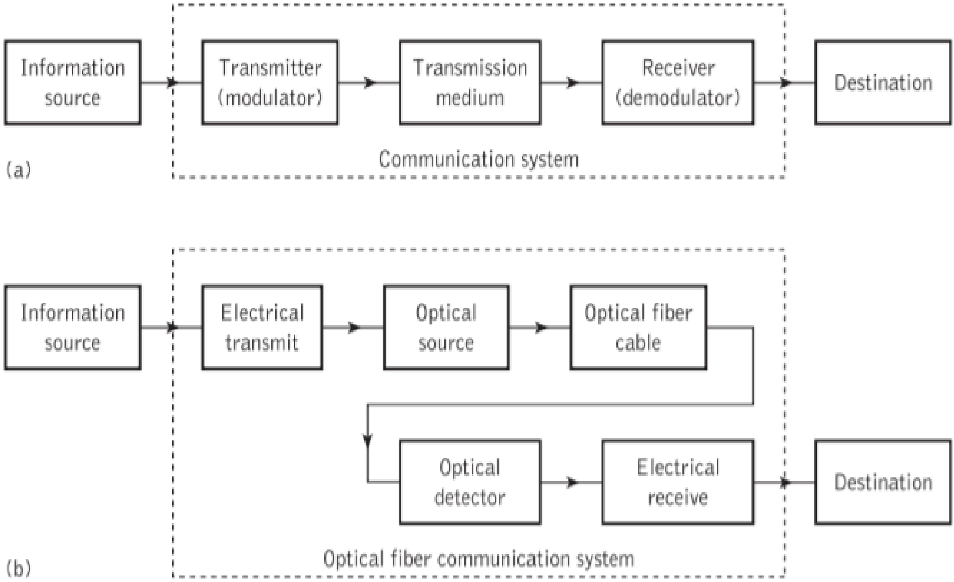

Figure 2: (a) The general communication system. (b) The optical fiber communication system

The optical source, which provides the electrical–optical conversion, may be either a semiconductor laser or light-emitting diode (LED). The transmission medium consists of an optical fiber cable and the receiver consists of an optical detector, which drives a further electrical stage and hence provides demodulation of the optical carrier. Photodiodes (*p–n*, *p–i–n* or avalanche) and, in some instances, phototransistors and photoconductors are utilized for the detection of the optical signal and the optical–electrical conversion.

The optical carrier may be modulated using either an analog or digital information signal. In the system shown in Figure 1.2(b), analog modulation involves the variation of the light emitted from the optical source in a continuous manner. With digital modulation, however, discrete changes in the light intensity are obtained (i.e. on–off pulses). Although often simpler to implement, analog modulation with an optical fiber communication system is less efficient, requiring a far higher signal-to-noise ratio at the receiver than digital modulation. Also, the linearity needed for analog modulation is not always provided by semiconductor optical sources, especially at high modulation frequencies. For these reasons, analog optical fiber communication links are generally limited to shorter distances and lower bandwidth operation than digital optical links.

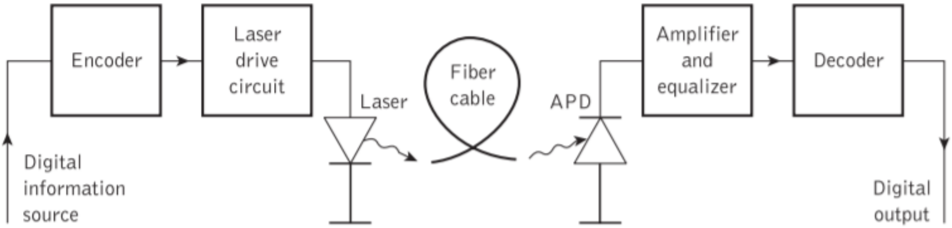

Figure 3: A digital optical fiber link using a semiconductor laser source and an avalanche photodiode (APD) detector.

Figure 3, shows a block schematic of a typical digital optical fiber link. Initially, the input digital signal from the information source is suitably encoded for optical transmission. The laser drive circuit directly modulates the intensity of the semiconductor laser with the encoded digital signal. Hence a digital optical signal is launched into the optical fiber cable.

The avalanche photodiode (APD) detector is followed by a front-end amplifier and equalizer or filter to provide gain as well as linear signal processing and noise bandwidth reduction. Finally, the signal obtained is decoded to give the original digital information.

1.3 ADVANTAGES OF OPTICAL FIBER COMMUNICATION

Communication using an optical carrier wave guided along a glass fiber has a number of extremely attractive features, several of which were apparent when the technique was originally conceived. Furthermore, the advances in the technology to date have surpassed even the most optimistic predictions, creating additional advantages. Hence it is useful to consider the merits and special features offered by optical fiber communications over more conventional electrical communications. In this context we commence with the originally foreseen advantages and then consider additional features which have become apparent as the technology has been developed.

Enormous potential bandwidth. The optical carrier frequency in the range 10^{13} to 10^{16} Hz (generally in the near infrared around 10^{14} Hz or 10^{5} GHz yields a far greater potential transmission bandwidth than metallic cable systems (i.e. coaxial cable bandwidth typically around 20 MHz over distances up to a maximum of 10 km) or even millimeter wave radio systems (i.e. systems currently operating with modulation bandwidths of 700 MHz over a few hundreds of meters). Indeed, by the year 2000 the typical bandwidth multiplied by length product for an optical fiber link incorporating fiber amplifiers was 5000 GHz km in comparison with the typical bandwidth–length product for coaxial cable of around 100 MHz km. Hence at this time optical fiber was already demonstrating a factor of 50 000 bandwidth improvement over coaxial cable while also providing this superior information-carrying capacity over much longer transmission distances [16].

Small size and weight. Optical fibers have very small diameters which are often no greater than the diameter of a human hair. Hence, even when such fibers are covered with protective coatings they are far smaller and much lighter than corresponding copper cables. This is a tremendous boon towards the alleviation of duct congestion in cities, as well as allowing for an expansion of signal transmission within mobiles such as aircraft, satellites and even ships.

Electrical isolation. Optical fibers which are fabricated from glass, or sometimes a plastic polymer, are electrical insulators and therefore, unlike their metallic counterparts, they do not exhibit earth loop and interface problems. Furthermore, this property makes optical fiber transmission ideally suited for communication in electrically hazardous environments as the fibers create no arcing or spark hazard at abrasions or short circuits.

*Immunity to interference and crosstalk***.** Optical fibers form a dielectric waveguide and are therefore free from electromagnetic interference (EMI), radio-frequency interference (RFI), or switching transients giving electromagnetic pulses (EMPs). Hence the operation of an optical fiber communication system is unaffected by transmission through an electrically noisy environment and the fiber cable requires no shielding from EMI. The fiber cable is also not susceptible to lightning strikes if used overhead rather than underground. Moreover, it is fairly easy to ensure that there is no optical interference between fibers and hence, unlike communication using electrical conductors, crosstalk is negligible, even when many fibers are cabled together.

Signal security. The light from optical fibers does not radiate significantly and there- fore they provide a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from a fiber in a noninvasive manner (i.e. without drawing optical power from the fiber). Therefore, in theory, any attempt to acquire a message signal transmitted optically may be detected. This feature is obviously attractive for military, banking and general data transmission (i.e. computer network) applications.

Low transmission loss. The development of optical fibers over the last 20 years has resulted in the production of optical fiber cables which exhibit very low attenuation or transmission loss in comparison with the best copper conductors. Fibers have been fabricated with losses as low as 0.15 dB km^{-1} and this feature has become a major advantage of optical fiber communications. It facilitates the implementation of communication links with extremely wide optical repeater or amplifier spacings, thus reducing both system cost and complexity. Together with the already proven modulation bandwidth capability of fiber cables, this property has provided a totally compelling case for the adoption of optical fiber communications in the majority of long-haul telecommunication applications, replacing not only copper cables, but also satellite communications, as a consequence of the very noticeable delay incurred for voice transmission when using this latter approach.

Ruggedness and flexibility. Although protective coatings are essential, optical fibers may be manufactured with very high tensile strengths. Perhaps surprisingly for a glassy substance, the fibers may also be bent to quite small radii or twisted without damage. Furthermore, cable structures have been developed which have proved flexible, compact and extremely rugged. Taking the size and weight advantage into account, these optical fiber cables are generally superior in terms of storage, transportation, handling and installation to corresponding copper cables, while exhibiting at least comparable strength and durability.

System reliability and ease of maintenance. These features primarily stem from the low-loss property of optical fiber cables which reduces the requirement for intermediate repeaters or line amplifiers to boost the transmitted signal strength. Hence with fewer optical repeaters or amplifiers, system reliability is generally enhanced in comparison with conventional electrical conductor systems. Furthermore, the reliability of the optical components is no longer a problem with predicted lifetimes of 20 to 30 years being quite common. Both these factors also tend to reduce maintenance time and costs.

Potential low cost. The glass, which generally provides the optical fiber transmission medium, is made from sand, which is not a scarce resource. So, in comparison with copper conductors, optical fibers offer the potential for low-cost line communication. Overall system costs when utilizing optical fiber communication on long-haul links, however, are substantially less than those for equivalent electrical line systems because of the low-loss and wideband properties of the optical transmission medium. The requirement for intermediate repeaters and the associated electronics is reduced, giving a substantial cost advantage. Although this cost benefit gives a net gain for long- haul links, it is not always the case in short-haul applications where the additional cost incurred, due to the electrical–optical conversion (and vice versa), may be a deciding factor.

The reducing costs of optical fiber communications has provided strong competition not only with electrical line transmission systems, but also for microwave and millimeter wave radio transmission systems. Although these systems are reasonably wideband, the relatively short-span 'line of sight' transmission necessitates expensive aerial towers at intervals no greater than a few tens of kilometers. Hence, with the exception of the telecommunication access network due primarily to current first installed cost constraints, optical fiber has become the dominant transmission medium within the major industrialized societies. Many advantages are therefore provided by the use of a lightwave carrier within a transmission medium consisting of an optical fiber.

1.4 OPTICAL WAVEGUIDE

The transmission of light via a dielectric waveguide structure was first proposed and investigated at the beginning of the twentieth century. However, a transparent dielectric rod, typically of silica glass with a refractive index of around 1.5, surrounded by air, proved to be an impractical waveguide due to its unsupported structure (especially when very thin waveguides were considered in order to limit the number of optical modes propagated) and the excessive losses at any discontinuities of the glass–air interface. Nevertheless, interest in the application of dielectric optical waveguides in such areas as optical imaging and medical diagnosis (e.g. endo- scopes) led to proposals for a clad dielectric rod in the mid-1950s in order to overcome these problems. This structure is illustrated in figure 4, which shows a transparent core with a refractive index n_1 surrounded by a transparent cladding of slightly lower refractive index n_2. The cladding supports the waveguide structure while also, when sufficiently thick, substantially reducing the radiation loss into the surrounding air. In essence, the light energy travels in both the core and the cladding allowing the associated fields to decay to a negligible value at the cladding–air interface.

The invention of the clad waveguide structure led to the first serious proposals by Kao and Hockham [5] and Werts [6], in 1966, to utilize optical fibers as a communications medium, even though they had losses in excess of 1000 dB km^{-1}. These proposals stimulated tremendous efforts to reduce the attenuation by purification of the materials. This has resulted in improved conventional glass refining techniques giving fibers with losses of around 4.2 dB km^{-1} [7]. Also, progress in glass refining processes such as depositing vapor-phase reagents to form silica [8] allowed fibers with losses below 1 dB km^{-1} to be fabricated. However, as silica fibers were studied in further detail it became apparent that transmission at longer wavelengths (1.1 to 1.6μm) would result in lower losses and reduced signal dispersion. This produced a shift in optical fiber source and detector technology in order to provide operation at these longer wavelengths. Hence at longer wavelengths, especially around 1.55μm, typical high-performance fibers have losses of 0.2 dB km^{-1} [9].

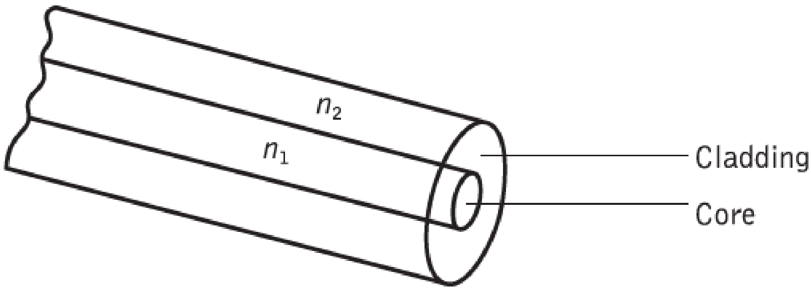

Figure 4: Optical fiber waveguide showing the core of refractive index n_1, surrounded by the cladding of slightly lower refractive index n_2

1.5 RAY THEORY TRANSMISSION

To consider the propagation of light within an optical fiber utilizing the ray theory model it is necessary to take account of the refractive index of the dielectric medium. The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. The basic laws of ray theory are quite self-explanatory

- In a homogeneous medium, light rays are straight lines.
- Light may be absorbed or reflected
- Reflected ray lies in the plane of incidence and angle of incidence will be equal to the angle of reflection.
- At the boundary between two media of different refractive indices, the refracted ray will lie in the plane of incidence. Snell's Law will give the relationship between the angles of incidence and refraction.

1.5.1 Total internal reflection

The refractive index of a medium is defined as the ratio of the velocity of light in a vacuum to the velocity of light in the medium. A ray of light travels more slowly in an optically dense medium than in one that is less dense, and the refractive index gives a measure of this effect. When a ray is incident on the interface between two dielectrics of differing refractive indices (e.g. glass–air), refraction occurs, as illustrated in Figure 5. It is observed that the ray approaching the interface is propagating in a dielectric of refractive index n_1 and is at an angle φ to the normal at the surface of the interface. If the dielectric on the other side of the interface has a refractive index n_2 which is less than n_1, then the refraction is such that the ray path in this lower index medium is at an angle to the normal. The angle of incidence and refraction 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

$$\frac{\sin \phi_1}{\sin \phi_2} = \frac{n_2}{n_1} \tag{1.1}$$

It may also be observed in Figure 5(a) 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.

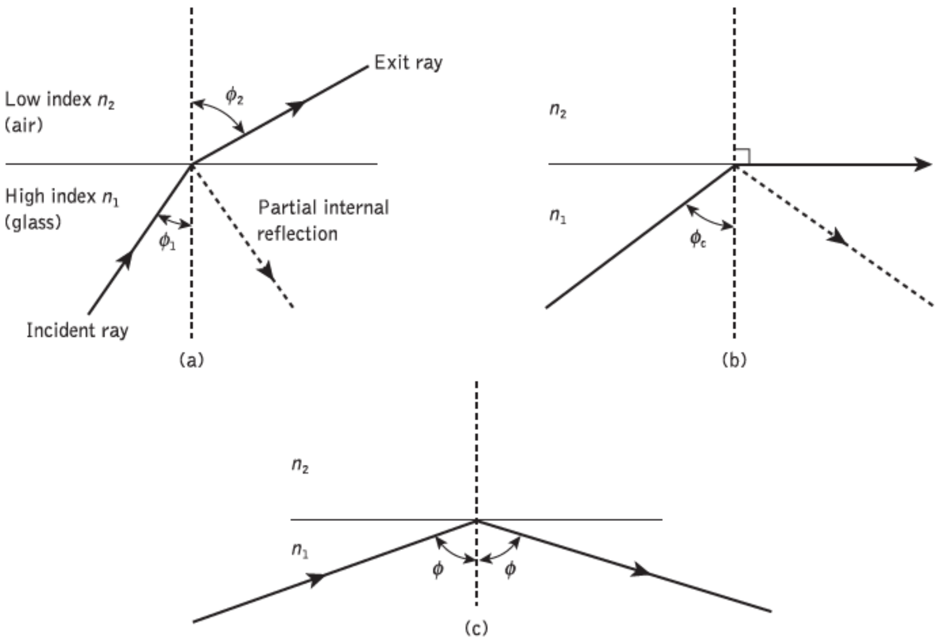

Figure 5: Light rays incident on a high to low refractive index interface (e.g. glass–air): (a) refraction; (b) the limiting case of refraction showing the critical angle Ø$_c$; (c) total internal reflection where Ø > Ø$_c$

When the angle of incidence is such that the refracted ray emerges parallel to the interface between the dielectrics, then it called as the critical angle (φ_c) and is the limiting case of refraction.

$$\sin \phi_c = \frac{n_2}{n_1} \tag{1.2}$$

At angles of incidence greater than the critical angle the light is reflected back into the originating dielectric medium (total internal reflection) with high efficiency (around 99.9%). Hence, it may be observed in Figure 5(c) 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 higher index, and the angle of incidence of the ray exceeds the critical value. This is the mechanism by which light at a sufficiently shallow angle (less than 90° may be considered to propagate down an optical fiber with low loss.

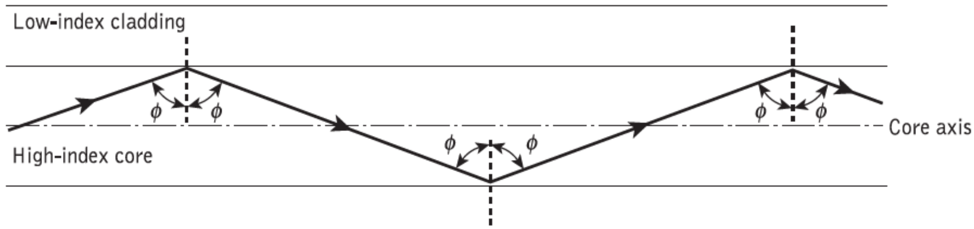

Figure 6: The transmission of a light ray in a perfect optical fiber

Figure 6 illustrates the transmission of a light ray in an optical fiber via a series of total internal reflections at the interface of the silica core and the slightly lower refractive index silica cladding. The ray has an angle of incidence φ at the interface which is greater than the critical angle and is reflected at the same angle to the normal. The light ray shown in Figure 6 is known as a meridional ray as it passes through the axis of the fiber core. This type of ray is the simplest to describe and is generally used when illustrating the fundamental transmission properties of optical fibers. It must also be noted that the light transmission illustrated in Figure 6 assumes a perfect fiber, and that any discontinuities or imperfections at the core–cladding interface would probably result in refraction rather than total internal reflection, with the subsequent loss of the light ray into the cladding.

1.5.2 Acceptance angle

Having considered the propagation of light in an optical fiber through total internal reflection at the core–cladding interface, it is useful to enlarge upon the geometric optics approach with reference to light rays entering the fiber. Since only rays with a sufficiently shallow grazing angle (i.e. with an angle to the normal greater than φ_c) at the core–cladding interface are transmitted by total internal reflection, it is clear that not all rays entering the fiber core will continue to be propagated down its length.

The geometry concerned with launching a light ray into an optical fiber is shown in Figure 7, which illustrates a meridional ray *A* at the critical angle φ_c within the fiber at the core– cladding interface. It may be observed that this ray enters the fiber core at an angle θ_a to the fiber axis and is refracted at the air–core interface before transmission to the core–cladding interface at the critical angle. Hence, any rays which are incident into the fiber core at an angle greater than θ_a will be transmitted to the core–cladding interface at an angle less than φ_c, and will not be totally internally reflected. This situation is also illustrated in Figure 7, where the incident ray *B* at an angle greater than θ_a is refracted into the cladding and eventually lost by radiation. *Thus for rays to be transmitted by total internal reflection within the fiber core they must be incident on the fiber 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 fiber in order to be propagated, and is often referred to as the acceptance angle for the fiber.

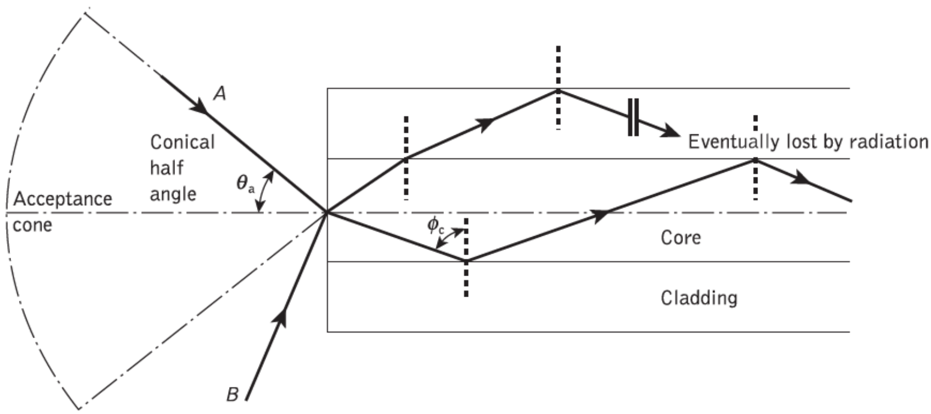

Figure 7: The acceptance angle (θ_a) when launching light into an optical fiber

If the fiber has a regular cross-section (i.e. the core–cladding interfaces are parallel and there are no discontinuities) an incident meridional ray at greater than the critical angle will continue to be reflected and will be transmitted through the fiber. From symmetry considerations it may be noted that the output angle to the axis will be equal to the input angle for the ray, assuming the ray emerges into a medium of the same refractive index from which it was input.

1.5.3 Numerical aperture

The acceptance angle for an optical fiber was defined in the preceding section. However, it is possible to continue the ray theory analysis 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 of the fiber. It must be noted that within this analysis, as with the preceding discussion of acceptance angle, we are concerned with meridional rays within the fiber. Figure 8 shows a light ray incident on the fiber core at an angle θ_1 to the fiber axis which is less than the acceptance angle for the fiber θ_a. The ray enters the fiber from a medium (air) of refractive index n_0, and the fiber core has a refractive index n_1, which is slightly greater than the cladding refractive index n_2.

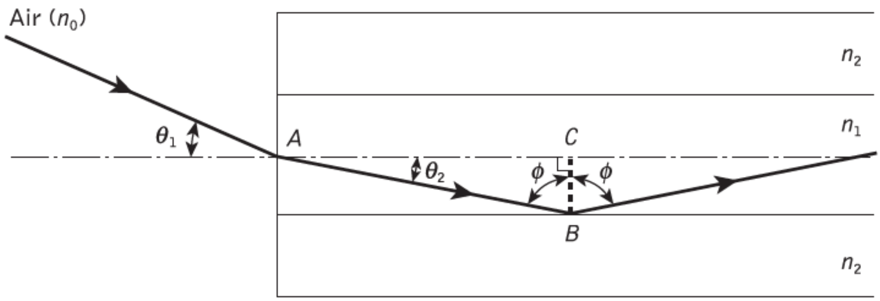

Figure 8: The ray path for a meridional ray launched into an optical fiber in air at an input angle less than the acceptance angle for the fiber

Assuming the entrance face at the fiber core to be normal to the axis, then considering the refraction at the air–core interface and using Snell's law given by Eq. (1.1):

$$n_0 \sin \theta_1 = n_1 \sin \theta_2 \tag{1.3}$$

Considering the right-angled triangle *ABC* indicated in Figure 2.5, then:

$$\phi = \frac{\pi}{2} - \theta_2 \tag{1.4}$$

where φ is greater than the critical angle at the core–cladding interface. Hence Eq. (1.3) becomes:

$$n_0 \sin \theta_1 = n_1 \cos \phi \tag{1.5}$$

Using the trigonometrical relationship $\sin^2\varphi + \cos^2\varphi = 1$, Eq. (1.5) may be written in the form:

$$n_0 \sin \theta_1 = n_1 (1 - \sin^2 \phi)^{\frac{1}{2}} \tag{1.6}$$

When the limiting case for total internal reflection is considered, φ becomes equal to the critical angle for the core–cladding interface and is given by Eq. (1.2). Also in this limiting case θ1 becomes the acceptance angle for the fiber θa. Combining these limiting cases into Eq. (1.6) gives:

$$n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{1.7}$$

Equation (1.7), apart from relating the acceptance angle to the refractive indices, serves as the basis for the definition of the important optical fiber parameter, the **numerical aperture (*NA*)**. Hence the *NA* is defined as:

$$NA = n_0 \sin \theta_a = (n_1^2 - n_2^2)^{\frac{1}{2}} \tag{1.8}$$

Since the *NA* is often used with the fiber in air where *n*0 is unity, it is simply equal to sin θ_a. It may also be noted that incident meridional rays over the range $0 \leq \theta 1 \leq \theta_a$ will be propagated within the fiber. The *NA* may also be given in terms of the relative refractive index difference between the core and the cladding which is defined as:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$
$$\simeq \frac{n_1 - n_2}{n_1} \qquad \text{for } \Delta \ll 1 \tag{1.9}$$

Hence combining Eq. (1.8) with Eq. (1.9) we can write:

$$NA = n_1 (2\Delta)^{\frac{1}{2}} \tag{1.10}$$

The relationships given in Eqs (1.8) and (1.10) for the numerical aperture are a very useful measure of the light-collecting ability of a fiber. They are independent of the fiber core diameter and will hold for diameters as small as 8 µm. However, for smaller diameters they break down 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 fiber but does not take into account interference between such components. When interference phenomena are considered it is found that only rays with certain discrete characteristics propagate in the fiber core. Thus the fiber will only support a discrete number of guided modes. This becomes critical in small core-diameter fibers which only support one or a few modes. Hence electromagnetic mode theory must be applied in these cases.

1.5.4 Skew rays

In the preceding sections we have considered the propagation of meridional rays in the optical waveguide. However, another category of ray exists which is transmitted without passing through the fiber axis. These rays, which greatly outnumber the meridional rays, follow a helical path through the fiber, as illustrated in Figure 9, and are called skew rays.

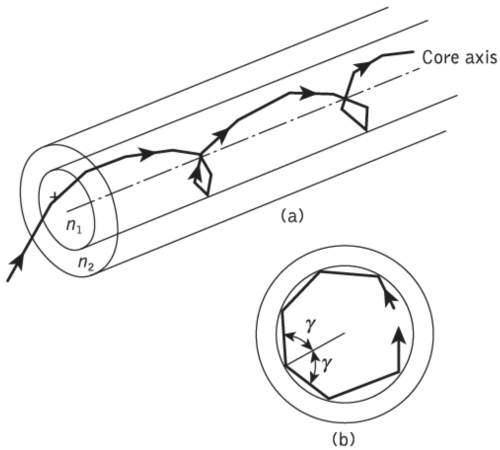

Figure 9: The helical path taken by a skew ray in an optical fiber: (a) skew ray path down the fiber; (b) cross-sectional view of the fiber

It is not easy to visualize the skew ray paths in two dimensions, but it may be observed from Figure 1.6(b) that the helical path traced through the fiber gives a change in direction of 2γ at each reflection, where γ is the angle between the projection of the ray in two dimensions and the radius of the fiber core at the point of reflection. Hence, unlike meridional rays, the point of emergence of skew rays from the fiber in air will depend upon the number of reflections they undergo rather than the input conditions to the fiber. When the light input to the fiber is non uniform, skew rays will therefore tend to have a smoothing effect on the distribution of the light as it is transmitted, giving a more uniform output. The amount of smoothing is dependent on the number of reflections encountered by the skew rays.

1.6 ELECTROMAGNETIC MODE THEORY FOR OPTICAL PROPAGATION

In order to obtain an improved model for the propagation of light in an optical fiber, electromagnetic wave theory must be considered. The basis for the study of electromagnetic wave propagation is provided by Maxwell's equations [13].

1.6.1 Electromagnetic waves

For a medium with zero conductivity these vector relationships may be written in terms of the electric field **E**, magnetic field **H**, electric flux density **D** and magnetic flux density **B** as the curl equations:

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \tag{1.18}$$

$$\nabla \times \mathbf{H} = \frac{\partial \mathbf{D}}{\partial t} \tag{1.19}$$

and the divergence conditions:

$$\nabla \cdot \mathbf{D} = 0 \qquad \text{(no free charges)} \tag{1.20}$$

$$\nabla \cdot \mathbf{B} = 0 \qquad \text{(no free poles)} \tag{1.21}$$

where 'Δ' is a vector operator.

The four field vectors are related by the relations:

$$\mathbf{D} = \varepsilon\mathbf{E} \qquad (1.22)$$
$$\mathbf{B} = \mu\mathbf{H}$$

where ε is the dielectric permittivity and μ is the magnetic permeability of the medium. Substituting for **D** and **B** and taking the curl of Eqs (1.18) and 1.19) gives:

$$\nabla \times (\nabla \times \mathbf{E}) = -\mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (1.23)$$

$$\nabla \times (\nabla \times \mathbf{H}) = -\mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} \qquad (1.24)$$

Then using the divergence conditions of Eqs (1.20) and (1.21) with the vector identity:

$$\nabla \times (\nabla \times \mathbf{Y}) = \nabla(\nabla \cdot \mathbf{Y}) - \nabla^2(\mathbf{Y})$$

we obtain the nondispersive wave equations:

$$\nabla^2\mathbf{E} = \mu\varepsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \qquad (1.25)$$

and

$$\nabla^2\mathbf{H} = \mu\varepsilon \frac{\partial^2 \mathbf{H}}{\partial t^2} \qquad (1.26)$$

Where ∇^2 is the Laplacian operator. For rectangular Cartesian and cylindrical polar coordinates the above wave equations hold for each component of the field vector, every component satisfying the scalar wave equation

$$\nabla^2\psi = \frac{1}{\upsilon_p^2} \frac{\partial^2 \psi}{\partial t^2} \qquad (1.27)$$

Where ψ may represent a component of the **E** or **H** field and up is the phase velocity (velocity of propagation of a point of constant phase in the wave) in the dielectric medium. It follows that:

$$\upsilon_p = \frac{1}{(\mu\varepsilon)^{\frac{1}{2}}} = \frac{1}{(\mu_r\mu_0\varepsilon_r\varepsilon_0)^{\frac{1}{2}}} \quad (1.28)$$

Where μ_r and ε_r are the relative permeability and permittivity for the dielectric medium and μ_0 and ε_0 are the permeability and permittivity of free space. The velocity of light in free space *c* is therefore:

$$c = \frac{1}{(\mu_0\varepsilon_0)^{\frac{1}{2}}} \quad (1.29)$$

If planar waveguides, described by rectangular Cartesian coordinates (*x*, *y*, *z*), or circular fibers, described by cylindrical polar coordinates (*r*, φ, *z*), are considered, then the Laplacian operator takes the form:

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial x^2} + \frac{\partial^2\psi}{\partial y^2} + \frac{\partial^2\psi}{\partial z^2} \quad (1.30)$$

Or

$$\nabla^2\psi = \frac{\partial^2\psi}{\partial r^2} + \frac{1}{r}\frac{\partial\psi}{\partial r} + \frac{1}{r^2}\frac{\partial^2\psi}{\partial\phi^2} + \frac{\partial^2\psi}{\partial z^2} \quad (1.31)$$

respectively.

It is necessary to consider both these forms for a complete treatment of optical propagation in the fiber, although many of the properties of interest may be dealt with using Cartesian coordinates. The basic solution of the wave equation is a sinusoidal wave, the most important form of which is a uniform plane wave given by

$$\psi = \psi_0 \exp[\mathrm{j}(\omega t - \mathbf{k}\cdot\mathbf{r})] \quad (1.32)$$

where ω is the angular frequency of the field, *t* is the time, **k** is the propagation vector which gives the direction of propagation and the rate of change of phase with distance, while the components of **r** specify the coordinate point at which the field is observed. When λ is the optical wavelength in a vacuum, the magnitude of the propagation vector or the vacuum phase propagation constant k (where $k = |\mathbf{k}|$) is given by:

$$k = \frac{2\pi}{\lambda} \tag{1.33}$$

It should be noted that in this case k is also referred to as the free space wave number.

1.6.2 Modes in a planar guide

The planar guide is the simplest form of optical waveguide. We may assume it consists of a slab of dielectric with refractive index $n1$ sandwiched between two regions of lower refractive index n_2. In order to obtain an improved model for optical propagation it is useful to consider the interference of plane wave components within this dielectric waveguide.

The conceptual transition from ray to wave theory may be aided by consideration of a plane monochromatic wave propagating in the direction of the ray path within the guide (see Figure 10(a)). As the refractive index within the guide is n_1, the optical wavelength in this region is reduced to λ/n_1, while the vacuum propagation constant is increased to n_1k. When θ is the angle between the wave propagation vector or the equivalent ray and the guide axis, the plane wave can be resolved into two component plane waves propagating in the z and x directions, as shown in Figure 1.8(a).

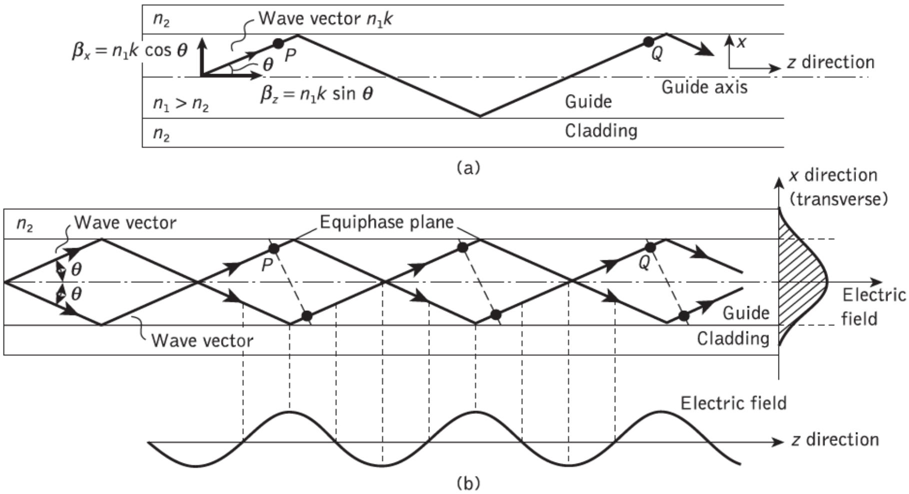

Figure 10: The formation of a mode in a planar dielectric guide: (a) a plane wave

propagating in the guide– the wave vector is resolved into components in the *z* and *x* directions; (b) the interference of plane waves in the guide forming the lowest order mode (*m* = 0)

The component of the phase propagation in the Z direction is given by:

$$\beta_z = n_1 k \cos \theta \qquad (1.34)$$

The component of the phase propagation constant in the *x* direction βx is:

$$\beta_x = n_1 k \sin \theta \qquad (1.35)$$

The component of the plane wave in the *x* direction is reflected at the interface between the higher and lower refractive index media. When the total phase change after two successive reflections at the upper and lower interfaces (between the points *P* and *Q*) is equal to $2m\pi$ radians, where *m* is an integer, then constructive interference occurs and a standing wave is obtained in the *x* direction. This situation is illustrated in Figure 10(b), where the interference of two plane waves is shown. In this illustration, it is assumed that the interference forms the lowest order (where $m = 0$) standing wave, where the electric field is a maximum at the center of the guide decaying towards zero at the boundary between the guide and cladding. However, it may be observed from Figure 10(b) that the electric field penetrates some distance into the cladding, a phenomenon which is discussed under mode field diameter.

Nevertheless, the optical wave is effectively confined within the guide and the electric field distribution in the *x* direction does not change as the wave propagates in the *z* direction. The sinusoidally varying electric field in the ***z*** direction is also shown in Figure 10(b). The stable field distribution in the ***x*** direction with only a periodic ***z*** dependence is known as a mode. A specific mode is obtained only when the angle between the propagation vectors or the rays and the interface have a particular value, as indicated in Figure 10(b). In effect, Eqs (1.34) and (1.35) define a group or congruence of rays which in the case described represents the lowest order mode. Hence the light propagating within the guide is formed into discrete modes, each typified by a distinct value of θ.

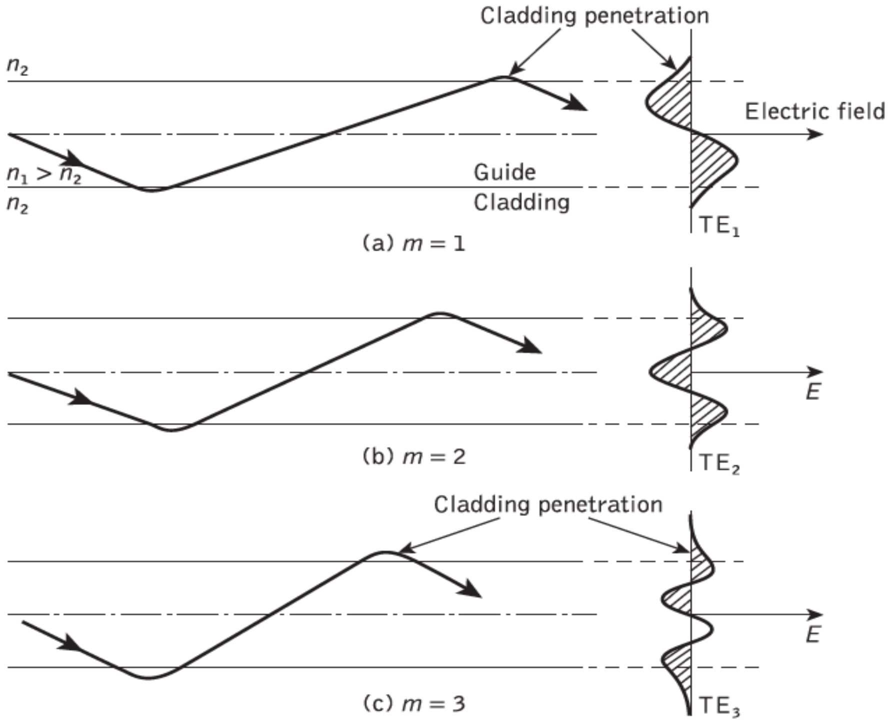

Figure 11: Physical model showing the ray propagation and the corresponding transverse electric (TE) field patterns of three lower order models (m =1, 2, 3) in the planar dielectric guide

To visualize the dominant modes propagating in the *z* direction we may consider plane waves corresponding to rays at different specific angles in the planar guide. These plane waves give constructive interference to form standing wave patterns across the guide following a sine or cosine formula. Figure 11 shows examples of such rays for m = 1, 2, 3, together with the electric field distributions in the *x* direction. It may be observed that *m* denotes the number of zeros in this transverse field pattern. In this way *m* signifies the order of the mode and is known as the mode number.

When light is described as an electromagnetic wave it consists of a periodically varying electric field **E** and magnetic field **H** which are orientated at right angles to each other. The transverse modes shown in Figure 11 illustrate the case when the electric field is perpendicular to the direction of propagation and hence $E_z = 0$, but a corresponding component of the magnetic field **H** is in the direction of propagation. In this instance, the

modes are said to be transverse electric (TE). Alternatively, when a component of the **E** field is in the direction of propagation, but $Hz = 0$, the modes formed are called transverse magnetic (TM). The mode numbers are incorporated into this nomenclature by referring to the TE_m and TM_m modes, as illustrated for the transverse electric modes shown in Figure 1.9. When the total field lies in the transverse plane, transverse electromagnetic (TEM) waves exist where both E_z and H_z are zero. However, although TEM waves occur in metallic conductors (e.g. coaxial cables) they are seldom found in optical waveguides.

1.7 Phase and Group velocity

The envelope of the wave package or group of waves travels at a group velocity υ_g. With in all electromagnetic waves, whether plane or otherwise, there are points of constant phase. For plane waves, these constant phase points form a surface which is referred to as a wavefront. As a monochromatic lightwave propagates along a waveguide in the *z* direction these points of constant phase travel at a phase velocity υ_p given by

$$\upsilon_p = \frac{\omega}{\beta} \tag{1.36}$$

where ω is the angular frequency of the wave.

However, it is impossible in practice to produce perfectly monochromatic lightwaves, and light energy is generally composed of a sum of plane wave components of different frequencies. Often the situation exists where a group of waves with closely similar frequencies propagate so that their resultant forms a packet of waves.

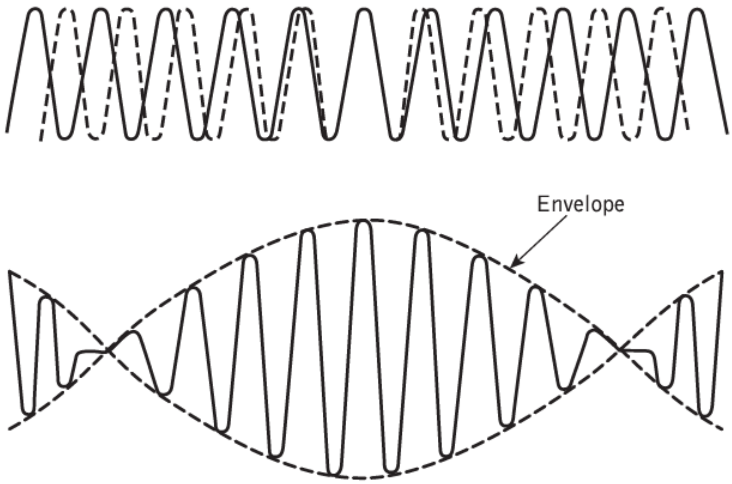

Figure 12: The formation of a wave packet from the combination of two waves with nearly equal frequencies. The envelope of the wave package or group of waves travels at a group velocity υ_g.

The formation of such a wave packet resulting from the combination of two waves of slightly different frequency propagating together is illustrated in Figure 12. This wave packet does not travel at the phase velocity of the individual waves but is observed to move at a group velocity υg given by:

$$\upsilon_g = \frac{\delta\omega}{\delta\beta} \tag{1.37}$$

The group velocity is of greatest importance in the study of the transmission characteristics of optical fibers as it relates to the propagation characteristics of observable wave groups or packets of light. If propagation in an infinite medium of refractive index n_1 is considered, then the propagation constant may be written as:

$$\beta = n_1 \frac{2\pi}{\lambda} = \frac{n_1\omega}{c} \tag{1.38}$$

Where c is the velocity of light in free space. Equation (1.38) follows from Eqs (1.33) and (1.34) where we assume propagation in the z direction only and hence cos θ is equal to unity. Using Eq. (1.36) we obtain the following relationship for the phase velocity:

$$\upsilon_p = \frac{c}{n_1} \tag{1.39}$$

Similarly, employing Eq. (1.37), where in the limit δω/δβ becomes dω/dβ, the group velocity:

$$\begin{aligned}\upsilon_g &= \frac{d\lambda}{d\beta} \cdot \frac{d\omega}{d\lambda} = \frac{d}{d\lambda}\left(n_1 \frac{2\pi}{\lambda}\right)^{-1} \left(\frac{-\omega}{\lambda}\right) \\ &= \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1} \\ &= \frac{c}{\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)} = \frac{c}{N_g}\end{aligned} \tag{1.40}$$

The parameter *N*g is known as the group index of the guide.

1.8 MODES IN CYLINDRICAL FIBER

In common with the planar guide, TE (where $E_z = 0$) and TM (where $H_z = 0$) modes are obtained within the dielectric cylinder. The cylindrical waveguide, however, is bounded in two dimensions rather than one. Thus two integers, *l* and *m*, are necessary in order to specify the modes, in contrast to the single integer (*m*) required for the planar guide.

For the cylindrical waveguide we therefore refer to TE_{lm} and TM_{lm} modes. These modes correspond to meridional rays traveling within the fiber. However, hybrid modes where E_z and H_z are nonzero also occur within the cylindrical waveguide. These modes, which result from skew ray propagation within the fiber, are designated HE_{lm} and EH_{lm} depending upon whether the components of **H** or **E** make the larger contribution to the transverse (to the fiber axis) field. Thus an exact description of the modal fields in a step index fiber proves somewhat complicated.

Fortunately, the analysis may be simplified when considering optical fibers for communication purposes. These fibers satisfy the weakly guiding approximation where the relative index difference Δ<<1. This corresponds to small grazing angles θ in Eq. (1.34). In fact is usually less than 0.03 (3%)

for optical communications fibers. For weakly guiding structures with dominant forward propagation, mode theory gives dominant transverse field components. Hence approximate solutions for the full set of HE, EH, TE and TM modes may be given by two linearly polarized components.

These linearly polarized (LP) modes are not exact modes of the fiber except for the fundamental (lowest order) mode. However, as in weakly guiding fibers is very small, then HE– EH mode pairs occur which have almost identical propagation constants. Such modes are said to be degenerate. The superpositions of these degenerating modes characterized by a common propagation constant correspond to particular LP modes regardless of their HE, EH, TE or TM field configurations. This linear combination of degenerate modes obtained from the exact solution produces a useful simplification in the analysis of weakly guiding fibers.

The relationship between the traditional HE, EH, TE and TM mode designations and the LP_{lm} mode designations is shown in Table 1.1. The mode subscripts *l* and *m* are related to the electric field intensity profile for a particular LP mode (see Figure 1.11(d)). There are in general 2*l* field maxima around the circumference of the fiber core and *m* field maxima along a radius vector. Furthermore, it may be observed from Table 1.1 that the notation for labeling the HE and EH modes has changed from that specified for the exact solution in the cylindrical waveguide mentioned previously.

Table 1: Correspondence between the lower order in linearly polarized modes and the traditional exact modes from which they are formed

Linearly polarized	*Exact*
LP_{01}	HE_{11}
LP_{11}	HE_{21}, TE_{01}, TM_{01}
LP_{21}	HE_{31}, EH_{11}
LP_{02}	HE_{12}
LP_{31}	HE_{41}, EH_{21}
LP_{12}	HE_{22}, TE_{02}, TM_{02}
LP_{lm}	HE_{2m}, TE_{0m}, TM_{0m}
LP_{lm} ($l \neq 0$ or 1)	$HE_{l+1.m}$, $EH_{l-1.m}$

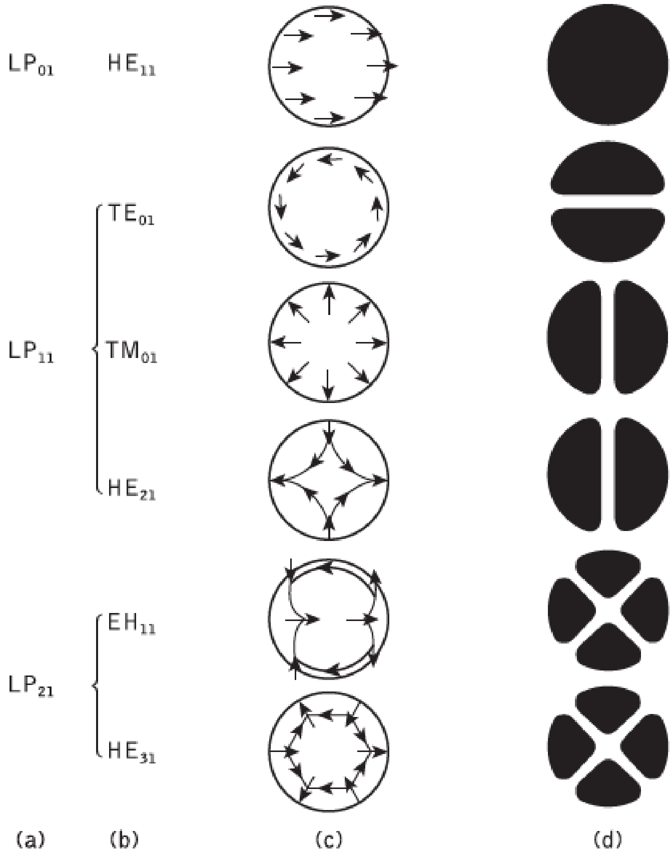

Figure 13: The electric field configurations for the three lowest LP modes illustrated in terms of their constituent exact modes: (a) LP mode designations; (b) exact mode designations; (c) electric field distribution of the exact modes; (d) intensity distribution of Ex for the exact modes indicating the electric field intensity profile for the corresponding LP modes

The subscript l in the LP notation now corresponds to HE and EH modes with labels $l + 1$ and $l - 1$ respectively. The electric field intensity profiles for the lowest three LP modes, together with the electric field distribution of their constituent exact modes, are shown in Figure 13. It may be observed from the field configurations of the exact modes that the field strength in the transverse direction (E_x or E_y) is identical for the modes which belong to the same LP mode. Hence the origin of the term 'linearly polarized'.

Using Eq. (1.31) for the cylindrical homogeneous core waveguide under the weak guidance conditions outlined above, the scalar wave equation can be written in the form

$$\frac{d^2\psi}{dr^2}+\frac{1}{r}\frac{d\psi}{dr}+\frac{1}{r^2}\frac{d^2\psi}{d\phi^2}+(n_1^2k^2-\beta^2)\psi=0 \tag{1.41}$$

where ψ is the field (**E** or **H**), *n*1 is the refractive index of the fiber core, *k* is the propagation constant for light in a vacuum, and *r* and φ are cylindrical coordinates. The propagation constants of the guided modes β lie in the range:

$$n_2k<\beta<n_1k \tag{1.42}$$

where n_2 is the refractive index of the fiber cladding. Solutions of the wave equation for the cylindrical fiber are separable, having the form:

$$\psi=E(r)\left[\begin{matrix}\cos l\phi\\ \sin l\phi\end{matrix}\exp(\omega t-\beta z)\right] \tag{1.43}$$

where in this case ψ represents the dominant transverse electric field component. The periodic dependence on φ following cos*l*φ or sin *l*φ gives a mode of radial order *l*. Hence the fiber supports a finite number of guided modes of the form of Eq. (1.43). Introducing the solutions given by Eq. (1.43) into Eq. (1.41) results in a differential equation of the form:

$$\frac{d^2\mathbf{E}}{dr^2}+\frac{1}{r}\frac{d\mathbf{E}}{dr}+\left[(n_1k^2-\beta^2)-\frac{l^2}{r^2}\right]\mathbf{E}=0 \tag{1.45}$$

For a step index fiber with a constant refractive index core, Eq. (1.43) is a Bessel differential equation and the solutions are cylinder functions.

1.9 MODE COUPLING

We have thus far considered the propagation aspects of perfect dielectric waveguides. However, waveguide perturbations such as deviations of the fiber axis from straightness, variations in the core diameter, irregularities at the core–cladding interface and refractive index variations may change the propagation characteristics of the fiber.These will have the effect of coupling energy traveling in one mode to another depending on the specific perturbation.

Ray theory aids the understanding of this phenomenon, as shown in Figure 14, which illustrates two types of perturbation. It may be observed that in both cases the ray no longer maintains the same angle with the axis. In electromagnetic wave theory this corres- ponds to a change in the propagating mode for the light. Thus individual modes do not normally propagate throughout the length of the fiber without large energy transfers to adjacent modes, even when the fiber is exceptionally good quality and is not strained or bent by its surroundings. This mode conversion is known as mode coupling or mixing. It is usually analyzed using coupled mode equations which can be obtained directly from Maxwell’s equations.

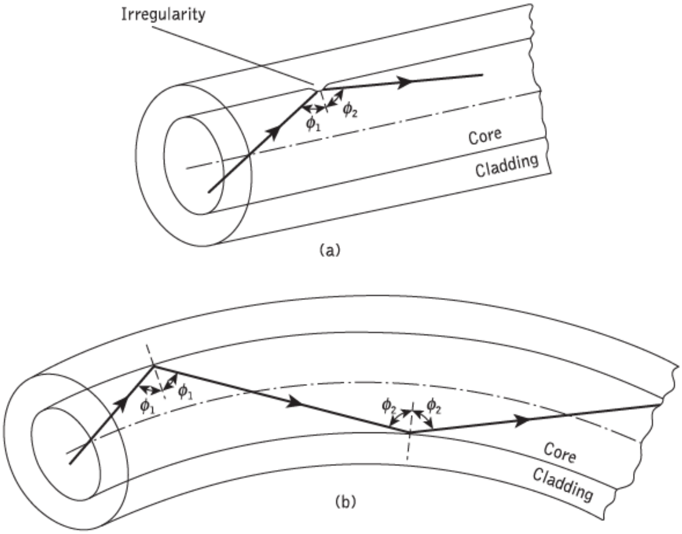

Figure 14: Ray theory illustrations showing two of the possible fiber perturbations which give mode coupling: (a) irregularity at the core–cladding interface; (b) fiber bend.

1.10 STEP INDEX FIBERS

The optical fiber considered in the preceding sections with a core of constant refractive index n_1 and a cladding of a slightly lower refractive index n_2 is known as step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core–cladding interface, as indicated in Figure 15, which illustrates the two major types of step index fiber.

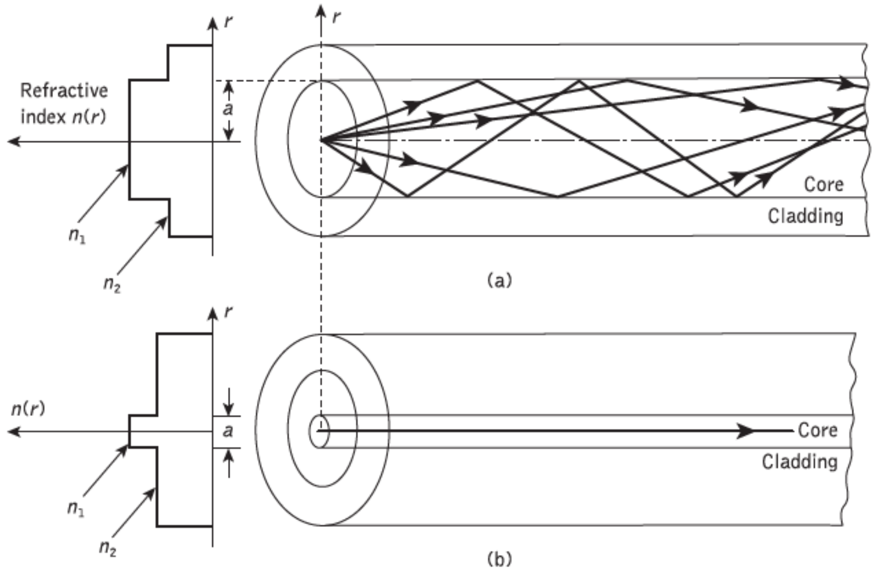

Figure 15: The refractive index profile and ray transmission in step index fibers: (a) multimode step index fiber; (b) single-mode step index fiber

The refractive index profile for both single mode and multimode step-index fibers may be defined as:

$$n(r) = \begin{cases} n_1 & r < a \quad \text{(core)} \\ n_2 & r \geq a \quad \text{(cladding)} \end{cases} \tag{1.48}$$

Figure 15(a) shows a multimode step index fiber with a core diameter of around 50µm or greater, which is large enough to allow the propagation of many modes within the fiber core. This is illustrated in Figure 15(a) by the many different possible ray paths through the fiber. Figure 15(b) shows a single-mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode (typically HE11), and hence the core diameter must be of the order of **2 to 10µm**. The propagation of a single mode is illustrated in Figure 15b as corresponding to a single ray path only (usually shown as the axial ray) through the fiber.

The single-mode step index fiber has the distinct advantage of low intermodal dispersion (broadening of transmitted light pulses), as only one mode is transmitted, whereas with multimode step index fiber considerable dispersion may occur due to the differing group velocities of the propagating modes. This in turn restricts the maximum bandwidth attainable with multimode step index fibers, especially when com- pared with single-mode fibers. However, for lower bandwidth applications multimode fibers have several advantages over single-mode fibers. These are:

- The use of spatially incoherent optical sources (e.g. most light-emitting diodes) which cannot be efficiently coupled to single-mode fibers.
- Larger numerical apertures, as well as core diameters, facilitating easier coupling to optical sources
- Lower tolerance requirements on fiber connectors

Multimode step index fibers allow the propagation of a finite number of guided modes along the channel. The number of guided modes is dependent upon the physical parameters (i.e. relative refractive index difference, core radius) of the fiber and the wavelengths of the transmitted light which are included in the normalized frequency *V* for the fiber. The total number of guided modes or mode volume M_s for a step index fiber is related to the *V* value for the fiber by the approximate expression

$$M_s \simeq \frac{V^2}{2} \qquad (1.49)$$

which allows an estimate of the number of guided modes propagating in a particular multimode step index fiber.

1.11 GRADED INDEX FIBERS

Graded index fibers do not have a constant refractive index in the core but a decreasing core index $n(r)$ with radial distance from a maximum value of n_1 at the axis to a constant value n_2 beyond the core radius a in the cladding.

This index variation may be represented as:

$$n(r) = \begin{cases} n_1(1 - 2\Delta(r/a)^{\alpha})^{\frac{1}{2}} & r < a \quad \text{(core)} \\ n_1(1 - 2\Delta)^{\frac{1}{2}} = n_2 & r \geq a \quad \text{(cladding)} \end{cases} \qquad (1.50)$$

where D is the relative refractive index difference and α is the profile parameter which gives the characteristic refractive index profile of the fiber core. Equation (1.50) which is a convenient method of expressing the refractive index profile of the fiber core as a variation of α, allows representation of the step index profile when $\alpha = \infty$, a parabolic profile when $\alpha = 2$ and a triangular profile when $\alpha = 1$. This range of refractive index profiles is illustrated in Figure 16.

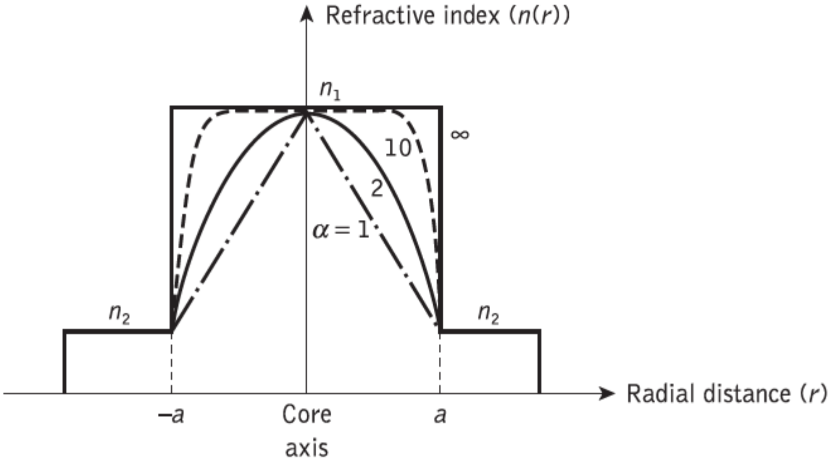

Figure 16: Possible fiber refractive index profiles for different values of α given in Eq. 1.50.

The graded index profiles which at present produce the best results for multimode optical propagation have a near parabolic refractive index profile core (α value around 2). Fibers with such core index profiles are well established and consequently when the term '**graded index**' is used without qualification it usually refers to a fiber with this profile. For this reason in this section we consider the waveguiding properties of graded index fiber with a parabolic refractive index profile core.

A multimode graded index fiber with a parabolic index profile core is illustrated in Figure 17. It may be observed that the meridional rays shown appear to follow curved paths through the fiber core. Using the concepts of geometric optics, the gradual decrease in refractive index from the center of the core creates many refractions of the rays as they are effectively incident on a large number or high to low index interfaces. This mechanism is illustrated in Figure 17, where a ray is shown to be gradually curved, with an ever-increasing angle of incidence, until the conditions for total internal reflection are met, and the ray travels back towards the core axis, again being continuously refracted.

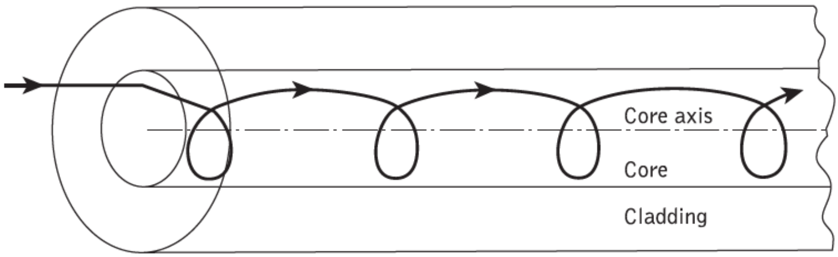

Figure 17: A helical skew ray path within a graded index fiber

Multimode graded index fibers exhibit far less intermodal dispersion than multimode step index fibers due to their refractive index profile. Although many different modes are excited in the graded index fiber, the different group velocities of the modes tend to be normalized by the index grading. Again considering ray theory, the rays traveling close to the fiber axis have shorter paths when compared with rays which travel. However, the near axial rays are transmitted through a region of higher refractive index and therefore travel with a lower velocity than the more extreme rays. This compensates for the shorter path lengths and reduces dispersion in the fiber.

Hence, multi-mode graded index fibers with parabolic or near-parabolic index profile cores have transmission bandwidth which may be orders of magnitude greater than multimode step index fiber bandwidths. Consequently, although they are not capable of the bandwidths attainable with single-mode fibers, such multimode graded index fibers have the advantage of large core diameters (greater than 30 μm) coupled with bandwidths suitable for long- distance communication.

1.12 Single-mode fiber

The advantage of the propagation of a single mode within an optical fiber is that the signal dispersion caused by the delay differences between different modes in a multimode fiber is eliminated. Hence, for the transmission of a single mode, the fiber must be designed to allow propagation of only one mode, while all other modes are attenuated by leakage or absorption. Following the preceding discussion of multimode fibers, this may be achieved through choice of a suitable normalized frequency for the fiber. For single-mode operation, only the fundamental LP_{01} mode can exist. Thus single-mode propagation of the LP01 mode in step index fibers is possible over the range:

$$0 \le V < 2.405 \qquad (1.51)$$

as there is no cutoff for the fundamental mode. It must be noted that there are in fact two modes with orthogonal polarization over this range, and the term single-mode applies to propagation of light of a particular polarization.

1.13 Cutoff wavelength

It may be noted that single-mode operation only occurs above a theoretical cutoff wavelength λc given by:

$$\lambda_c = \frac{2\pi a n_1}{V_c} (2\Delta)^{\frac{1}{2}} \qquad (1.52)$$

Where *V*c is the cutoff normalized frequency. Hence λc is the wavelength above which a particular fiber becomes single-moded.

Also, for step index fiber where *V*c = 2.405, the cutoff wavelength is given by:

$$\lambda_c = \frac{V\lambda}{2.405} \qquad (1.53)$$

1.14 Mode-field diameter (MFD) and spot size

MFD is an important parameter for characterizing single-mode fiber properties which takes into account the wavelength-dependent field penetration into the fiber cladding. In this context, it is a better measure of the functional properties of single-mode fiber than the core diameter. For step index and graded (near parabolic profile) single-mode fibers operating near the cutoff wavelength λc, the field is well approximated by a Gaussian distribution. In this case, the MFD is generally taken as the distance between the opposite $1/e = 0.37$ field amplitude points and the power $1/e^2 = 0.135$ points in relation to the corresponding values on the fiber axis.

Another parameter which is directly related to the MFD of a single-mode fiber is the spot size (or mode-field radius) ω_0. Hence MFD = $2\omega_0$, where ω_0 is the nominal half width of the input excitation. However, for most refractive index profiles and at typical operating wavelengths, the MFD is slightly larger than the single-mode fiber core diameter.

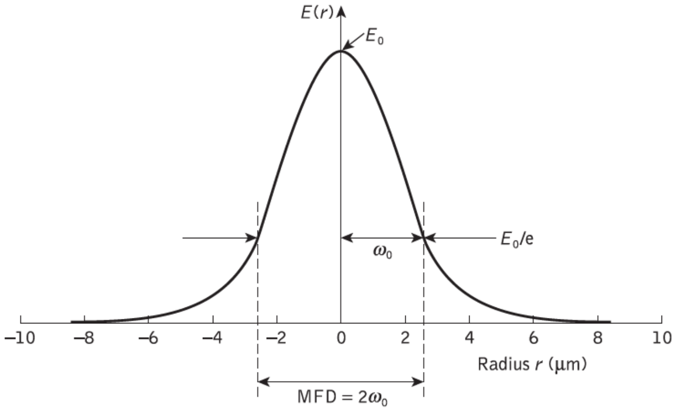

Figure 18: Field amplitude distribution *E*(*r*) of the fundamental mode in a single-mode fiber illustrating the mode-field diameter (MFD) and spot size (ω_0)

1.15 Conclusion:

In this chapter, the discussion has concentrated on optical fibers comprising solid silica core and cladding regions in which the light is guided by a small increase in refractive index in the core facilitated through doping the silicon with germanium. More recently, however, a new class of microstructured optical fiber containing a fine array of air holes running longitudinally down the fiber cladding has been developed. Since the microstructure within the fiber is often highly periodic due to the fabrication process, these fibers are usually referred to as photonic crystal fibers (PCFs). The existence of two different guidance mechanisms makes PCFs versatile in their range of potential applications. For example, PCFs have been used to realize various optical components and devices including long period gratings, multimode interference power splitters, tunable coupled cavity fiber lasers, fiber amplifiers, multichannel add/drop filters, wavelength converters and wavelength demultiplexers.

Photonic bandgap (PBG) fibers are a class of microstructured fiber in which a periodic arrangement of air holes is required to ensure guidance. This periodic arrangement of cladding air holes provides for the formation of a photonic bandgap in the transverse plane of the fiber. As a PBG fiber exhibits a two-dimensional bandgap, then wavelengths within this bandgap cannot propagate perpendicular to the fiber axis (i.e. in the cladding) and they can therefore be confined to propagate within a region in which the refractive index is lower than the surrounding material. Hence utilizing the photonic bandgap effect light can, for example, be guided within a low-index, air-filled core region creating fiber properties quite different from those obtained without the bandgap.

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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT-II -OPTICAL COMMUNICATIONS- SEC1403

TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

2.1 Introduction

The basic transmission mechanisms of the various types of optical fiber waveguide have been discussed in Previous Chapter. However, the factors which affect the performance of optical fibers as a transmission medium were not dealt with in detail. These transmission characteristics are of' utmost importance when the suitability of' optical fibers communication purposes is investigated. The transmission characteristics of most interest are those of' attenuation (or loss) and bandwidth.

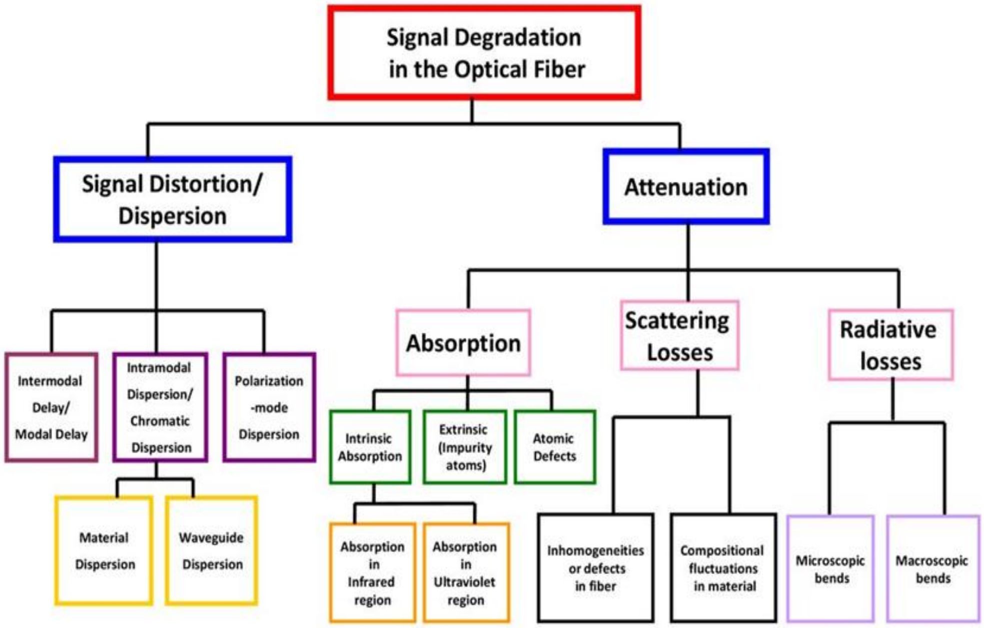
The huge potential bandwidth of' optical communications helped stimulate the birth of the idea that a dielectric waveguide made of glass could be used to carry wideband telecommunication signals. However, at the time the idea may have seemed somewhat ludicrous as a typical block of glass could support optical transmission for at best a few tens of meters before it was attenuated to an unacceptable level. Nevertheless, careful investigation of' the attenuation showed that it was largely due to absorption in the glass, caused by impurities such as iron, copper, manganese and other transition metals which occur in the third row of the periodic table. Hence, research was stimulated towards a new alteration of 'pure' glasses for use in optical fiber communications.

A major breakthrough came in 1970 when the first fiber with an attenuation below 20 dB km-' was reported. This level of attenuation was seen as the absolute minimum that had to be achieved before an optical fiber system could in any way compete economically with existing communication systems. Since 1970 tremendous improvements have been made, leading to silica-based glass fibers with losses of less than 0.2 dB km-' in the laboratory.

The other characteristic of primary importance is the bandwidth of the fiber. This is limited by the signal dispersion within the fiber, which determines the number of bits of information transmitted in a given time period. Therefore, once the attenuation was reduced to acceptable levels attention was directed towards the dispersive properties of fibers Again, this has led to substantial improvements, giving wideband fiber bandwidths of many tens of gigahertz over a number of kilometers.

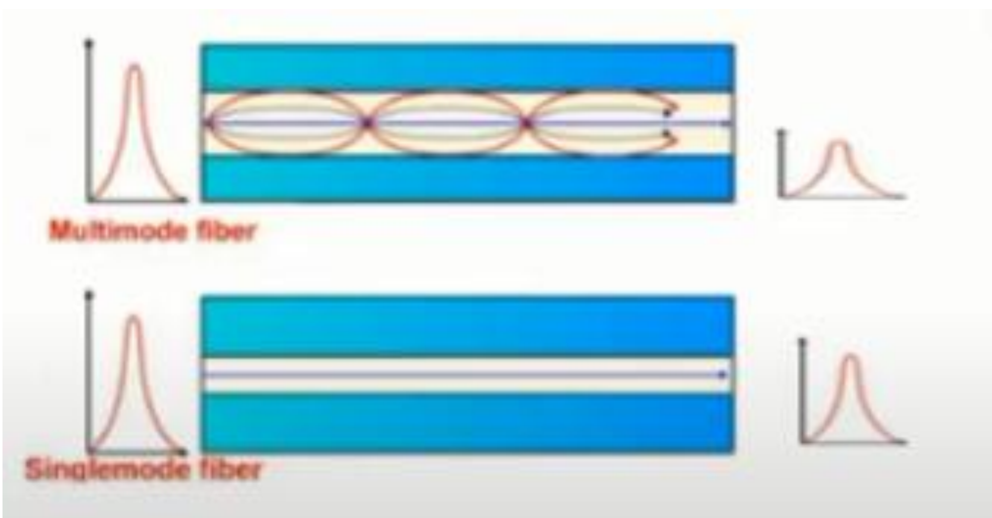
In order to appreciate these advances and possible future developments, the optical transmission characteristics of fibers must be considered in greater depth. Therefore, in this chapter we discuss the mechanisms within optical fibers which give rise to the major transmission characteristics mentioned previously (attenuation and dispersion), whilst also considering other, perhaps less obvious, effects when light is propagating down an optical fiber (modal noise, polarization and nonlinear phenomena).

2.2 SIGNAL DEGRADATION IN OFC



2.3 SIGNAL ATTENUATION:

2.3.1 ATTENUATION IN OFC



Signal attenuation in an optical fiber is defined as the decrease in light power during light propagation along an optical fiber. It is also known as fiber loss or signal loss in an optical fiber. It results in a reduction of power of light wave as it travels down the optical fiber, It determines the maximum repeater less separation between the transmitter and the receiver.

Due to attenuation, the power of light wave decreases exponentially with distance.

Let $P(o)$ = optical power in an optical fiber at the origin

$P(z)$ = optical power in a fiber at a distance z

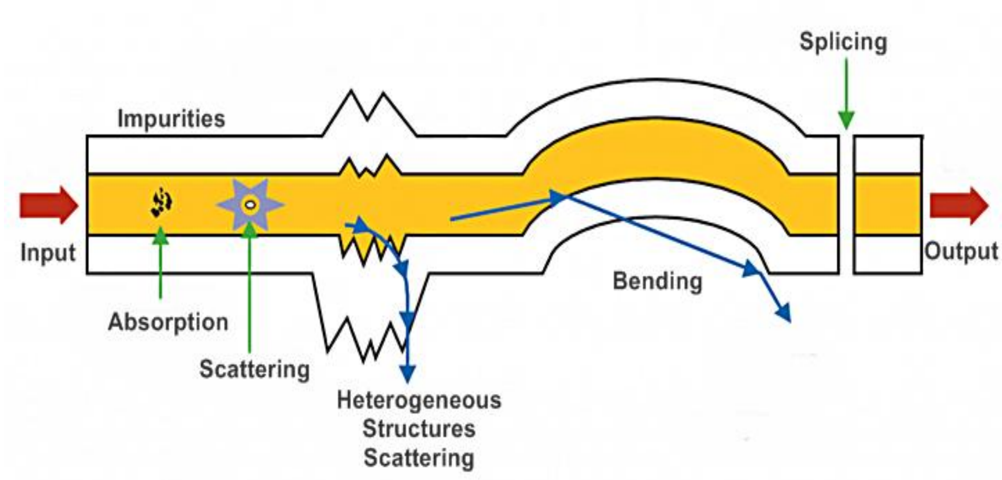
$$\therefore \quad P(z) = P(o)\, e^{-\alpha_p z}$$

where, $\alpha_p = \frac{1}{z}\log\left[\frac{P(o)}{P(z)}\right]$

Signal attenuation within optical fiber is usually measured in terms of decibel/km, also known as attenuation coefficient or attenuation rate.

$$\therefore \quad \alpha_p \text{ (dB/km)} = \frac{10}{z}\log\left[\frac{P(o)}{P(z)}\right]$$

2.3.2 Causes of Attenuation in OFC



2.4 Types of losses in optical fiber cable are:

(i) Absorption losses

(ii) Bending losses

(iii) Scattering losses

2.4.1 Absorption losses : (Material Absorption losses)

Absorption losses in optical fiber are the major cause of losses during the transmission. When the photon interacts with the components of the glass, an electron or metal ions, the light power is absorbed. The defects and impurities in silica fibers are dependent on the manufacturing processes involved.

Absorption is caused by three different mechanisms:

a. Absorption by atomic defects in the glass composition.
b. Extrinsic absorption by impurity atoms in the glass material.
c. Intrinsic absorption by the basic constituent atoms of the fiber material.

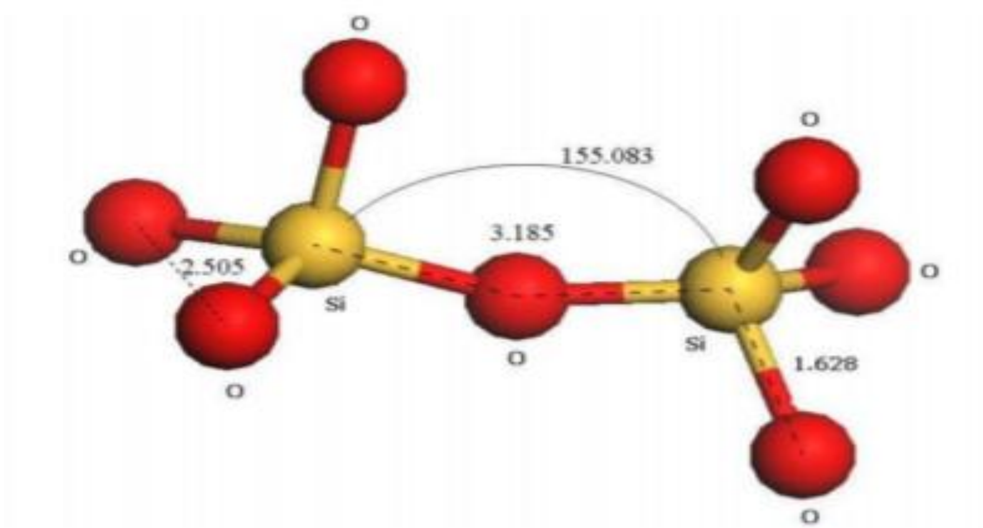
2.4.1a Absorption by atomic defects

Atomic defects are imperfections in the atomic structure of the fiber material.
Examples:

- Missing molecules
- High density clusters of atom groups
- Oxygen defects in the glass structure.
- Absorption losses arising from these defects are negligible compared with intrinsic(energy band) and impurity absorption.
- But can be significant if the fiber is exposed to ionization radiations.(nuclear reactor environment, Space environments, medical radiation therapies,etc.)
- Radiation damages a material by changing its internal structure. The damage effects depend on the
- energy of the ionizing particles or rays (e.g., electrons, neutrons, or gamma rays), the radiation flux

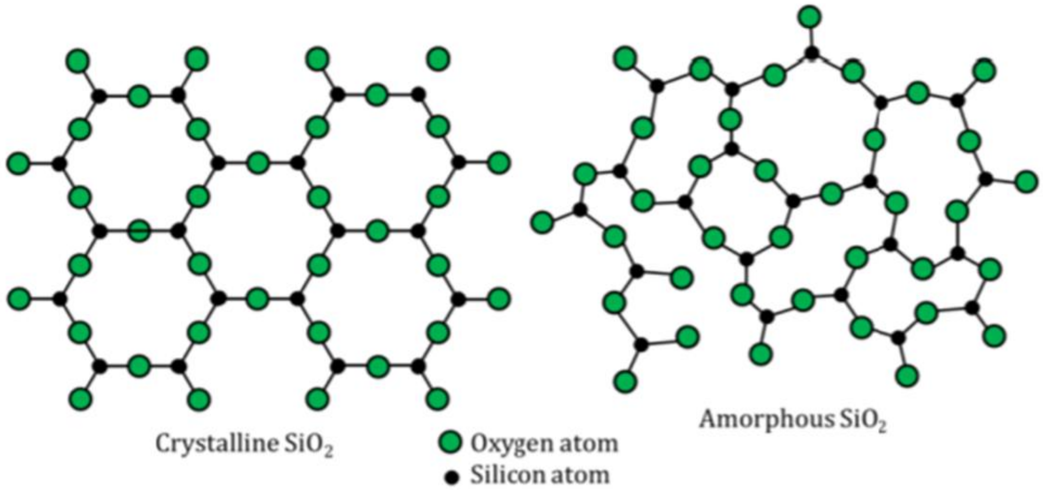
Atomic structure of fused silica fiber,

Silica optical fibers are composed of amorphous, synthetic silicon dioxide, commonly called fused silica. The basic building block of amorphous silica is a tetrahedron with an oxygen atom at each corner and a silicon atom in the center. In the absence of defects and impurities, each of the corner oxygen atoms are shared by neighboring silicon atoms so that the ratio of oxygen to silicon is 2 to 1.

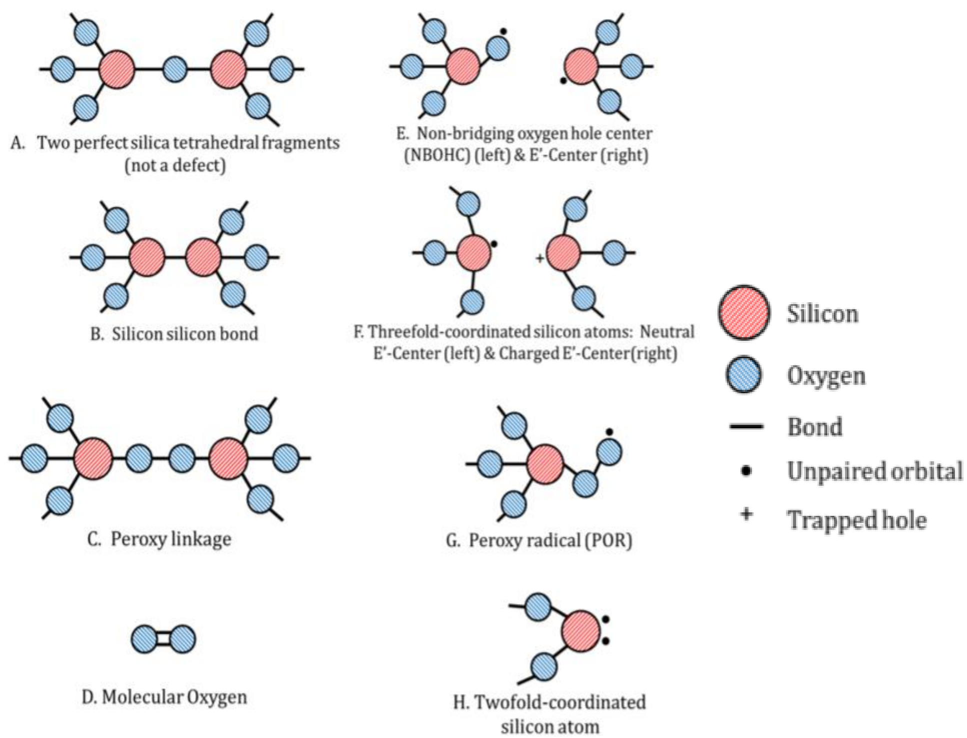


Atomic defects in fused silica fiber,

- Silicon and oxygen atoms existing in configurations other than SiO4 tetrahedra are considered intrinsic defects and cause optical attenuation in silica. Perfect Crystallization of a long and thin geometry, such as an optical fiber is practically impossible. So the OFC have amorphous atomic structure.

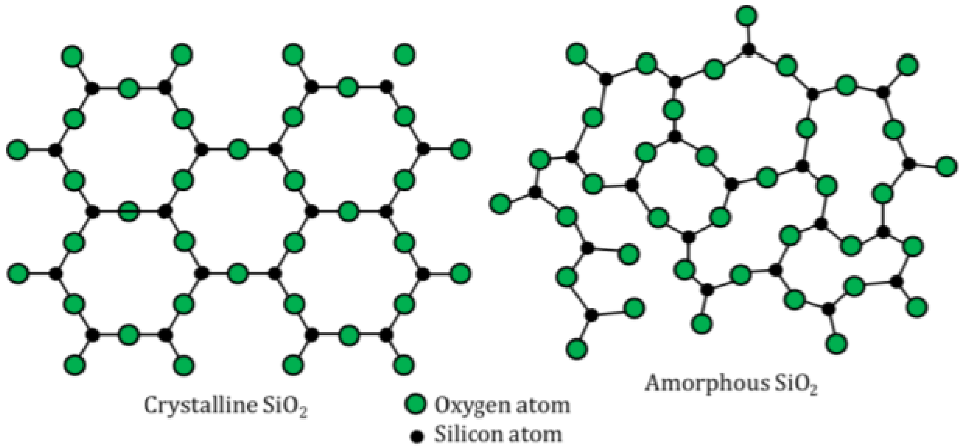


Defect Structures in Fused Silica



Atomic structure of fused silica fiber

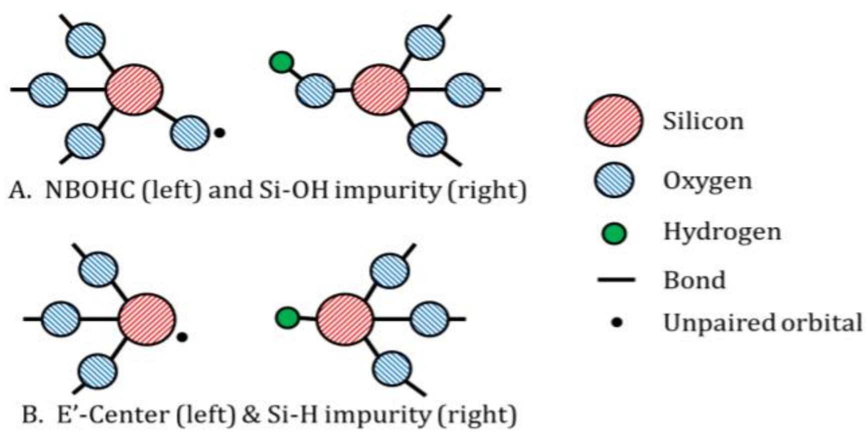
- Figure below shows a two-dimensional representation of quartz and silica.The bond angles for the silica structure vary and the number of oxygen atoms in a closed loop, in this example, varies from 4 to 6. The bond angle and ring order distributions are dependent on manufacturing processes and affect the material properties



Impurities in fused silica fiber

Silica optical fibers are intentionally manufactured to have either a high or a low concentration of hydrogen, resulting in different intrinsic attenuation profiles. Low-OH optical fibers are usable between 380-2400nm and high-OH fibers are usable between 180-1150nm.Chlorine introduced during the manufacturing process to remove hydrogen ions from the perform material, unintentionally remains in the silica and is an impurity. Fluorine and germanium are intentional impurities commonly used to decrease or increase, respectively, the refractive index of the silica in optical fibers Transition metal ions, such as iron, copper and vanadium

Common Hydrogen Impurity configurations in Silica



2.4.2 Absorption in OFC

The composition of the material and the fabrication process of the fiber gives rise to material absorption. This results in the mechanism where optical power transmitted is lost as heat in the waveguide. The material absorption is of two types:

(a) Extrinsic absorption

(b) Intrinsic absorption.

2.4.2a Extrinsic absorption : Extrinsic absorption is caused by the presence of impurities in fiber like iron, cobalt, chromium, copper and OH ions in glass material. These impurities are incorporated during the fabrication process and it is very hard to eliminate. Extrinsic absorption is caused by the electronic transition of these metal ions from one energy level to another. Extrinsic absorption also occurs when hydroxyl ions (OH-) are introduced into the fiber. Water in silica glass forms a silicon hydroxyl (Si—OH) band. This band has a fundamental absorption at 2700 run. However, the harmonics or overtones of the fundamental absorption occur in the region of operation. These harmonic increases extrinsic absorption at 1383nxn, 1250 nm and 950 run.

Extrinsic Absorption losses by impurity ions in OFC

Absorption losses caused by some of the more common metallic ionimpurities in glasses, together with the absorption peak wavelength

	Peak wavelength (nm)	*One part in 10^9 (dB km^{-1})*
Cr^{3+}	625	1.6
C^{2+}	685	0.1
Cu^{2+}	850	1.1
Fe^{2+}	1100	0.68
Fe^{3+}	400	0.15
Ni^{2+}	650	0.1
Mn^{3+}	460	0.2
V^{4+}	725	2.7

(2.4.2b) Intrinsic absorption

Intrinsic absorption is caused by basic fiber material properties. If an optical fiber were absolutely pure, with no imperfections or impurities, then all absorption would be intrinsic. Intrinsic absorption results from electronic absorption bands in ultra violet region and from atomic vibration bands in the near infrared region. Absorption occurs when a photon interacts with an electron in the valence band and excites it to higher energy level. These intrinsic losses are mostly insignificant in a wide region where fiber can operate but these inhibit the extension of fiber systems towards ultraviolet as well as infrared regions.

Intrinsic absorption is very strong in the short wavelength ultraviolet portion of electromagnetic spectrum.

- Intrinsic absorption is associated with the basic fiber material (e.g., pure SiO2)

Intrinsic Absorption in OFC

Electronic absorption (EA) occurs when a photon interacts with an electron in the valance band and excites it to a higher energy level. The electronic absorption is associated with the band gap of the material. The UV edge of EA follows the empirical formula

$$\alpha_{uv} = Ce^{E/E_o}$$

where C and E_0 are empirical constants and E is the photon energy

Ultraviolet absorption decays exponentially with increasing wavelength and is small compared with scattering loss in the near infrared region. UV loss in dB/km at any λ as a function of mole fraction x of GeO_2 is

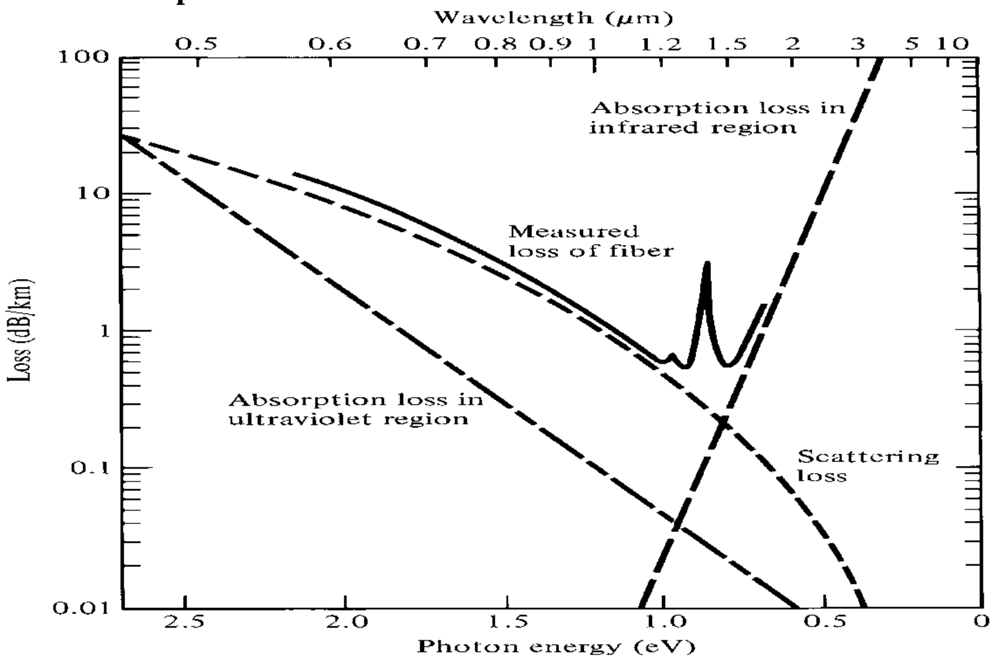
$$\alpha_{uv} = \frac{154.2x}{46.6x+60} \times 10^{-2} \exp\left(\frac{4.63}{\lambda}\right)$$

Intrinsic Absorption in OFC

- In the near-IR region above 1.2 mm, the optical fiber loss is predominantly determined by the presence of OH ions and the inherent infrared absorption of the constituent material.
- The inherent infrared absorption is associated with the characteristic vibration frequency of the particular chemical bond between the atoms in the fiber.
- An interaction between the **vibrating bond** and the electromagnetic field of the optical signal results in a transfer of energy from the field to the bond, thereby giving rise to absorption.
- An empirical expression for the infrared absorption in dB/km for GeO2-SiO2 glass with wavelength given in mm is:

$$\alpha_{IR} = 7.81 \times 10^{11} \times \exp\left(\frac{-48.48}{\lambda}\right)$$

- **Absorption characteristics of Silica OFC**



****Optical fiber attenuation characteristics and their limiting mechanisms for a GeO2 doped low loss water content silica fiber.**

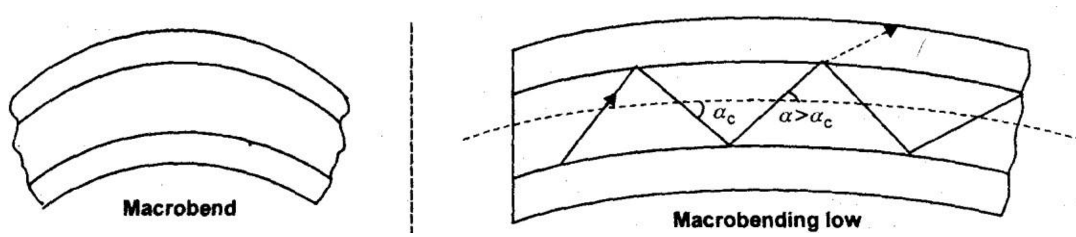
2.5 **Bending losses** : (Radiative losses)

Bending losses occur whenever an optical fiber undergoes a bend of finite radius of curvature. This is one of the major causes of total attenuation that light experiences while propagating through an optical fiber. Fibers can be subject to two types of bends, so, there are mainly two types of bending losses.

(a) Macro bending losses

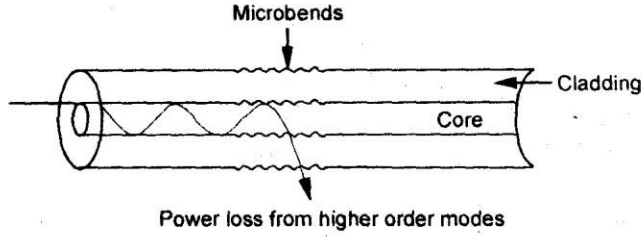
(b) Micro bending losses

2.5.1a Macro bending losses : Micro bends are the bends having radii that are large compared to the fiber diameter e.g. such bends occur when a fiber cable turns a corner.



Whenever an optical fiber cable is bent, then the ray of light forms a propagation angle that is more than critical angle when it strikes the fiber. Due to this total internal reflection is not achieved in bent fiber. Some portion of the light beam escapes from the core of the fiber and the power of the light at its receiving end is less than the power of the light emitted into the fiber from a light source.

2.5.1b Microbending losses: Microbending loss is caused by the micro deformation of the fiber axis. Microbends do not have regular shapes or distributions along the fiber.



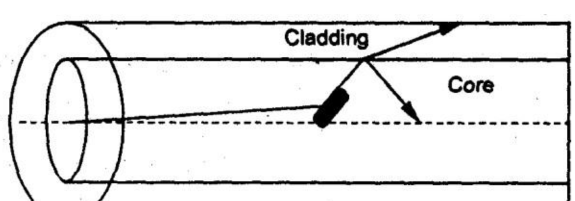
Mechanism of microbending loss

These may have different radii over small sections and are distributed randomly over the length of the fiber. Although light travels along straight segment of a fiber, light beam meets these imperfections and gets deflected. The beam that initially travels at the critical propagation angle changes its angle of propagation after reflection at these imperfections. So, condition of total internal reflection is not met and a portion of the beam will be refracted and will leak out of the core. Fig. shows mechanism of micro bending losses.

2.6 Scattering tosses

Scattering losses are due to microscopic variations in the material density from compositional fluctuations and from structural defects occurring during manufacture. Molecular density is not uniform since glass is made up of several oxides such as Ge02, Si02 and P205. Even very small changes in the values of the core refractive index will be seen by a traveling beam as an optical obstacle and this obstacle will change the direction of original beam. This effect will inhibit attainment of the condition of total internal reflection at core-cladding boundary, resulting in power loss. Since some light will pass out of the core. Rayleigh scattering accounts for about 96 percent of attenuation in optical fiber. If the scattered light maintains an angle that supports forward travel within the core, no attenuation occurs. If the light is scattered at an angle that does not support forward travel, however, the light is directed out of the core then attenuation occurs.

2.6.1 Rayleigh scattering is a fundamental loss mechanism arising from microscopic fluctuations in density. It is a dominant loss in low absorption window between the ultraviolet and infrared absorption tails. When light strikes an object, it is reflected ml different directions which is called light scattering. In the optical fiber, due to impurity particle, scattering occurs in the core or cladding. If there is any impurity particle in the



Scattering loss

path of light in the core, the particle will scatter the light in another direction and affect the total internal reflection at the boundary of core-cladding. When the fiber material are prepared, there may be some in homogeneities or imperfections in the core layer Due to in homogeneity, light beam propagating at an angle close to or more than critic angle will hit the obstacle and bend its direction because of scattering. The beam will be refracted into cladding layer as shown in Fig.

The in homogeneity can resu1 into variation of refractive index and the variation c refractive index may be such that the particular location with large refraction index will act as an obstacle and cause scattering loss. This type of loss is called Rayleigh scattering

$$Y_R = \frac{8\pi^3}{3\lambda^4} n^8 p^2 \beta_c k T_F$$

where, λ = Optical wavelength
n = Refractive index of medium
p = Average photo elastic coefficient
β_c = Isothermal compressibility
T_F = Fictive temperature
k = Boltz'mann constant

loss. Rayleigh scattering loss occurs whenever a light wave travels through a medium having scattering objects smaller than a wavelength. Rayleigh scattering coefficient. It is given by

The transmission loss factor or transmissivity of the fiber TL is related to Rayleigh scattering coefficient by:

$$T_L = \exp(-Y_R L)$$

where, L = length of the fiber in m.

2.6.2 Mie Scattering: Linear scattering occur at in homogeneities which are comparable to in size with the guided wavelength. When the size of scattering in homogeneities is $\lambda/10$ greater than the scattered intensity has an angular dependence and can be quite large. The scattering occurring due to such in homogeneities is mainly in forward direction and this type of scattering is known as Mie scattering. Depending on the fiber material, design and manufacture, Mie scattering can cause considerable power loss. The in homogeneities can be minimized by reducing imperfection during glass manufacturing process and by carefully controlled extrusion and coating on the fiber.

Non linear scattering cause disproportionate attenuation at high optical power levels. This causes the transfer of optical power from one mode either in forward or backward direction to the same or other modes at a different frequency. The important types of non linear scattering within optical fibers are

(i) Stimulated Brillouin Scattering (SBS)

(ii) Stimulated Raman Scattering (SRS)

(I) Stimulated Briilouin Scattering (SBS)

2.6.3 Stimulated Brillouin scattering is the modulation of light through thermal vibrations within the fiber Modulation frequency for the scattered light separates the incident light into upper and lower side bands. The incident photon produces a photon of acoustic frequency as well as a scattered photon. This produces an optical frequency shift which varies with scattering angle because the frequency of the sound wave varies with acoustic wavelength. The frequency shift is maximum in backward direction reducing to zero in forward direction making SBS a mainly backward process.

The optical power level at which Brillouin scattering becomes significant in a single mode fiber is given by an empirical formula. The threshold power level B is given by

$$P_B = 4.4 \times 10^{-3}\, d^2 \lambda^2 \alpha_{dB} \Delta T \text{ watts}$$

d = Fiber core diameter

λ = operating wavelength

α_{dB} = fiber attenuation in dB/km

ΔT = source bandwidth.

In current systems SBS has not been much of the problem for the following reasons:

(i) Direct modulation of the transmit laser's injections current produces a chirp and broadens the signal. This significantly reduces the effect of SBS.

(ii) The SBS effect is less in 1300 nm systems than 1550 nm systems due to the higher attenuation of the fiber.

(iii) SBS effect decreases with increase in speed because of the signal broadening affect of the modulation;

But SBS can be a major problem in three situations.

(i) In long distance systems where the span between amplifiers is great and the bit rate low.

(ii) In WDM systems (upto 10 Gbps) where the spectral width of the signal is very normal.

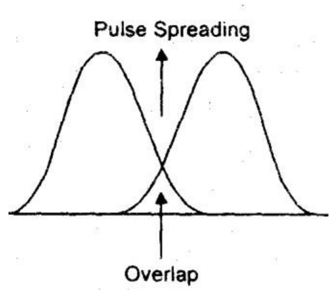
(iii) In remote pumping of an erbium doped fiber amplifier (EDFA) through a separate fiber.

(ii) Stimulated Raman Scattering (SRS)

2.6.4 Stimulated Raman Scattering (SRS) generates a high frequency optical phonon in the scattering process and is similar to SBS except that acoustic phonon is generated in SBS rather than optical phonon. SRS occurs in both the forward and backward direction in the optical fiber and has an optical power threshold of up to three orders of magnitude higher than the Brillouin threshold in a particular fiber. So the stimulated Raman scattering is an interaction between the light wave and the vibration modes of silica molecules. SRS generates scattered light at a wavelength larger than that of the incident light.

2.7 DISPERSION IN OFC

"Spreading of optical pulses as they travel down the fiber" is known as dispersion. It is the time distortion of an optical signal that results from many discrete wavelength components travelling at different rates. The dispersion leads to the degradation of the signal quality at the output end. Dispersion is the time domain spreading or broadening of the transmitted pulse as they travel down the optical fiber. Dispersion produce bit errors. Dispersion resultswhen some components of the input signal spend more time traversing the fiber than other components. Light rays with steep incident angles have longer path lengths than lower-angle rays. In a pulse modulated system, this causes the received pulse to be spread out over a longer period.It is noted that actually no power is lost to dispersion.It spreads the output pulse in the time domain and changes its shape so that it may merge into the succeeding or previous pulses. In a fiber three distinct types of dispersions are observed



Dispersion the broadening of the signal pulse width due to dependence of the refractive index of the material of the fiber on the wavelength of the carrier is called dispersion. The dispersion leads to the degradation of the signal. Quality at the output end due to overlapping of the pulses. There are three kinds of dispersion mechanisms in the fiber.

(1) Intermodal Dispersion

(ii) Intermodal Dispersion

(iii) Polarization Mode Dispersion

2.7.1 Intermodal Dispersion

Pulse widening caused by the mode structure of a light beam inside the fiber is called inter modal (modal) dispersion; This type of dispersion occurs due to the fact that the light inside the fiber propagates in different modes. The higher order modes travel a longer distance and arrive at the receiver end later than the lower order modes. Thus one mode travels more slowly than another mode. So, intermodal dispersion is a result of different values of the group delay for each individual mode at a single frequency. It mainly occurs in multimode fibers. Intermodal dispersion limi4s both the bandwidth as well as the distance. The maximum pulse broadening arising from intermodal dispersion

$$\therefore \quad \delta T_{mod} = T_{max} - T_{min} = \frac{n_1 \Delta L}{c}$$

is the difference between the travel time Tmax of the higher order mode and the travel time Tmin of the fundamental mode

2.7.2 Intramodal dispersion

It is a pulse spreading that occurs within single mode fiber. It is also known as chromatic dispersion. It is caused by the dependence of the optical properties on wavelength. It limits both the bandwidth and the distance that information can be transmitted. Chromatic dispersion consists of two mechanisms:

(a) Material Dispersion

(b) Wave guide Dispersion

2.7.2a Material Dispersion: It is the pulse spreading due to dispersive properties of the material. Material dispersion is caused by the wavelength dependence of the silica's refractive index. An information carrying light pulse contains different wavelengths because a light source radiates light of a spectral width. So, the components of the pulse with different wavelengths will travel within the fiber at different velocities and will arrive at the fiber end at different times, causing the spread of the pulse. The amount of pulse spreading caused by material dispersion per length is given by:

$$\frac{\Delta t_{mat}}{L}\left(\frac{Ps}{Km}\right) = D_{mat}(\lambda)\,\Delta\lambda$$

where, $D_{mat}(\lambda)$ = Material dispersion parameter

$\Delta\lambda$ = spectral width of light source

L = fiber length.

2.7.2b Waveguide Dispersion: Waveguide dispersion is most significant in single mode fibers. An information carrying light pulse after entering in a single mode fiber is distributed between the core and cladding. Its major portion travels within the core, the rest within the cladding. Both portions propagate at different velocities. Since core and cladding have different refractive indexes, the pulse will spread because light is confined within the structure having different refractive indexes. The amount of pulse spreading caused by waveguide. Dispersion per unit time is given by:

$$\Delta t_{wg}/L = D_{wg}(\lambda)\,\Delta\lambda$$

$\Delta t_{wg}/L$ = waveguide dispersion per unit length

D_{wg} = waveguide dispersion parameter

$\Delta\lambda$ = spectral width of light source

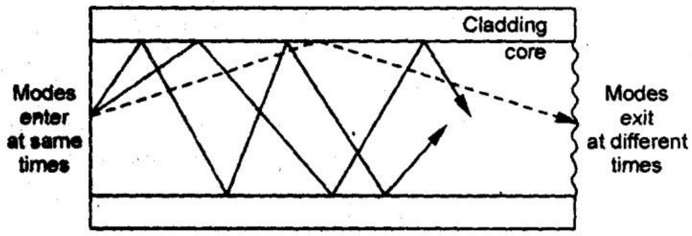
Intermodal dispersion is the sum of material and waveguide dispersion.

2.7.3 Dispersion units

Modal dispersion in an optical fiber is specified by the characteristics pulse spread per kilometer length in the units of ns/km as it is independent of the Iinewidth of the source. Material and waveguide dispersion depend on the source line width, so these are expressed as ns/km.nm.

2.8 Intermodal dispersion in multimode step index fiber.

Pulse widening caused by the mode structure of light beam inside the fiber is called intermodal (modal) dispersion. It mainly occurs in multimode fibers. Intermodal dispersion occurs because each mode travels a different distance over the same time span as shown in Fig.



Intermodal dispersion in multimode fibers

The autocarrelation function of is (t) is related to spectral density Ss(F) by Wiener-Khinchin theorem.

$$< i_s (t)\, i_s (t + \tau) > = \int_{-\infty}^{\infty} S_S (F) \exp. (2\pi i f\tau)\, df \qquad \ldots (1)$$

where angle brackets denote an ensemble average over and fluctuations.

The spectral density of shot noise is constant and is given by $S_S (F) = q\, I_p$, where

Ss(F) is two sided spectral density +ve and -ye frequencies are included in above = n (I). If only + ye frequencies are considered by changing the lower limit of integration to zeros, one sided spectral density becomes $2q\, I_p$.

Nosie variance is obtained by setting r = 0 in equation (1),

$$\sigma_s^2 = < i_s^2 (t) >$$

$$= \int_{-\infty}^{\infty} S_S (f)\, df = 2q\, I_p\, \Delta_f$$

where Δ_f = effective noise bandwidth of

$$\sigma_s^2 = 2q\, I_p \int_0^{\infty} |\, H_T (f)\, |^2\, d_f$$

$$= 2q\, I_p\, \Delta_f$$

where, $$\Delta f = \int_0^{\infty} |\, H_T (f)\, |^2\, d_f$$

receives. If we consider current fluctuations and include total transfer for two HT (F).

Since, dark current ‘d also generates shot noise. Its contribution is included by replacing I_p by $I_p + I_d$

$$\therefore \quad \text{Total short noise} = \sigma_s^2 = 2q\,(I_p + I_d)\,\Delta_f$$

where, σ_s = Root mean square value of noise current induced by shot noise.

where, n_2 = refractive index of the cladding

$$\therefore \quad T_{max} = \frac{Ln_1}{c\left(\frac{n_2}{n_1}\right)} = \frac{Ln_1^2}{cn_2}$$

The difference in time taken by axial ray and the meridional ray

$$\delta T = T_{max} - T_{min} = \frac{Ln_1^2}{cn_2} - \frac{Ln_1}{c}$$

$$= \frac{Ln_1}{c}\left[\frac{n_1}{n_2} - 1\right] = \frac{Ln_1}{c}\left[\frac{n_1 - n_2}{n_2}\right]$$

$$= \frac{Ln_1}{c}\Delta$$

- where, $\Delta = \frac{n_1 - n_2}{n_2}$ relative refractive index difference between the core and the cladding.

$$\text{But} \quad NA = n_1\,(2\Delta)^{1/2}$$

$$\Rightarrow \quad \left(\frac{NA}{n_1}\right)^2 = 2\Delta \quad \Rightarrow \quad \Delta = \frac{1}{2}\left(\frac{NA}{n_1}\right)^2$$

$$\therefore \quad \delta T = \frac{Ln_1}{c} \times \frac{1}{2}\left(\frac{NA}{n_1}\right)^2$$

$$\delta T = \frac{L}{2n_1 c}(NA)^2$$

This equation represents the maximum pulse broadening in time due to intermodal dispersion in multimode step index fiber.

2.9 Polarization Mode Dispersion (PMD) :

Pulse spreading caused by a change of fiber polarization properties is called PMD. PMD is a serious limitation for fiber optic communication systems operating 40Gb/s per channel. It occurs in single mode fibers when fibers are not cylindrical symmetrical Single mode fibers support one mode which consists of two orthogonal polarization modes Ideally the core of an optical fiber has an index of refraction that is uniform over the entire cross-section. Mechanical stresses and external environmental effects can cause slight changes in the core of the fiber which causes a change in index of eraction. This can cause one of orthogonal modes to travel faster than the other, causing dispersion of optical pulse, so PMD is the result of birefringence which is the difference in refractive indices along perpendicular axis in the fiber. Birefringence arises due to intrinsic and extrinsic non homogeneity of fiber core diameter.

2.9.1 Causes of PMD

In single mode fiber, PMD is random. It varies from fiber to fiber because of the randomness of the underlying geometric stress irregularities. The birefringence which causes PMD is due to intrinsic and extrinsic factors.

(i) Intrinsic Factors: Intrinsic factors are those that are present in the fiber during manufacturing stage It can include elliptical core, elliptical cladding, internal stresses etc. During manufacturing of fiber, the fiber drawing process can induce some asymmetry that cause birefringence.

(ii) Extrinsic Factors: Extrinsic factors are those that induce birefringence after manufacture. Birefringence occurs when external forces act on the fiber. These external forces can be radial compressive forces when fiber lies against each other, compressive and tensile forces when fiber is bent and shear forces when fiber is twisted. Cabling of fiber after manufacture can cause stresses that induce birefringence. It also occurs due to seasonal heating and cooling of optical fiber.

2.10 Group velocity dispersion.

Ans. Group Velocity Dispersion: GVD is the phenomenon that the group velocity of light in a transparent medium depends on the optical frequency or wavelength

$$\text{GVD} = \frac{\partial}{\partial w}\left(\frac{1}{vg}\right) = \frac{\partial}{\partial w}\left(\frac{\partial k}{\partial w}\right) = \frac{\partial^2 k}{\partial w^2}$$

The group velocity dispersion is the group delay dispersion per unit length. The basic units are S 2

/m.

For optical fibers, the group velocity dispersion usually defined as a derivative w.r.t, wavelength. This can be calculated as

$$D\lambda = \frac{-2\pi c}{\lambda^2}\text{GVD} = \frac{2\pi c}{\lambda^2}\frac{\partial^2 k}{\partial w^2}$$

This is usually specified with units of ps/nmkm. GVD is responsible for dispersive broadening of pulses as well as for the group velocity mismatch of different waves in parametric nonlinear interactions.

GVD causes a short pulse of light to spread in time as a result of different frequency components of pulse travelling at different velocities

2.11 FIBER CONNECTORS AND SPLICES:

Ans. Good connector should have following requirements:

(i) Low coupling losses

(ii) Ease of assembly

(iii) Low environmental sensitivity

(iv) Low cost

(v) Reliable construction

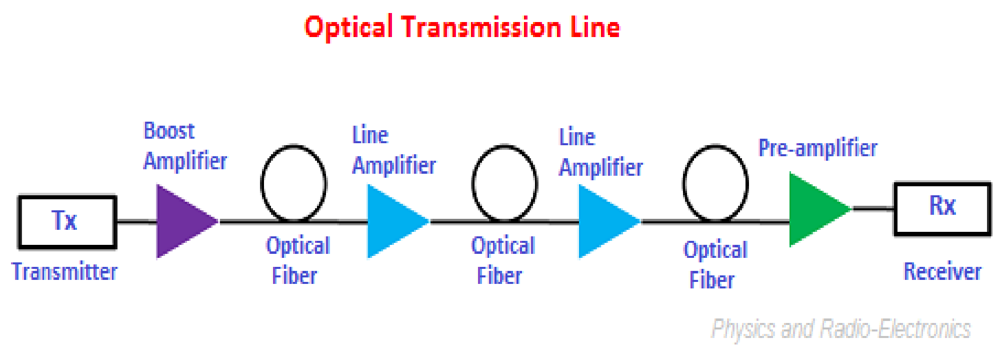
(vi) Ease of connection

Fiber splice: it is a permanent or semi-permanent joint between two fibers. It is used to create long optical links. Fiber splice is used in situations where frequent connection and disconnection is not needed. Splices are of two types : midspan splice in which two cables are connected and pigtail splice in which there is a connector at one end of the fiber and other end is free for splicing to a cable.

Fiber Connector: It is a detachable connection between two fibers. Connectors are used to link fiber cable with the transmitter or the receiver. Fiber connectors are classified into two broad categories: the butt connector and the Expanded beam connector. In the butt connectors two fiber ends are aligned in such a way that the fiber core axis coincide and are then butted to each other. In the expanded beam connector, lenses are used on the ends of the fibers. This collimates the light emerging from transmitter fiber to be focused on to the core of the receiving fiber.

2.12 OPTICAL AMPLIFIERS

- Optical amplifier is a device used in an optical communication system to directly amplify (boost) optical data signal without changing it into its electrical form.



2.12.1 Need for Optical Signal Amplification

In optical fiber communication, light signals are transmitted through the optical fiber for very large distances. When transmission distances become hundreds of kilometers, some signal loss will occur. In order to compensate this optical signal loss, we need to amplify the optical signals. In the past, optical regenerators are installed in the fiber optic link for every 80 km to 100km. The regenerator station will electronically regenerate the optical signals to overcome the optical signal loss due to the attenuation of optical fiber.With the advent of optical amplifiers, optical signal transmission distance can be easily extended without the need of regenerator station.

2.12.2 Optical Amplifiers-Applications

Power Amplifier/Booster
Power amplifiers (also referred to as booster amplifiers) are placed directly after the optical transmitter. This application requires the EDFA to take a large signal input and provide the maximum output level. Small signal response is not as important because the direct transmitter output is usually -10 dBm or higher. The noise added by the amplifier at this point is also not as critical because the incoming signal has a large signal-to-noise ratio (SNR).

In-line amplifier
In-line amplifiers or in-line repeaters, modify a small input signal and boost it for retransmission down the fiber. Controlling the small signal performance and noise added by the EDFA reduces the risk of limiting a system's length due to the noise produced by the amplifying components.

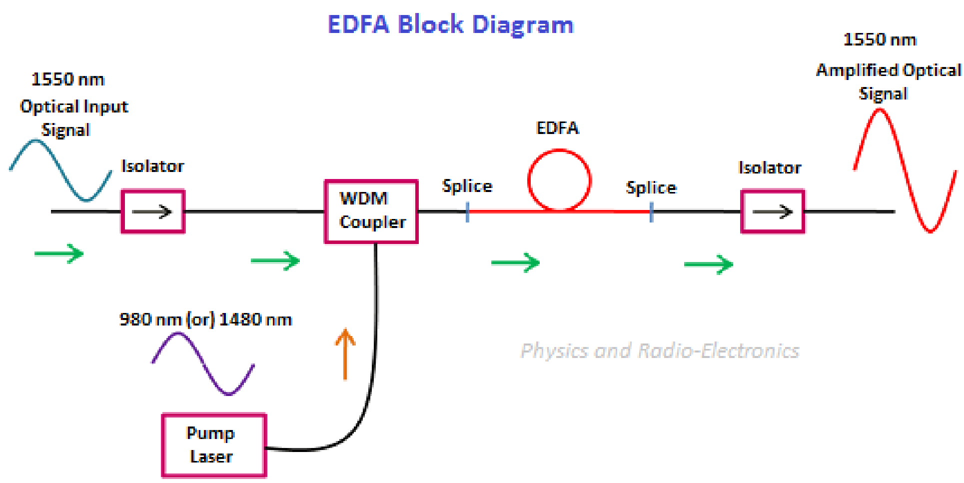
Preamplifier
Past receiver sensitivity of -30 dBm at 622 Mb/s was acceptable; however, presently, the demands require sensitivity of -40 dBm or -45 dBm. This performance can be achieved by placing an optical amplifier prior to the receiver.Boosting the signal at this point presents a much larger signal into the receiver, thus easing the demands of the receiver design. This application requires careful attention to the noise added by the EDFA; the noise added by the amplifier must be minimal to maximize the received SNR.

2.13 Types of Optical Amplifiers

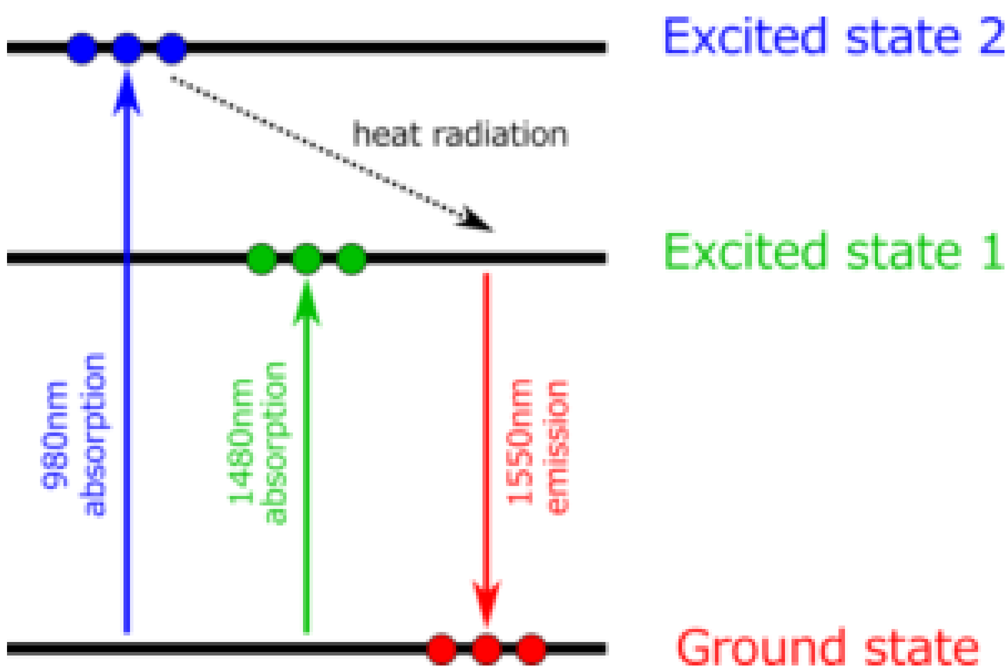
- Erbium Doped fiber amplifier (EDFA)
- Semiconductor optical amplifier (SOA) and
- Fiber Raman amplifier

2.13.1 EDFA Optical Amplifier

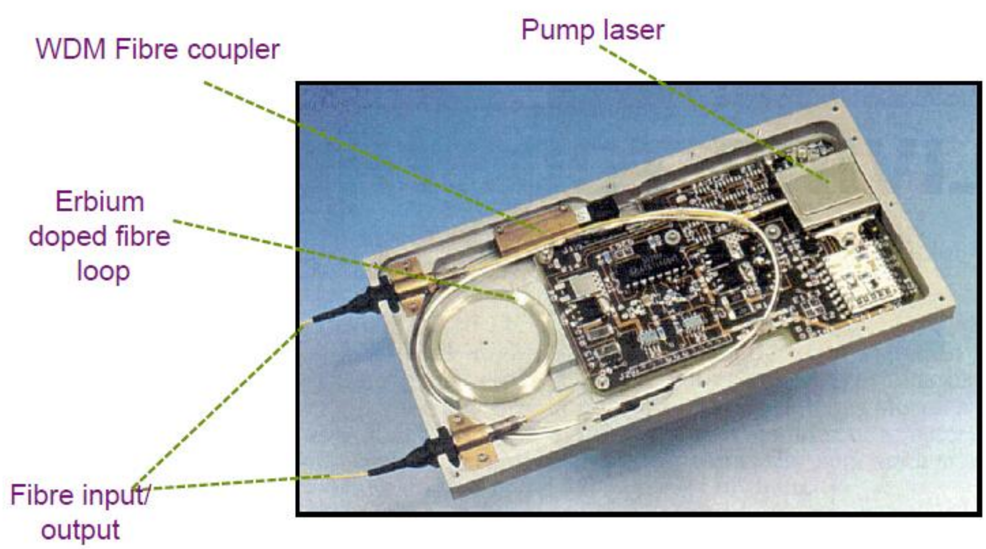
Erbium is a rare-earth element that, when excited, emits light around 1550 nm.
In EDFA, energy is transferred from the pumped light at 1480nm to the weak incoming light signal around 1550nm



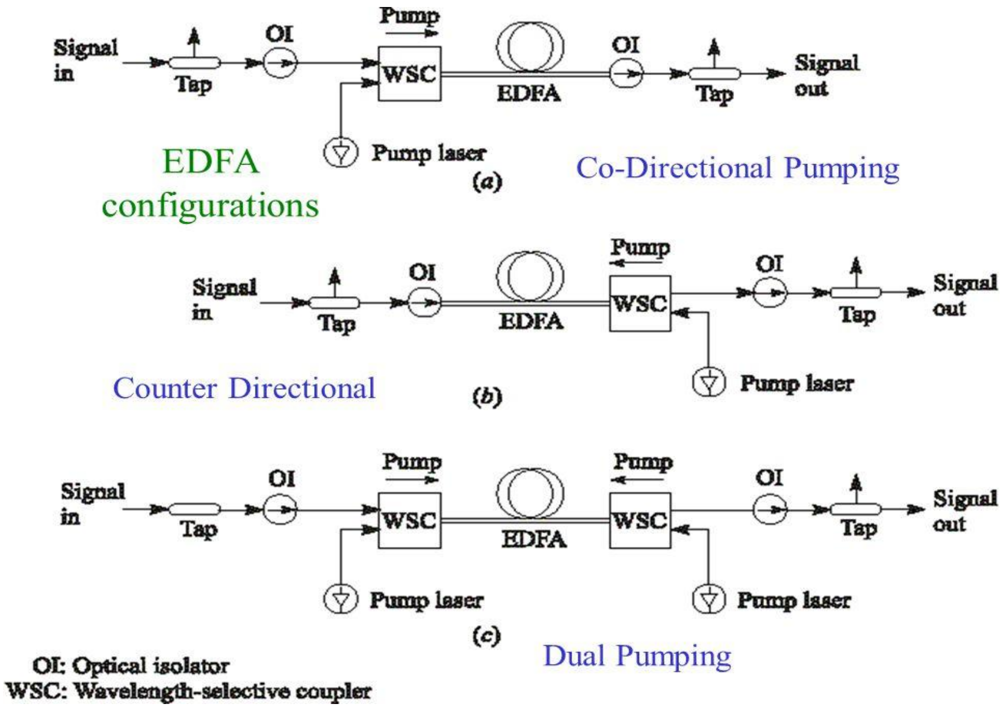
EDFA Optical Amplifier- working principle



EDFA Optical Amplifier



EDFA- Architectures



EDFA Architectures-Comparison

- Single pumping → typ. +17dB gain
- Dual pumping → typ. +35dB gain
- Counter-directional pumping → allows higher gain
- Co-directional pumping → gives better noise performance

EDFA - Merits & De-merits

Merits
- EDFA has high pump power utilization (>50%)
- Directly and simultaneously amplify a wide wavelength band (>80nm) in the 1550nm region, with a relatively flat gain
- Flatness can be improved by gain-flattening optical filters
- Gain in excess of 50 dB
- Low noise figure suitable for long haul applications

De-Merits
- Size of EDFA is not small
- It can not be integrated with other semiconductor devices

2.13.2 Raman Fiber Amplifier

In a FRA, the optical signal is amplified due to **stimulated Raman scattering (SRS).**
The **gain medium is undoped optical fiber**.
Power is transferred to the optical signal by a nonlinear optical process known as the

Raman effect.

The fiber **gain media** of the former is generally within **10 km**.

In addition, it requires on higher pump power, generally in a few to a dozen watts that can produce 40 dB or even over gains.

It is mainly used to amplify the optical signal band of which EDFA cannot satisfy.

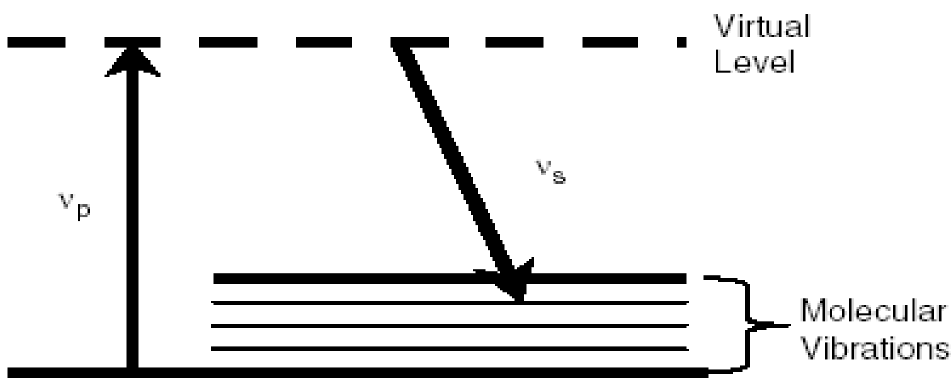
Stimulated Raman Scattering

A pump photon, v_p, excites a molecule up to a virtual level (nonresonant state). The molecule quickly decays to a lower energy level emitting a signal photon $v_s$in the process.

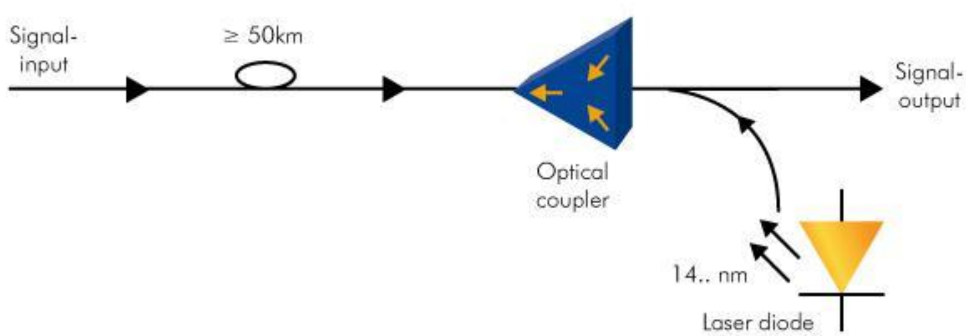
The difference in energy between the pump and signal photons is dissipated by the molecular vibrations of the host material. These vibrational levels determine the frequency shift and shape of the Raman gain curve.

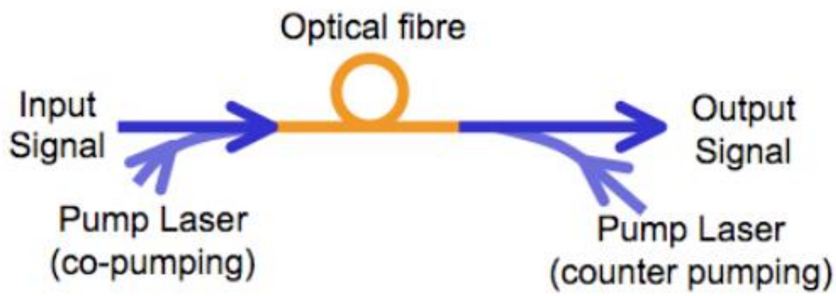
The frequency (or wavelength) difference between the pump and the signal photon (v_p-v_s) is called the Stokes shift, and in standard transmission fibers with a Ge-doped core, the peak of this frequency shift is about 13.2 THz.

For high pump power, the scattered light can grow rapidly.



Fiber Raman Amplifier-Architecture





FRA- Merits & De-Merits

Merits

- Variable wavelength amplification possible
- Compatible with installed SM fiber
- Can result in a lower average power over a span, good for lower crosstalk
- Very broadband operation may be possible

De-Merits

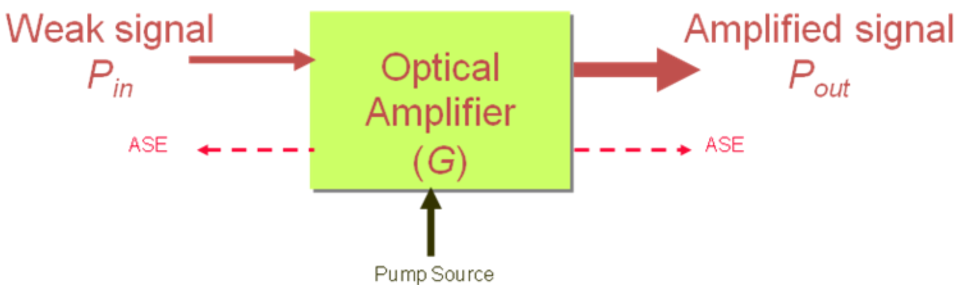
- High pump power requirements, high pump power lasers have only recently arrived
- Sophisticated gain control needed
- Noise is also an issue

Optical Amplifiers-Comparison

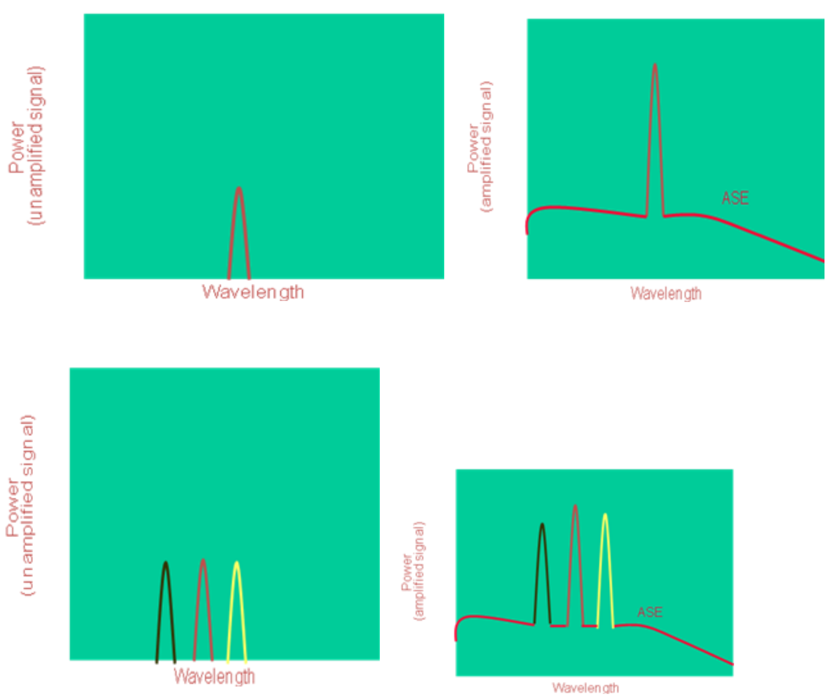
Property	EDFA	Raman	SOA
Gain (dB)	> 40	> 25	>30
Wavelength (nm)	1530-1560	1280-1650	1280-1650
Bandwidth (3dB)	30-60	Pump dependent	60
Max. Saturation (dBm)	22	0.75 × pump	18
Polarization Sensitivity	No	No	Yes
Noise Figure (dB)	5	5	8
Pump Power	25 dBm	>30 dBm	< 400 mA
Time Constant	10^{-2} s	10^{-15} s	2×10^{-9}
Size	Rack mounted	Bulk module	Compact
Switchable	No	No	Yes
Cost Factor	Medium	High	Low

2.14 Noise in Optical Amplifiers

Amplification gain: Up to a factor of 10,000 (+40 dB)
In WDM: Several signals within the amplifier's gain (G) bandwidth are amplified, but not to the same extent
It generates its own noise source known as Amplified Spontaneous Emission (ASE) noise.



Effect of ASE noise



2.14.1 Noise Figure of Optical Amplifiers

- ❖ Required figure of merit to compare amplifier noise performance

- Defined when the input signal is coherent

$$\text{Noise Figure (NF)} = \frac{\text{Input signal} - \text{to} - \text{noise ratio}\,(SNR_i)}{\text{Output signal} - \text{to} - \text{noise ratio}\,(SNR_o)}$$

- NF is a positive number, nearly always > 2 (I.e. 3 dB)
- Good performance: when NF ~ 3 dB
- NF is one of a number of factors that determine the overall BER of a network.

2.15 Gain of Amplifiers

Gain bandwidth

- Refers to the range of frequencies or wavelengths over which the amplifier is effective.
- In a network, the gain bandwidth limits the number of wavelengths available for a given channel spacing.

Gain efficiency

Measures the gain as a function of input power in dB/mW.

Gain saturation

- Is the value of output power at which the output power no longer increases with an increase in the input power.
- The saturation power is typically defined as the output power at which there is a 3-dB reduction in the ratio of output power to input power (the small-signal gain).

Fiber Capacity

Find the maximum bit rate (capacity) of the multimode fiber given in Example 3.7

n_1=1.480,

n_2 = 1.465, and Δ = 0.01,

$$BL < \frac{n_2}{n_1^2}\frac{c}{\Delta}$$

Solution

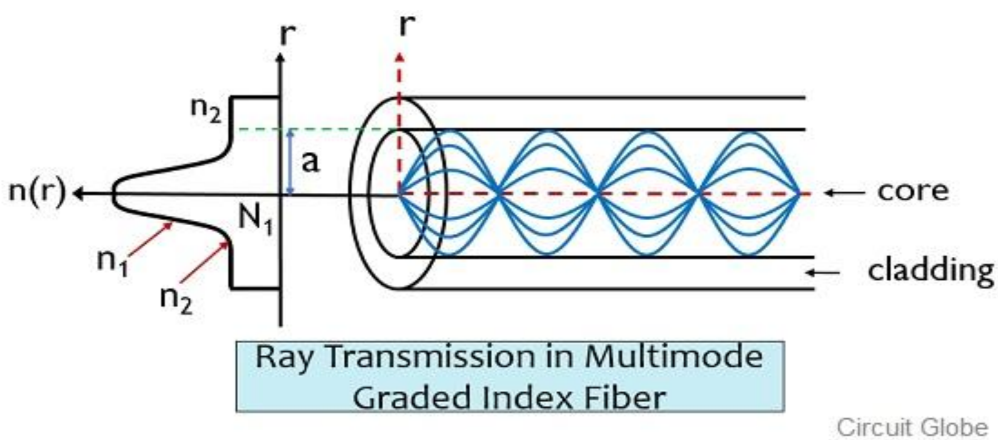
BL = 20 Mb/s-km

2.16 Graded Index Fiber

Graded index multimode fiber is a type of optical fiber where the refractive index is higher at the axis of the core and then it decreases gradually towards the core-cladding interface. The change in refractive index causes refraction rather than total internal reflection.

$$n(r) = \begin{cases} n_1 \left[1 - 2\Delta\left(\frac{r}{a}\right)^{\alpha}\right]^{1/2} & \text{for } 0 \leq r \leq a \\ n_1 (1 - 2\Delta)^{1/2} \approx n_1 (1 - \Delta) = n_2 & \text{for } r \geq a \end{cases}$$

Light propogation in Graded Index Multimode Fiber



Example 2.21 **Bandwidth of an Optical Fiber Cable**

Determine the transmission bandwidth of a 300-meter optical fiber cable having specified Bandwidth-Length Product (BLP) of 600 MHz-km.

Solution:

Given Bandwidth × Length = 600 MHz-km

For 300-meter length of optical fiber cable, we have

$$\text{Bandwidth of optical fiber} = \frac{600 \text{ MHz-km}}{300 \times 10^{-3} \text{ km}} = 2 \times 10^{3} \text{ MHz, or } 2 \text{ GHz} \qquad \textbf{Ans.}$$

Example 2.22 **Maximum Distance between Repeaters**

An optical fiber cable has a specified bandwidth-length product of 500 MHz-km. If it is required to obtain a transmission bandwidth of 85 MHz for a particular mode of propagation, determine the maximum distance that can be used between repeaters.

Solution:

Given Bandwidth × Length = 500 MHz-km

$$\text{That is, the maximum distance between repeaters} = \frac{500 \text{ MHz-km}}{\text{Bandwidth}}$$

For the given bandwidth of 85 MHz for a particular mode of transmission, we have

$$\text{Maximum distance between repeaters} = \frac{500 \text{ MHz-km}}{85 \text{ MHz}} = 5.9 \text{ km} \qquad \textbf{Ans.}$$

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DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – III – Optical Communications – SEC1403

UNIT III

OPTICAL TRANSMITTERS AND RECEIVERS

Fiber optic Transmitter module Optical sources- LEDs, LASER diodes Principles of operation: concepts of line width, phase noise Optical detectors- PN, P-I-N, Avalanche photodiodes Principles of operation: concepts of responsivity, sensitivity and quantum efficiency, noise in detection Fiber optic Receiver module

INTRODUCTION

Optical sources

Optical transmitter converts electrical input signal into corresponding optical signal. The optical signal is then launched into the fiber. Optical source is the major component in an optical transmitter. Popularly used optical transmitters are Light Emitting Diode (LED) and semiconductor Laser Diodes (LD).

Characteristics of Light Source

- It must be possible to operate the device continuously at a variety of temperatures for many years.
- It must be possible to modulate the light output over a wide range of modulating frequencies.
- For fiber links, the wavelength of the output should coincide with one of transmission windows.
- To couple large amount of power into an optical fiber, the emitting area should be small.
- To reduce material dispersion in an optical fiber link, the output spectrum should be narrow. V
- The power requirement for its operation must be low
- The light source must be compatible with the modem solid state devices.
- The optical output power must be directly modulated by varying the input current to the device.
- Better linearity to prevent harmonics and intermodulation distortion.
- High coupling efficiency.
- High optical output power.
- High reliability.

Low weight and low cost Two types of light sources used in fiber optics are light emitting diodes

(LEDs) and laser diodes (LDs).

Light Emitting Diodes (LEDs)

Conventional p-n junction is called as homojunction as same semiconductor material is used on both sides junction. As the carriers are not confined to the immediate vacinity of junction. Hence high current densities cannot be realized.

The carrier confinement problem can be resolved by sandwiching a thin layer between p-type and n-type layers. The middle layer mayor may not be doped. The carrier confinement occurs due to band gap discontinuity of the junction. Such a junction is called heterojunction and the device is called double heterostructure.

LED Strucrures

HeteroJunctions

A heterojunction is an interface between two adjoining single crystal semiconductors with different bandgap.

Hetercjunctions are of two types, lsotype (n-n or p-p) or Antisotype (p-n).

Double Heterojunctions (DH)

In order to achieve efficient confinement of emitted radiation double heterojunctions are used in LED structures. A heterojunction is a junction formed by dissimilar semiconductors. Double heterojunction (DR) is formed by two different semiconductors on each side of active region.

LED configurations

There are two LED configurations used in optical fiber links .

1. Surface emitting LED.
2. Edge emitting LED.

Both devices use a OH structure to constrain the carriers and the light to an active layer.

Surface Emitting LEDs

In surface emitting LEDs the plane of active light emitting region is oriented perpendicularly to the axis of the fiber. A DH diode IS grown on an N-type substrate at the top of the diode as shown in Fig.3.1. A circular well is etched through the substrate of the device. A fiber is then connected to accept the emitted light.

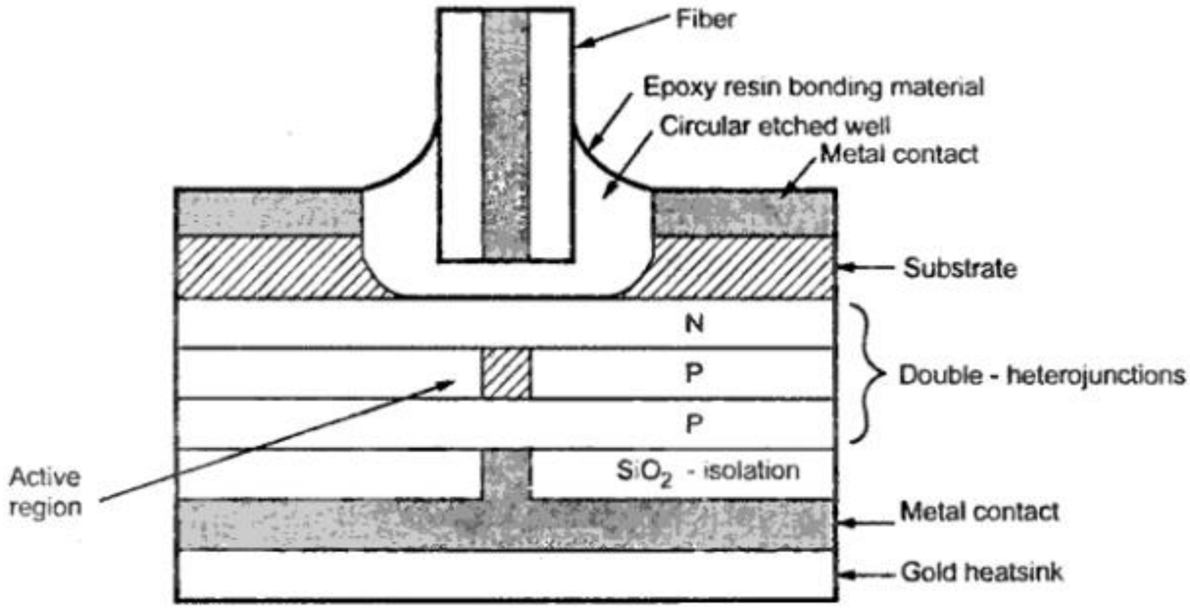


Figure 3.1 Cross section of surface emitting LED

At the back of device is a gold heat sink. The current flows through the p-type material and forms the small circular active region resulting in the intense beam of light.

Diameter of circular active area = 50 μm
Thickness of circular active area = 2.5 μm
Current density= 2000 A/cm^2 half-power
Emission pattern = Isotropic, 120^0 beamwidth.

The isotropic emission pattern from surface emitting LED is of lambartian pattern. In Lambartian pattern, the emitting surface is uniformly bright, but its projected area diminishes as cos θ, where θ is the angle between the viewing direction and the normal to the surface as shown in Fig. 3.2. The beam intensity is maximim along the normal.

The power is reduced to 50% of its peak when $\theta=6O^0$. Therefore the total half-power beamwidth is 120^0 . The radiation pattern decides the coupling efficiency of LED.

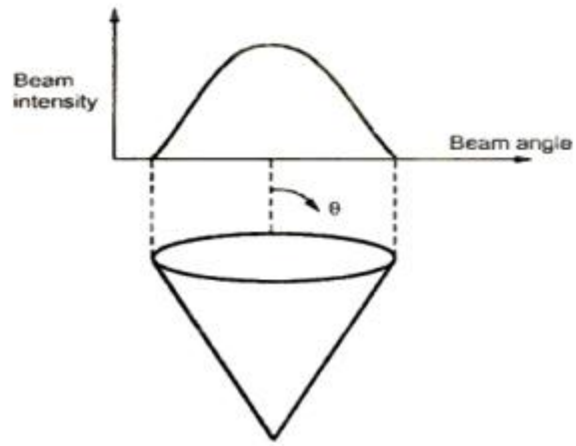


Figure. 3.2. Lambartian radiation

Edge Emitting LEDs (ELEDs)

In order to reduce the losses caused by absorption in the active layer and to make the beam more directional, the light is collected from the edge of the LED. Such a device is known as edge emitting LED or ELED.

It consists of an active junction region which is the source of incoherent light and two guiding layers. The refractive index of guiding layers is lower than active region but higher than outer surrounding material. Thus a waveguide channel is form and optical radiation is directed into the fiber. Fig. 3.3 shows structure of ELED.

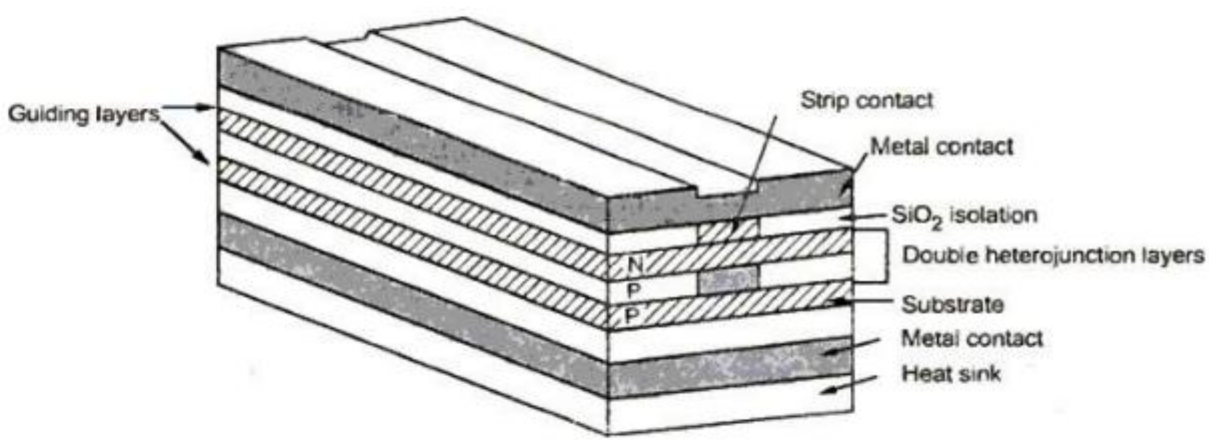


Figure. 3.3 Structure of edge emitting. DH, strip contact LED

Edge emitter's emission pattern is more concentrated (directional) providing improved coupling efficiency. The beam is Lambartian in the plane parallel to the junction but diverges more slowly in the plane perpendicular to the junction. In this plane, the beam divergence is limited. In the parallel plane. there is no beam confinement and the radiation is Lambartian.

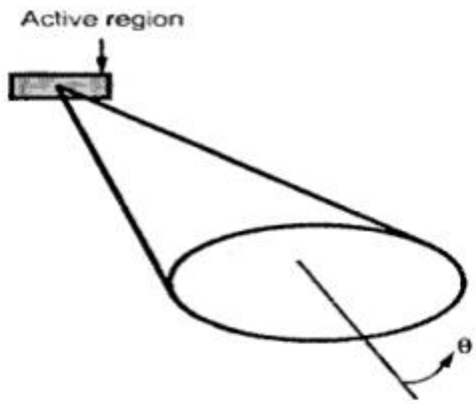


Figure. 3.4 Unsymmetric radiation from an edge emitting LED

To maximize the useful output power, a reflector may be placed at the end of the diode opposite the emitting edge. Fig. 3.4 shows radiation from ELED.

Advantages of LED
1. Simple design.
2. Ease of manufacture.
3. Simple system integration.
4. Low cost.
5. High reliability.

Disadvantages of LED
1. Refraction of light at semiconductor/air interface.
2. The average life time of a radiative recombination is only a few nanoseconds, therefore modulation BW is limited to only few hundred megahertz.
3. Low coupling efficiency.
4. Large chromatic dispersion.

Injection Laser Diode (ILD)

The laser is a device which amplifies the light, hence the LASER is an acronym for light amplification by stimulated emission of radiation.

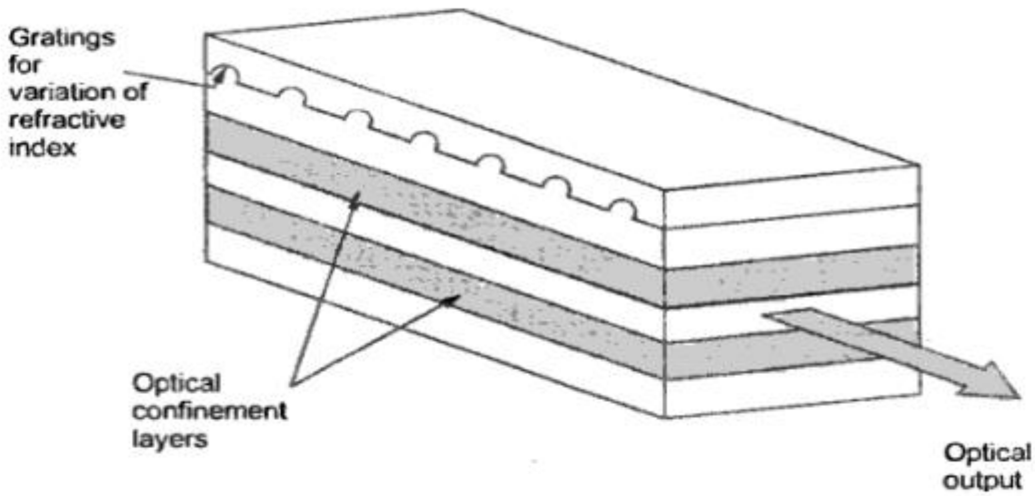
The operation of the device may be described by the formation of an electromagnetic standing wave within a cavity (optical resonator) which provides an output of monochromatic highly coherent radiation. Principle: Material absorbs light rather than emitting.
Three different fundamental process occurs between the two energy states of an atom.
1) Absorption
2) Spontaneous emission
3) Stimulated emission.

Laser action is the result of three process absorption of energy packets (photons) spontaneous emission, and. stimulated emission. (These processes are represented by the simple two-energylevel diagrams).

Where, E1 is the lower state energy level. E2 is the higher state energy level.

Distributed Feedback (DFB)laser

In DFB laser the Iasing action is obtained by periodic variations of refractive index along the longitudinal dimension of the diode. Fig. 3.5 shows the structure of DFB laser diode.



The electromagnetic wave propagating in longitudinal direction is expressed as

$$E(z, t) = I(z)e^{j(\omega t - \beta z)}$$

where,

I(z) is optical field intensity.

ω is optical radian frequency

β is propagation constant.

Lasing (light amplification) occurs when gain of modes exceeds above optical loss during one round trip through the cavity i.e. z = 2L If R1 and R2 are the mirror reflectivities of the two ends of laser diode. Now the expression for lasing expressing is modified as,

$$I(2L) = I(0)R_1R_2e^{[2L\{\Gamma g(h\nu) - \alpha(h\nu)\}]}$$

Advantages of Laser Diode

1. Simple economic design.
2. High optical power
3. Production of light can be precisely controlled.
4. Can be used al high temperatures.
5. Better modulation capability.
6. High coupling efficiency.

Disadvantages of Laser Diode

1. At the end of fiber, a speckle pattern appears as two coherent light beams add or subtract their electric field depending upon their relative phases.

2. Laser diode is extremely sensitive to overload currents and. at high transmission rates, when laser is required to operate continuously the use of large drive current produces unfavorable thermal characteristics and necessitates the use of cooling and power stabilization.

Line Width of an Light sources

Emitted wavelength is related to photon energy by,

$$\lambda = \frac{hc}{E_g}$$

By differentiating,

$$\frac{d\lambda}{dE_g} = -\frac{hc}{E_g^2}$$

Assuming $\Delta\lambda$ is small

$$\Delta\lambda = \left|\frac{hc}{E^2_g}\right| \Delta E_g$$

From semiconductor physics, $\Delta E_g = \Delta(h\nu) \approx 3k_BT$,

$$|\Delta\lambda| = \lambda^2 \frac{3k_B T}{hc}$$

These are typical values and the exact value depends on the LED structure.

Phase Noise

Phase noise is most often obtained from beat measurements – either from a beat note between two different lasers, or between the laser output and a delayed portion of it, often with an additional frequency shift provided by an acousto-optic modulator. The delay is often achieved with a long optical fiber.

If this can be longer than the coherence length, one can use simple processing techniques as the fluctuations of both signals are statistically independent.

If this is impractical, more sophisticated techniques of data analysis can be employed. The most flexible measurement scheme is again based on recording the beat signal with a sampling card, even though the initial efforts for data processing are more extensive than with a spectrum analyzer and is shown in fig. 3.6.

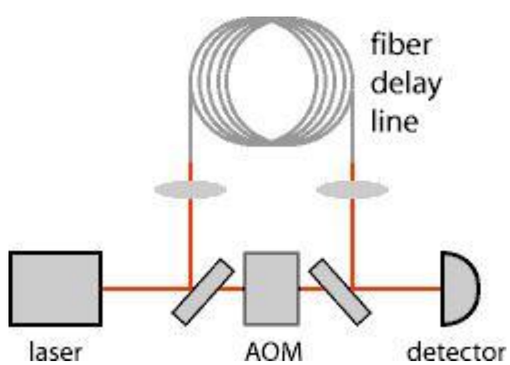


Figure. 3.6 Phase noise in optical sources

Switching Characteristics

An optical switch may operate by mechanical means, such as physically shifting an optical fiber to drive one or more alternative fibers, or by electro-optic effects, magneto-optic effects, or other methods. Slow optical switches, such as those using moving fibers, may be used for alternate routing of

an optical switch transmission path, such as routing around a fault. Fast optical switches, such as those using electro-optic or magneto-optic effects, may be used to perform logic operations; also included in this category are semiconductor optical amplifiers, which are optoelectronic devices that can be used as optical switches and be integrated with discrete or integrated microelectronic circuits

Modulation Characteristics

An optical modulator is a device which is used to modulate a beam of light. The beam may be carried over free space, or propagated through an optical waveguide. Depending on the parameter of a light beam which is manipulated, modulators may be categorized into amplitude modulators, phase modulators, polarization modulators etc. Often the easiest way to obtain modulation of intensity of a

light beam, is to modulate the current driving the light source, e.g. a laser diode. This sort of modulation is called direct modulation, as opposed to the external modulation performed by a light modulator. For this reason light modulators are, e.g. in fiber optic communications, called external light modulators.

With laser diodes where narrow line width is required, direct modulation is avoided due to a high bandwidth "chirping" effect when applying and removing the current to the laser.

.Optical Detectors

Detectors perform the opposite function of light emitters. They convert optical signals back into electrical impulses that are used by the receiving end of the fiber optic data, video, or audio link. The most common detector is the semiconductor photodiode, which produces current in response to incident light.

Principles of Optical Detectors

The photo detector works on the principle of optical absorption. The main requirement of light detector or photo detector is its fast response. For fiber optic communication purpose most suited photodetectors are PIN (p-type- Intrinsic-n-type diodes and APD (Avalanche photodiodes)

The performance parameters of a photo detector are responsivity, quantum efficiency, response time and dark current

Cut-off Wavelength (λc)

Any particular semiconductor can absorb photon over a limited wavelength range. The highest wavelength is known as cui-off wavelength (i.e). The cut-off wavelength is determined by band gap energy and is given by

$$\lambda_c = \frac{hc}{E_g} = \frac{1.24}{E_g}$$

where,

λg in electron volts
(eV)

λc cut-off wavelength is in μm,

Quantum Efficiency

The quantum efficiency is defined as the number of electron-hole carrier pair generated per incident photon of energy hv and is given as

$$\eta = \frac{\text{Number of electron hole pairs generated}}{\text{Number of incident photons}}$$

$$\eta = \frac{I_{p/q}}{P_{in} / h\nu}$$

Detector Responsivity

The responsivity of a photo detector is the ratio 01 the current output in amperes to the incident optical power in watts

$$\Re = \frac{I_p}{P_{in}}$$

$$\eta = \frac{I_{p/q}}{P_{in} / h\nu} = \frac{I_p}{q} \frac{h\nu}{P_{in}}$$

$$\frac{I_p}{P_{in}} = \frac{\eta q}{h\nu}$$

$$\boxed{\Re = \frac{\eta q}{h\nu} = \frac{\eta q \lambda}{hc}}$$

Working of Photodiodes

In order to convert the modulated light back into an electrical signal, photodiodes of photodetectors are used. As the intensity of optical signal at the receiver is very low, the detector has to meet high performance specifications.

- The conversion efficiency must be high at the operating wavelength.
- The speed of response must be high enough to ensure that signal distortion does not occur.
- The detection process introduces the minimum amount of noise.
- It must be possible to operate continuously over a wide range of temperatures for many years.
- The detector size must be compatible with the fiber dimensions.

V-I Characteristics of Photodiode

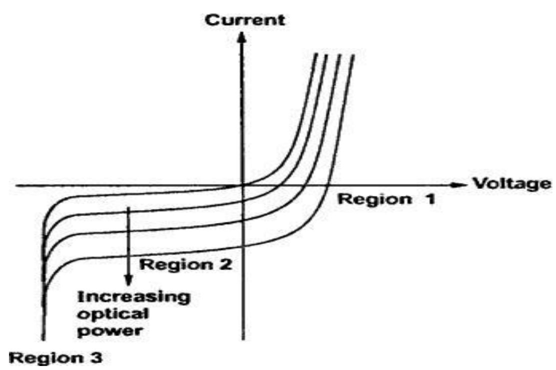


Figure. 3.7 V-I Characteristics of Photodiode

V-I Characteristics of Photodiode is shown in figure 3.7 with different three regions.

Forward bias, region 1: A change in incident power causes a change in terminal voltage, it is called as photovoil.lic mode. If the diode is operated in this mode, the frequency response of the diode is poor and so photovoltaic operation is rarely used in optical links.

Reverse bias, region 2: A change in optical power produces a proportional change in diode current, it is called as photoconductive mode of operation which most detectors use.

Avalanche breakdown region 3: When biased in this region, a photo generated electron-hole pair causes avalanche breakdown, resulting in large diode for a single incident photon.

PIN Photodiode

PIN diode consists of an intrinsic semiconductor sandwiched between two heavily doped p-type and n-type semiconductors as shown in Fig. 3.8.

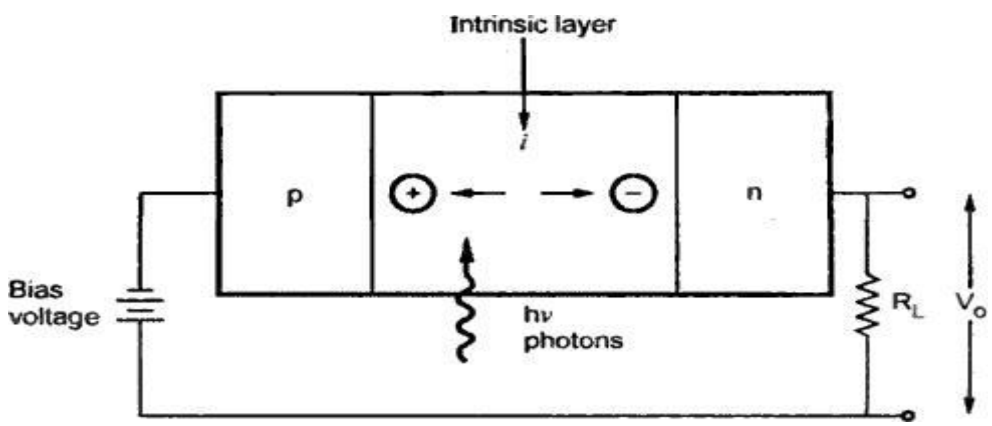


Figure. 3.8 PIN Photodiode

Sufficient reverse voltage is applied so as to keep intrinsic region free from carriers, so its resistance is high, most of diode voltage appears across it, and the electrical forces are strong within it. The incident photons give up their energy and excite an electron from valance to conduction band. Thus a free electron hole pair is generated, these are called as photocarriers. These carriers ate collected across the reverse biased junction resulting in rise in current in external circuit called photocurrent.

In the absence of light, PIN photodiodes behave electrically just like an ordinary rectifier diode. If forward biased, they conduct large amount of current.

PIN detectors can be operated in two modes Photovolt.lic and photoconductive. In photovoltaic mode, no bias is applied to the detector. In this case the detector works very slow, and output is approximately logarithmic to the input light level. Real world fiber optic receivers never use the photovoltaic mode.

In photoconductive mode, the detector is reverse biased. The output in this case is a current that is very linear with the input light power.

The intrinsic region somewhat improves the sensitivity of the device. It does not provide internal gain. The combination of different semiconductors operating at different wavelengths allows the selection of material capable of responding to the desired operating wavelength.

Table 3.1. Characteristics of Common PIN Photodiodes

Sr. No.	Parameters	Symbol	Unit	Si	Ge	InGaAs
1.	Wavelength	λ	μ m	0.4 - 1.1	0.8 - 1.8	1.0 - 1.7
2.	Reponsivity	$\Re$	A/W	0.4 - 0.6	0.5 - 0.7	0.6 - 0.9
3.	Quantum efficiency	η	%	75 - 90	50 - 55	60 - 70
4.	Dark current	I_d	nA	1 - 10	50 - 500	1 - 20
5.	Rise time	T_r	nS	0.5 - 1	0.1 - 0.5	0.02 - 0.5
6.	Bandwidth	B	GHz	0.3 - 0.6	0.5 - 3	1 - 10
7.	Bias voltage	V_b	V	50 - 100	5 - 10	5 - 6

Avalanche Photodiode (APD)

When a p-n junction diode is applied with high reverse bias breakdown can occur by two separate mechanisms direct ionization of the lattice atoms, zener breakdown and high velocity carriers causing impact ionization of the lattice atoms called avalanche breakdown. APDs use the avalanche breakdown phenomena for its operation. The APD has its internal gain which increases its responsivity.

Fig. 3.9 shows the schematic structure of an APD. By virtue of the doping concentration and physical construction of the n^+ p junction, the electric field is high enough to cause impact ionization. Under normal operating bias, the I layer (the p^- region) is completely depicted. This is known as reach through condition, hence APDs are also known as reach through APD or RAPDs.

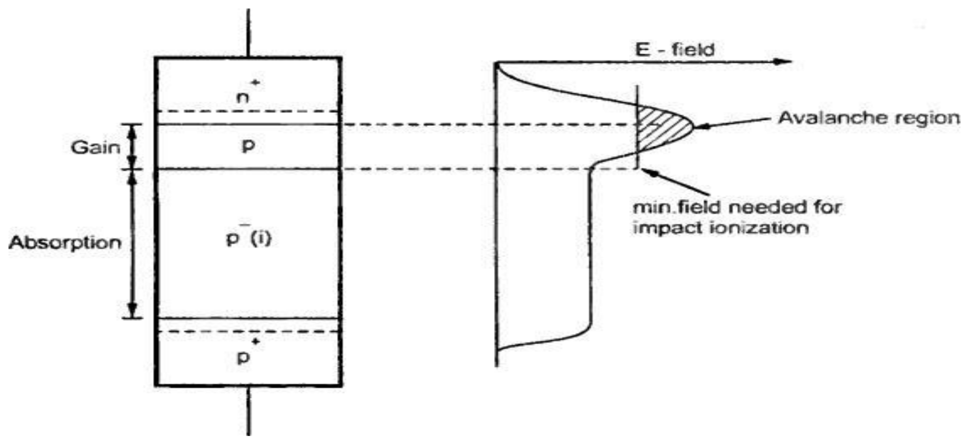


Figure. 3.9 APD schematic and variation of E-field across diode

Similar to PIN photodiode, light absorption in APDs is most efficient in I-layer. In this region. the E·field separates the carriers and electrons drift into the avalanche region where carrier multiplication occurs. If the APD is biased close to breakdown, it will result in reverse leakage current. Thus APDs are usually biased just below breakdown, with the bias voltage being tightly controlled.

The multiplication for all carriers generated in the photodiode is given as

$$M = \frac{I_M}{I_P}$$

I_M - Average value of total multiplied output current.

Ip - Primary un multiplied photocurrent.

Responsivity of APD is given by

$$\Re_{APD} = \frac{\eta q}{h\nu} M$$

Table 3.2 Comparision of PIN and APD

Sr. No.	Parameters	PIN	APD
1.	Sensitivity	Less sensitive (0 - 12 dB).	More sensitive (5 to 15 dB).
2.	Biasing	Low reverse biased voltage (5 to 10 V).	High reverse biased voltage (20 - 400 volts).
3.	Wavelength region	300 - 1100 nm.	400-100 nm.
4.	Gain	No internal gain.	Internal gain.
5.	S/N ratio	Poor.	Better.
6.	Detector circuit	Simple.	More complex.
7.	Conversion efficiency	0.5 to 1.0 Amps/watt.	0.5 to 100 Amps/watt.
8.	Cost	Cheaper.	More expensive.
9.	Support circuitry required	None.	High voltage and temperature compensation.

Important Formulae for PIN and APD

PIN photodiode

1. $$\lambda_c = \frac{1.24}{E_g}$$

2. $$\eta = \frac{I_p / q}{P_0 / h\nu}$$

3. $$\Re = \frac{\eta q}{h\nu} = \frac{I_p}{P_0}$$

APD

1. $$B = \frac{1}{2\pi R_T C_T}$$

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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – IV – Optical Communications – SEC1403

UNIT IV

Couplers, Connectors and Optical Link

Couplers: 2x2 coupler, Tap coupler, star coupler Connectors: Cylindrical ferrule, Biconical Ferrule, Double eccentric Splices: Fusion splices, Mechanical splices, Multiple splices Design considerations in optical links, Point to point Links: Link Power budget, Rise Time budget Analog Links: CNR Multichannel transmission techniques-Multichannel Frequency Modulation, Subcarrier multiplexing WDM Concepts and Components

INTRODUCTION

Optical Coupler

A fiber optic coupler is a device used in optical fiber systems with one or more input fibers and one or several output fibers. Light entering an input fiber can appear at one or more outputs and its power distribution potentially depending on the wavelength and polarization.
A fiber optic coupler is an optical device capable of connecting one or more fiber ends in order to allow the transmission of light waves in multiple paths. The device is capable of combining two or more inputs into a single output and also dividing a single input into two or more outputs.

Optical Splitter

In splitting function, the fiber optic coupler split the input signal in two or more outputs. Such types of couplers are known as optical splitters. A splitter divides the optical power into two or several equal parts among the fibers.

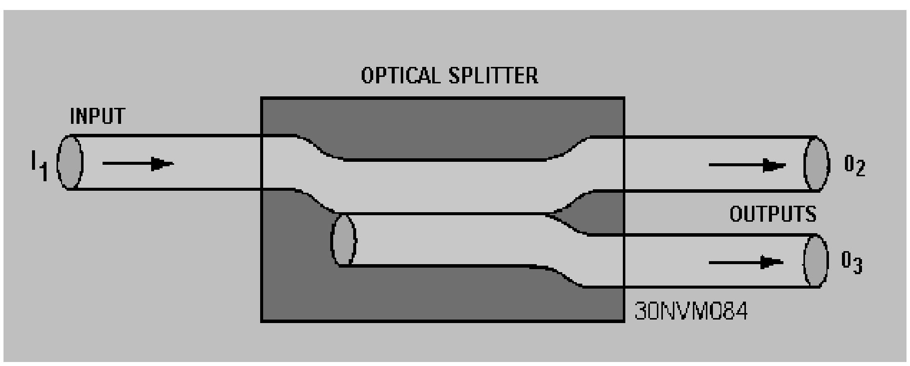


Figure 4.1 Optical Splitter

Optical Combiners

An optical combiner is used to combine two or more inputs into one single output. An optical combiner combines the optical power carried by two or several input fibers into a single output fiber.

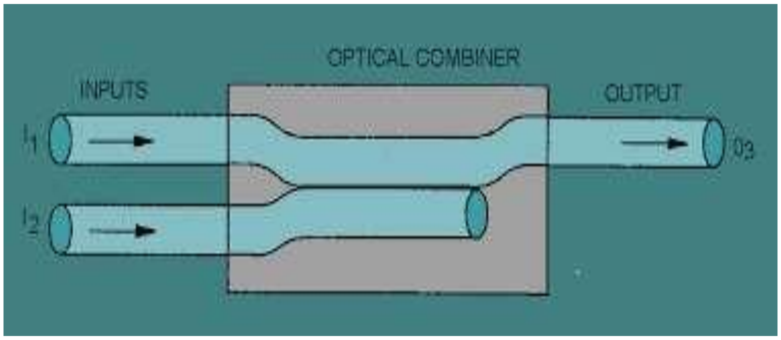


Figure 4.2 Optical Combiner

TYPES OF COUPLERS

If we see optical couplers by shape, there is

1. X Couplers (2X2 Coupler)
2. Star Couplers
3. Y Coupler (Tap Coupler)
4. Tree Couplers
5. T coupler

Which split the optical signal based on the power.

X Couplers (2X2 Coupler)

X couplers carry out the function of a splitter and a combiner in one package. The X coupler combines and divides the optical power from the two input fibers between the two output fibers. Another name for the X coupler is **2 x 2 coupler**.

Figure 4.3 X coupler

Star Coupler

A star coupler generally has several input and output port combinations, in which the optical power is distributed from more than two input ports among several output ports. The number of input and output ports may or may not be equal in star couplers such as 2×4, 4×4, 8×16, etc. However, in all possible input and output port combinations, the distribution of power among the output ports remains equal.

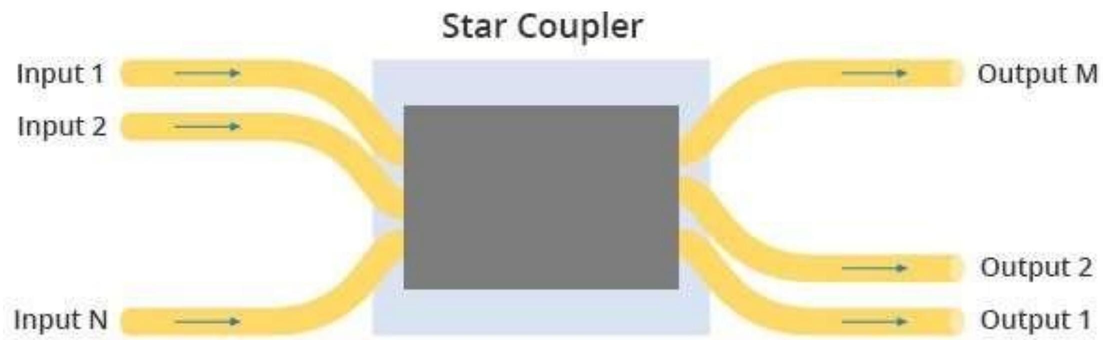


Figure 4.4 Star coupler

Y Coupler (Tap Coupler)

A Y coupler resembles the letter Y. Y coupler is also called tap coupler.
This type of coupler simply divides the signal into two outputs. The power distribution ratio between two outputs can be precisely controlled, such as 10/90 percent, 20/80 percent, 30/70 percent, 40/60 percent or 50/50 percent.

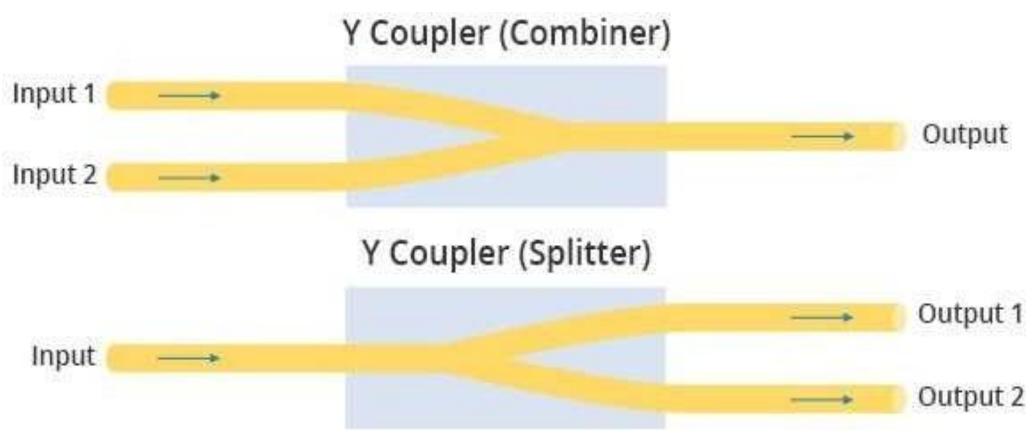


Figure 4.5 Y coupler

T Coupler

Unlike the Y coupler, a T coupler has an uneven power distribution. The power of one output signal is greater than the other output signal. Popular splitting ratios include 10:90 percent and 20:80 percent. This optical coupler is often used in small networks with less port counts.

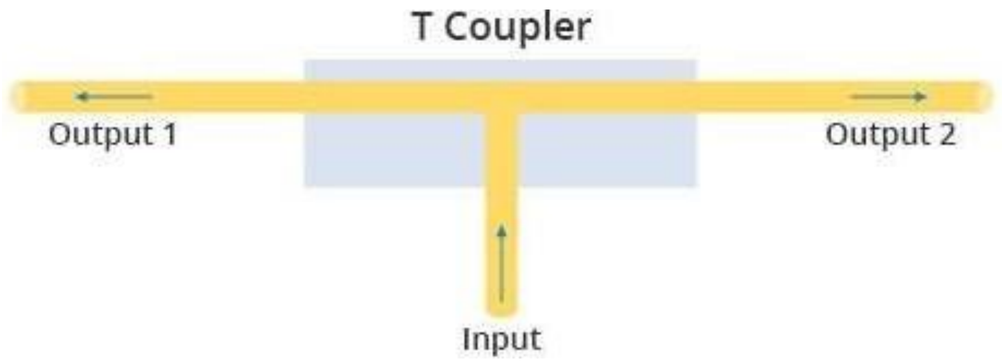


Figure 4.6 T coupler

T-Coupler APPLICATIONS

T couplers can be cascade to connect multiple terminals on a network, as shown below.

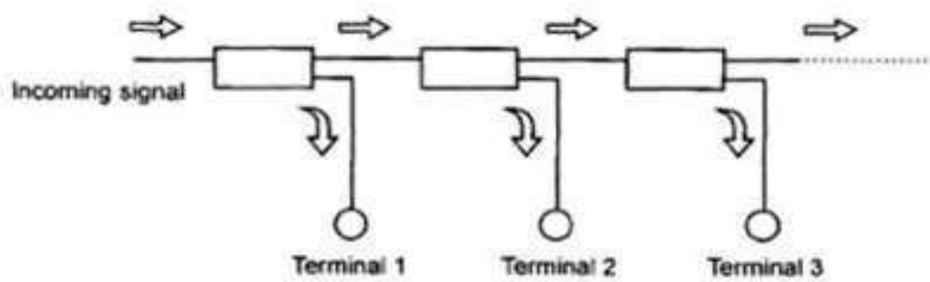


Figure 4.7 Advantages of T coupler

Advantages of T and Y Coupler

T couplers are readily available and can be terminated with standard connectors such as SC, ST, FC, LC, etc. You can quickly set up a small network with T couplers cascaded that way.

Tree Coupler

A tree coupler is also a multiport coupler. It splits optical power from one input fiber to more than two output fibers.
A tree coupler may also be used reversely to combine the optical signal from more than two input fibers to one output fiber.

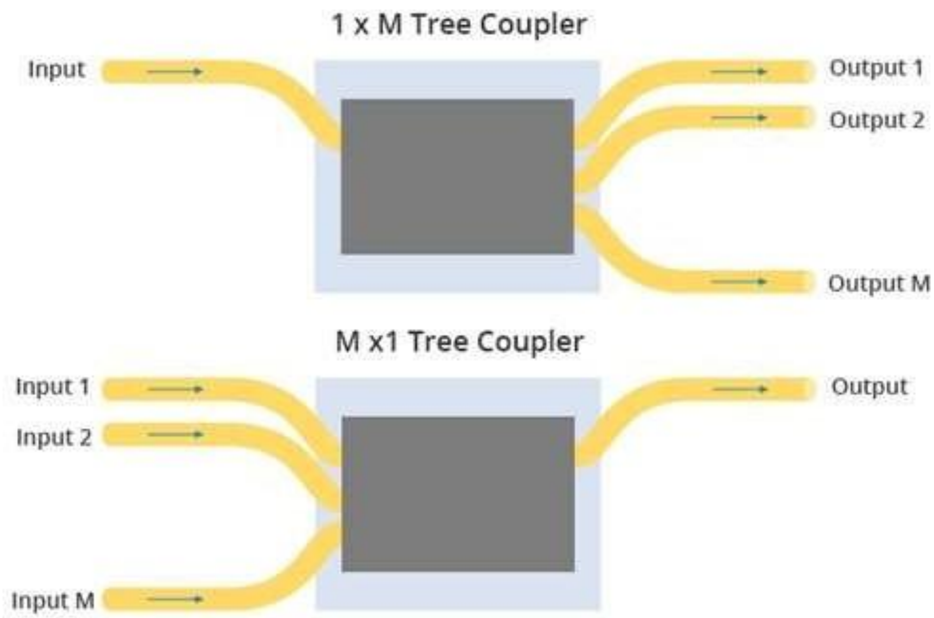


Figure 4.8 Tree coupler

Applications of Fiber Optic Couplers

Optical fiber couplers, which either combine or split optical signals, have been used in modern fiber optic networks, biomedical imaging systems, and optical fiber sensor systems.

In local area network (LAN) applications, fiber optic couplers are used in either bus architecture or star architecture.

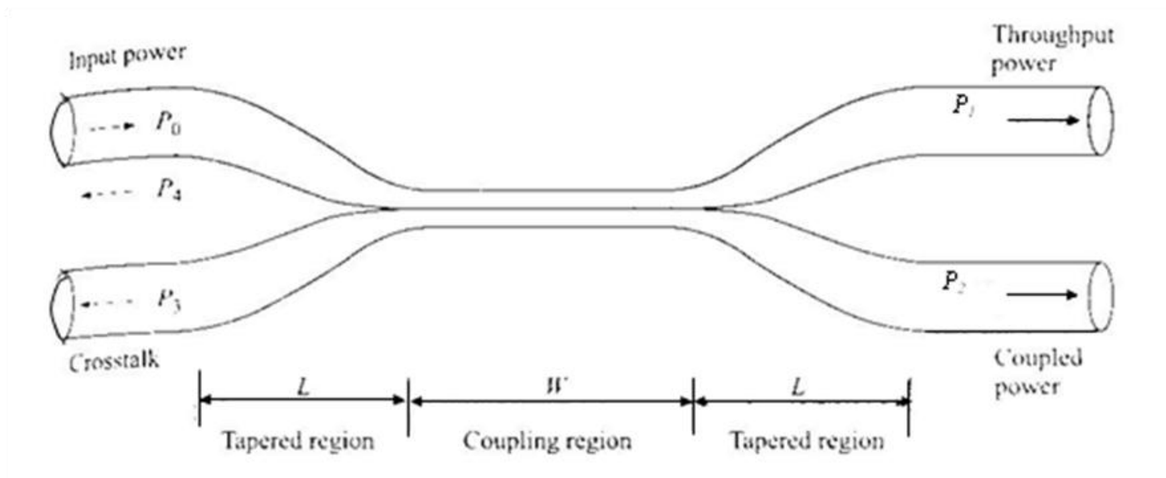


Figure 4.9 Cross-sectional view of a fused-fiber coupler having a coupling region W and two tapered regions of length L. The total span 2L + W is the coupler draw length.

Performance(Parameters) of 2× 2 optical coupler

Splitting ratio or Coupling ratio = $\left(\dfrac{P_2}{P_1+P_2}\right)\times 100\%$ (4.1)

Excess loss = $10\log\left(\dfrac{P_0}{P_1+P_2}\right)$ (4.2)

Insertion loss = $10\log\left(\dfrac{P_i}{P_j}\right)$ (4.3)

Crosstalk or Directivity = $10\log\left(\dfrac{P_3}{P_0}\right)$ (4.4)

Example 1:

A 2×2 biconical tapered fiber coupler has an input optical power level of P_0 = 200 μW. The output powers at the other three ports are P_1 = 90 μW, P_2 = 85 μW, and P_3 = 6.3 nW. Find all the parameters.

Solution:

Splitting ratio or Coupling ratio = $\left(\dfrac{85}{90+85}\right)\times 100\% = 48.6\%$

Excess loss = $10\log\left(\dfrac{200}{90+85}\right) = 0.58\text{dB}$

Insertion loss (port 0 to port 1) = $10\log\left(\dfrac{200}{90}\right) = 3.47\text{dB}$

Insertion loss (port 0 to port 2) = $10\log\left(\dfrac{200}{85}\right) = 3.72\text{dB}$

Crosstalk or Directivity = $10\log\left(\dfrac{6.3\times 10^{-3}}{200}\right) = -45\text{dB}$

Connector

An optical fiber connector is a flexible device that connects fiber cables requiring a quick connection and disconnection. Optical fibers terminate fiber-optic connections to fiber equipment or join two fiber connections without splicing. Hundreds of optical fiber connector types are available, but the key differentiator is defined by the mechanical coupling techniques and dimensions. Optical fiber connectors ensure stable connections, as they ensure the fiber ends are optically smooth and the end-to-end positions are properly aligned.
An optical fiber connector is also known as a fiber optic connector.

Requirements of Optical Fiber Connectors

Some of the principal requirements of a good connector design are as follows:
Low coupling losses: The connector assembly must maintain stringent alignment tolerances to assure low mating losses. These low losses must not change significantly during operation or after numerous connects and disconnects.
Interchangeability: Connectors of the same type must be
compatible from one manufacturer to another.
Low environmental sensitivity. Conditions such as temperature, dust, and moisture should have a small effect on connector-loss variations.
Low cost and reliable construction. The connector must have a precision suitable to the application but its cost must not be a major factor in the fiber system.
Ease of connection and **Ease of assembly.**

Ferrule Connectors

Ferrule connectors use two cylindrical plugs (referred to as ferrules), an alignment sleeve, and sometimes axial springs to perform fiber alignment. Figure 4.10 provides an illustration of this basic ferrule connector design. Precision holes drilled or molded through the center of each ferrule allow for fiber insertion and alignment. Precise fiber alignment depends on the accuracy of the central hole of each ferrule. When the fiber ends are inserted, an adhesive (normally an epoxy resin) bonds the fiber inside the ferrule. The fiber-end faces are polished until they are flush with the end of the ferrule to achieve a low-loss fiber connection. Fiber alignment occurs when the ferrules are inserted into the alignment sleeve. The inside diameter of the alignment sleeve aligns the ferrules, which in turn align the fibers. Ferrule connectors lock the ferrules in the alignment sleeve using a threaded outer shell or some other type of coupling mechanism.

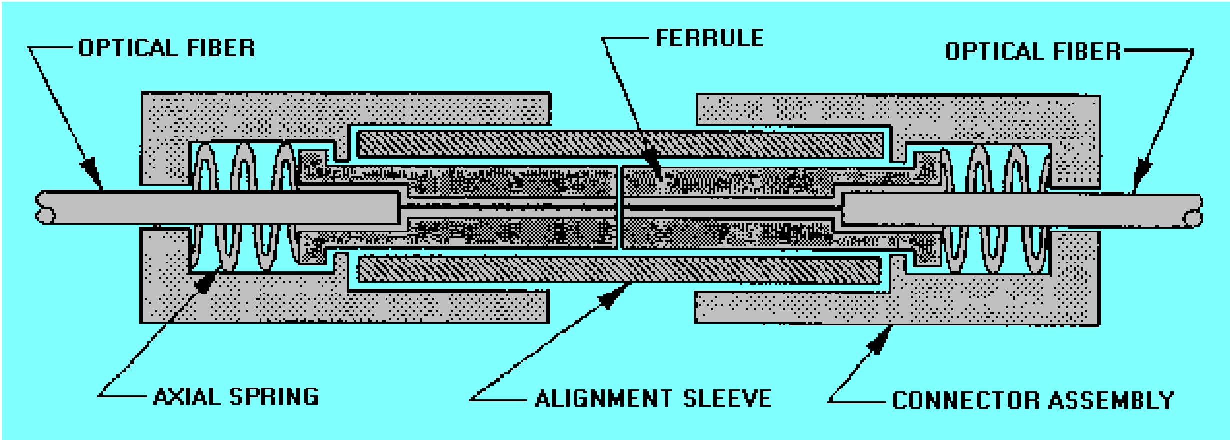


Figure 4.10 Basic Ferrule Connectors

Cylindrical Ferrule Connectors

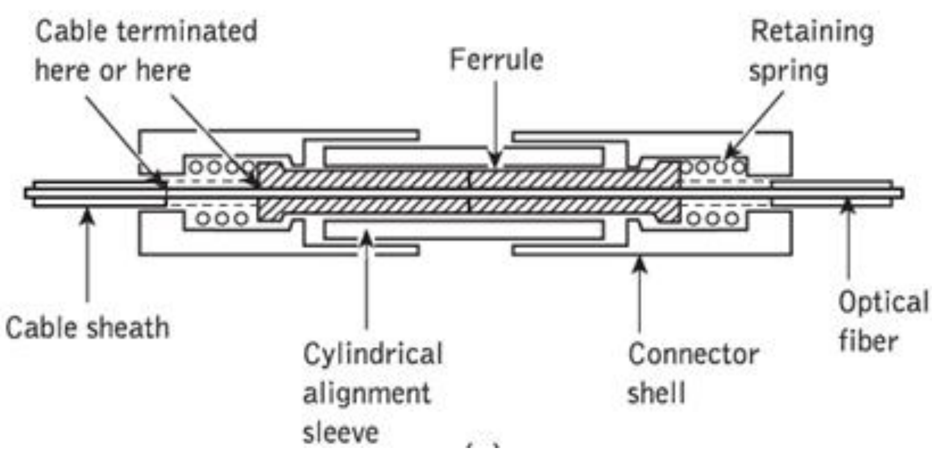


Figure 4.11 Cylindrical Ferrule Connectors

The two fibers to be connected are permanently bonded(with epoxy resin) in metal plugs known as ferrules which have an accurately drilled central hole in their end faces where the stripped fiber is located.

Within the connector the two ferrules are placed in an alignment sleeve which using accurately machined component allows the fibre ends to be butt jointed. The ferrules are held in place via a retaining mechanism which is a spring.

It is essential with this type of connector that the fiber end faces are smooth and square.

This may be achieved with varying success by
a. Cleaving the fiber before insertion into the ferrule.
b.Inserting and bonding before cleaving the fiber close to the ferrule end face.
c.and polishing the fiber end face until it is flush with the end of the ferrule.

As stated before, fiber alignment depends on an accurate hole through the center of the ferrule. Normally, ferrule connectors use ceramic or metal ferrules. The center hole is generally drilled in a metal ferrule.

Drilling an accurate hole through the entire metal ferrule can be difficult. To improve fiber alignment, some metal ferrule connectors use precision watch-jeweled centering.

In precision watch-jeweled centering, a watch jewel with a precision centered hole is placed in the tip of the ferrule.

The central hole of the watch jewel centers the fiber with respect to the axis of the cylindrical ferrule.

The watch jewel provides for better fiber alignment, because regulating the hole tolerance of the watch jewel is easier than maintaining a precise hole diameter when drilling through an entire ferrule.

The center hole in a ceramic ferrule is created by forming the ferrule around a precision wire, which is then removed.

This method produces holes accurately centered in the ferrule. Most cylindrical ferrule connectors now use ceramic ferrules.

The Straight Tip (ST®) connector is an example of a ceramic ferrule connector. (ST® is a registered trademark of AT&T.)
Other cylindrical ferrule connectors have a ferrule that contains both metal and ceramic.

For these connectors a ceramic capillary is placed within the tip of a metal ferrule to provide for precision fiber alignment.

The ceramic capillary is a ceramic tube with a small inner diameter that is just larger than the diameter of the fiber.

Biconical Connector

Biconical connectors use two conical plugs,a double conical alignment sleeve, and axial springs to perform fiber alignment.

Formation of the plugs and alignment sleeve involves transfer molding. Transfer molding uses silica-filled epoxy resin to mold the conical plug directly to the fiber or around a cast (precision wire).

After connecting the conical plugs to the optical fibers, the fiber-end faces are polished before the plugs are inserted into the molded alignment sleeve.

During fiber insertion, the inside surface of the double conical sleeve performs fiber alignment, while the axial springs push the fiber ends into close contact.

If the alignment sleeve permits the fibers to actually become in contact, then the axial spring provides enough force to maintain fiber contact but prevent damage to the fiber-end faces.

Normally, biconical connectors lock the fibers in alignment using a threaded outer shell.

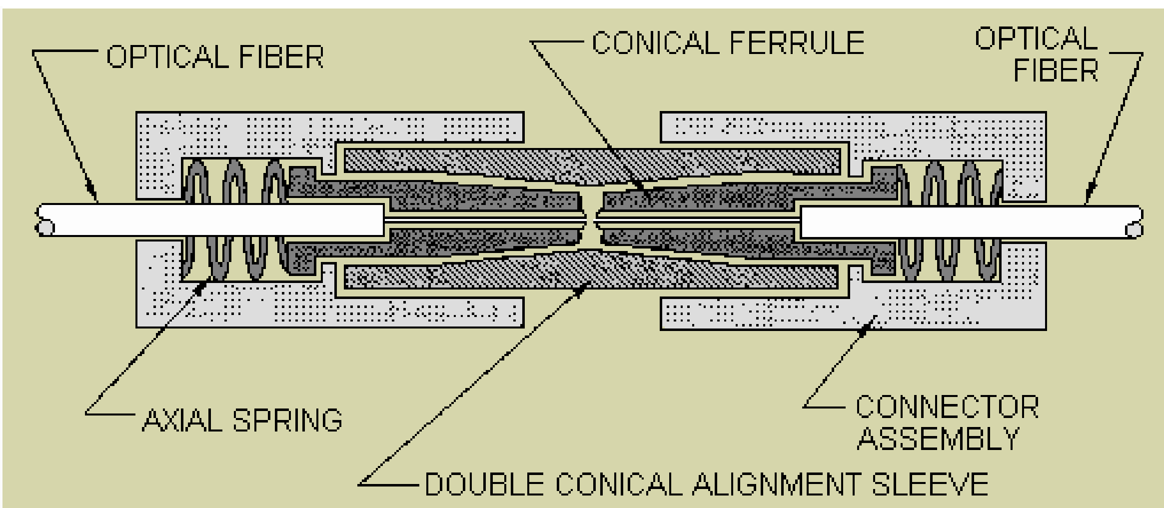


Figure 4.12 Biconical Connector

Splicing of Optical Fibers

Definition: Splicing of optical fibers is a technique used to join two optical fibers.
This technique is used in optical fiber communication, in order to form long optical links for better as well as long-distance optical signal transmission.

Splicers are basically couplers that form a connection between two fibers or fiber bundles.
At the time of splicing two optical fibers, the geometry of the fibers, their proper alignment and mechanical strength must be taken into consideration.

Splicing Techniques of Optical Fiber

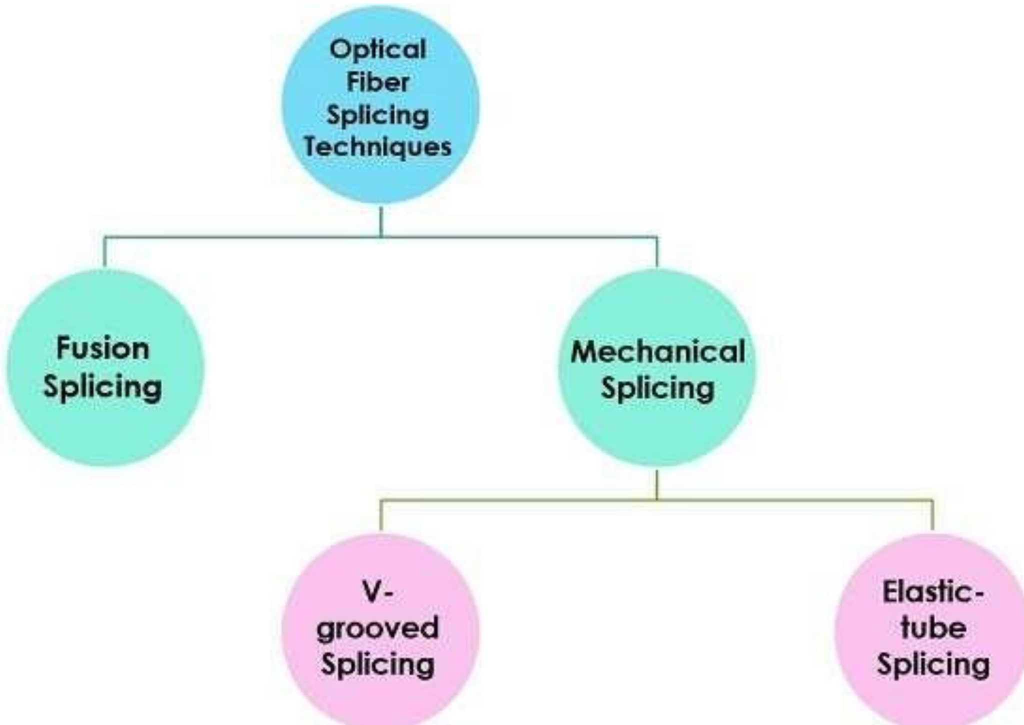


Figure 4.13 Splicing Techniques of Optical Fiber

Fusion splicing

Splicing any fiber by making use of the fusion technique provides a permanent (long-lasting) contact between the two fibers.

In the fusion splicing, the two fibers are thermally joined together. In this particular technique, an electrical instrument is necessarily used, that acts as an electric arc so as to form a thermal connection between the two.

First, the two fibers are aligned and butted in the way of their connection, this alignment is done in a fiber holder. After this, the **electric arc** comes into action as when it gets switched on then it produces some energy, that heats the butt joint.

The heating effect melts the ends of the fiber and then the two gets bonded together. After the two forms a bond then their junction is covered with either polyethylene jacket or plastic coating so as to protect the joint.

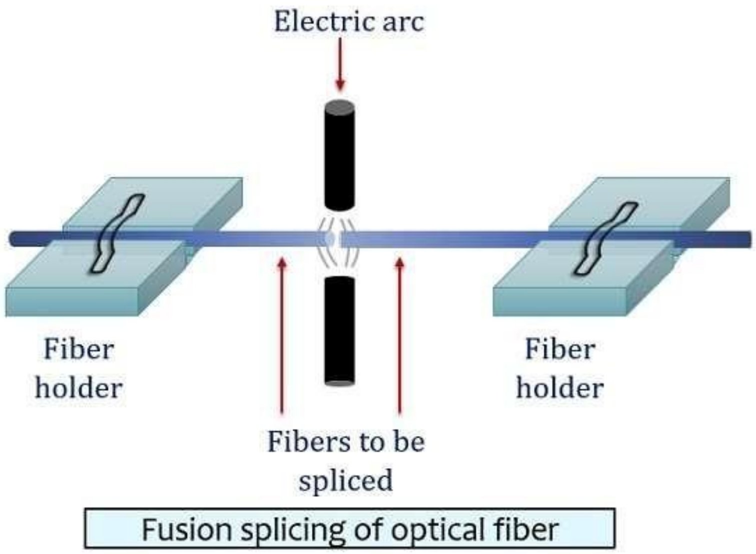


Figure 4.13 Fusion Splicing of Optical Fiber

By making use of fusion splicing technique, the splice generated losses are very less. The loss range lies between **0.05 to 0.10 dB**, both in case of single mode as well as multimode optical fibers.

The technique that provides this amount of losses is very practical and useful. As only very little portion of transmitted power gets lost.

However, when fusion splicing is done, then the supply of heat that is to be provided must be in adequate amount. This is so because sometimes excess heat can generate fragile (delicate) joint.

V-Grooved Splicing

In this splicing technique, initially a **V-shaped substrate** is taken and the two fiber ends are butted in the groove.

The two gets placed inside the groove in proper alignment then they are bonded by an adhesive or index matching gel. This adhesive provides proper grip to the connection.

The V substrate can be either composed of plastic, silicon, ceramic or any metal.

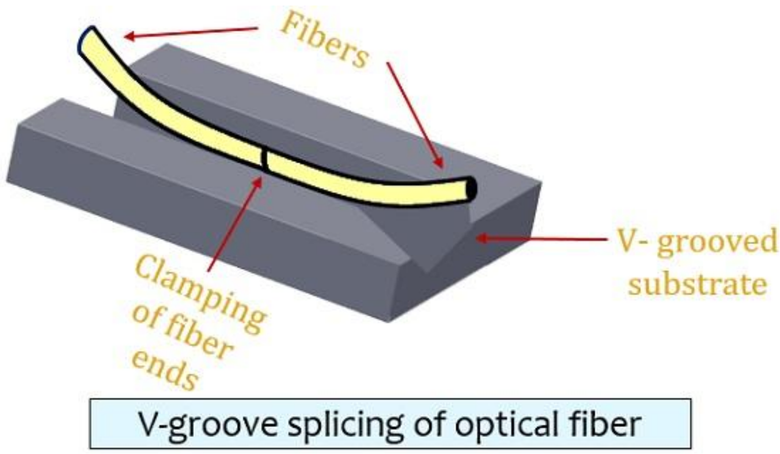


Figure 4.14 V-groove Splicing of Optical Fiber

However, the fiber losses are more in case of this technique as compared to the fusion technique. Also, these losses majorly depend on the core and cladding diameter as well as core position with respect to the centre.

It is to be noted here that the **two fibers do not form a continuous smooth connection** as in the previously discussed case.

Also, the joint is semi-permanent.

Elastic-Tube Splicing

It is a technique of splicing the fiber with the help of the elastic tube and majorly finds its application in case of the multimode optical fiber.

The fiber loss, in this case, is almost similar to that of the fusion technique. However, the need for equipment and skill is somewhat less than the fusion splicing technique.

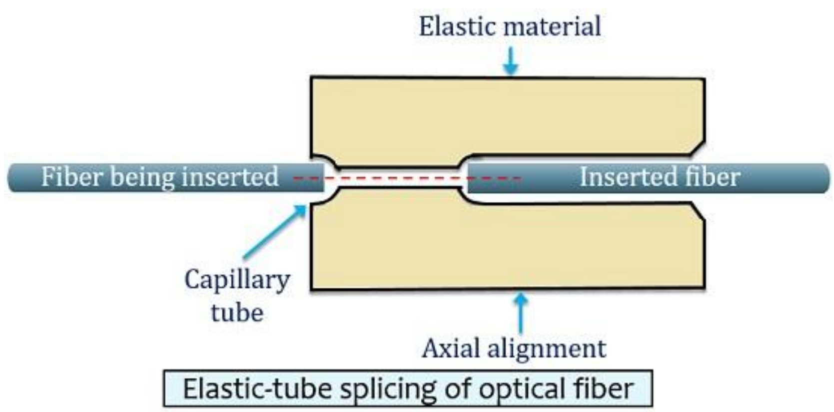


Figure 4.14 Elastic-Tube Splicing of Optical Fiber

Basically, the elastic material is rubber, inside which a small hole is present. The diameter of this hole is somewhat less than the diameter of the fiber to be spliced. Also, tapering is done at the ends of both the fibers in order to allow easy insertion inside the tube.

So, when the fiber with a slightly larger diameter than the hole is inserted inside the hole then, it eventually gets expanded as a symmetrical force is exerted by the material on the fiber. Due to this symmetricity, proper alignment between the two fibers is achieved. In this method, different diameters of fiber can be spliced as here the fiber moves according to the axis of the tube.

Advantages of fiber splicing
It allows long-distance optical signal transmission.
Less reflection at the time of signal transmission.
Splicing provides almost permanent connection of the two fibers.

Disadvantages of fiber splicing
Sometimes the fiber losses are very much higher than the acceptable limits.
Splicing increases, the overall cost of the optical fiber communication system.
Splicing basically provides **permanent or semi-permanent joints**. Also, sometimes the two fibers are joint on a temporary basis. So, connecting the two optical fibers temporarily is done by connectors.

Design Considerations in Optical Link

POINT-TO-POINT LINKS

The simplest transmission link is a point-to point line having a transmitter at one end and a receiver on the other, as shown below:

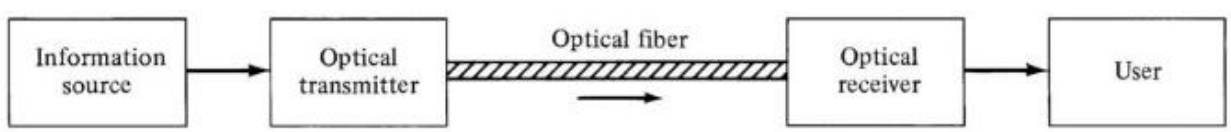


Figure 4.15 Point-To-Point Links

The design of an optical link involves many interrelated variables such as the fiber, source, and photo detector operating characteristics, so that the link design and analysis may require several iterations before they are working satisfactorily.

The key system requirements needed in analyzing a link are:

1. The desired (or possible) transmission distance

2. The data rate or channel bandwidth
3. The bit error rate (BER)

To fulfill these requirements the designer has a choice of the following components and their associated characteristics:

1. Multimode or single-mode optical fiber
   a) Core size
   b) Core refractive-index profile
   c) Bandwidth or dispersion
   d) Attenuation
   e) Numerical aperture or mode-field diameter.

2. LED or laser diode optical source
   (a) Emission wavelength
   (b) Spectral line width
   (c) Output power
   (d) Effective radiating area
   (e) Emission pattern
   (f) Number of emitting modes

3.pin or avalanche photodiode
   (a) Responsivity (~quantum efficiency)
   (b) Operating wavelength
   (c) Speed
   (d) Sensitivity

Two types of design and analysis procedures are normally carried out for digital optical systems

I. Link Power Budget There is enough power margin in the system to meet the given BER

II. Rise Time Budget Each element of the link is fast enough to meet the given bit rate

These two budgets give necessary conditions for satisfactory operation.

All datalinks are limited by the power budget of the link.

The power budget is the difference between the output power of the transmitter and the input power requirements of the receiver, both of which are defined as power coupled into or out of optical fiber of a type specified by the link.

Link Power Budget

The optical power budget in a fiber-optic communication link is the allocation of available optical power (launched into a given fiber by a given source) among various loss-producing mechanisms such as launch coupling loss, fiber attenuation, splice losses and connector losses, to ensure that adequate signal strength (optical power) is available at the receiver.

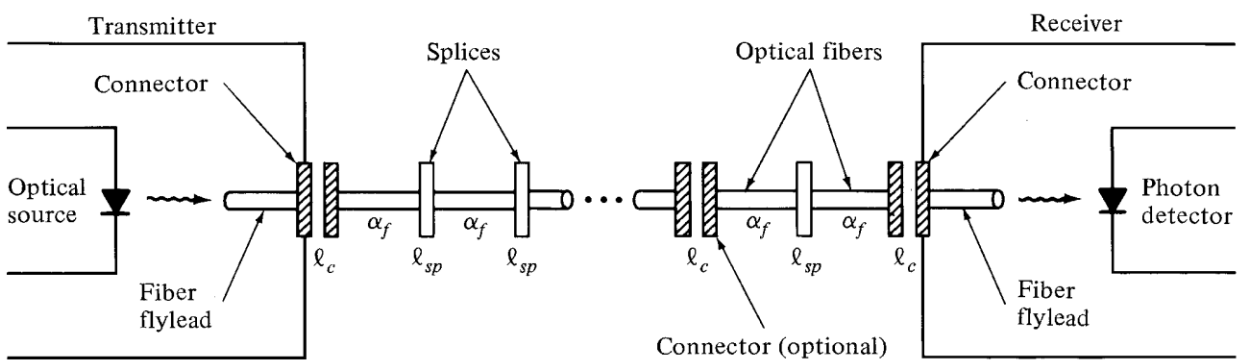


Figure 4.16 Link Power Budget

Each of these losses is expressed in decibels as

$$\text{loss}=10\log P_{out}/P_{in}$$

where Pin and Pout are the optical powers entering and exiting respectively a fiber, splice, connector, or other link element.

The total channel loss C_{l} for the fiber length L can be given as:

$$C_l=(\alpha_{splice}+\alpha_{fc}).L+\alpha_{con}$$

Where,

α_{splice} is loss due to splice
α_{fc} is loss due to fiber cable
α_{con} is loss due to connector

A system margin M_a is incorporated into the optical power budget to allow for component ageing, temperature fluctuations and losses arising from components that may be added in future.

$$\therefore \text{channel loss } (C_l)=(\alpha_{splice}+\alpha_{fc}).L+\alpha_{con}+M_a$$

The link loss budget simply considers the total optical power loss Pt that is allowed between the light source and the photo detector and allocates this loss to factors such as cable attenuation, connector and splice losses, losses in other link components, and system margin.

Thus, if Ps is the optical power emerging from the end of a fiber flylead attached to the source and if Pr is the minimum receiver sensitivity needed for a specific BER, then

$P_t = P_s - P_r P_t = P_s - P_r$

$\therefore P_t = (\alpha_{splice} + \alpha_{fc}).L + \alpha_{con} + M_a$

Manufacturers sometimes specify an optical power budget for the fiber that is optimum for their equipment.

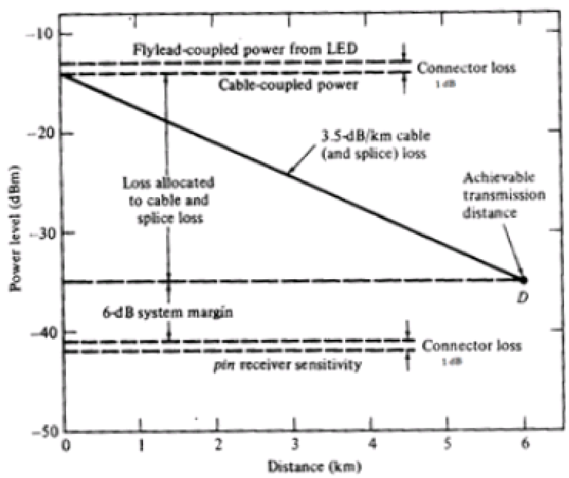


Figure 4.17 Link Power Budget Graph

Rise-Time Budget

A rise-time budget analysis is a convenient method for determining the dispersion limitation of an optical link. This is particularly useful for a digital link.

In this approach the total rise time tsys of the link is the root-sum-square calculation of the rise times from each contributor ti to the pulse rise-time degradation, that is, if there are N components in a link that affect the rise time then.

$$t_{sys} = \left(\sum_{i=1}^{N} t_i{}^2\right)^{1/2}$$

The five basic elements that may limit the system speed significantly are the transmitter rise time t_{TX}, the modal dispersion rise time t_{MOD} of multimode fiber, the chromatic dispersion rise time t_$_{CD}$ of the fiber, the polarization mode dispersion rise time t_{PMD} of the fiber, and the receiver rise time t_{RX}.

$$t_{sys} = (t_{TX}^2 + t_{MOD}^2 + t_{CD}^2 + t_{PMD}^2 + t_{RX}^2)^{\frac{1}{2}}$$

The purpose of rise time budget is to ensure that the system operates properly at intended bit rate. Generally the total transition-time degradation tsys of a digital link should not exceed 70 percent of an NRZ (non-return-to-zero) bit period or 35 percent for RZ (return-to-zero) data.

$$t_{sys} = \frac{0.35}{BW} \text{ for R.Z}$$

$$t_{sys} = \frac{0.35}{BW} \text{ for NRZ}$$

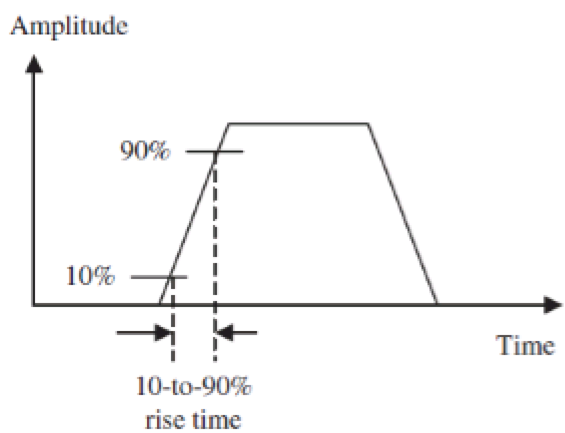


Figure 4.18 Rise Time Budget Graph

Power Budget Example:

Specify a 20-Mb/s data rate and a BER = 10^{-9}. With a Si *pin* photodiode at 850 nm, the required receiver input signal is –42 dBm. Select a GaAlAs LED that couples 50 mW into a 50-μm core diameter fiber flylead. Assume a 1-dB loss occurs at each cable interface and a 6-dB system margin.

The possible transmission distance L = 6 km can be found from
$P_T = P_S – P_R = 29\ dB = 2l_c + \alpha L$ + system margin = 2(1dB) + αL + 6 dB

Rise Time Budget Example 1:

We assume that the LED together with its drive circuit has a rise time of 15 ns. Taking a typical LED spectral width of 40nm, we have a material-dispersion-related rise-time degradation of 21 ns over the 6-km link. Assuming the receiver has a 25-MHz bandwidth, the contribution to the rise-time degradation from the receiver is 14 ns. If the fiber we select has a 400-MHz · km bandwidth-distance product and with q = 0.7, the modal-dispersion-induced fiber rise time is 3.9 ns. Calculate the total rise of the optical link.

$$
\begin{aligned}
t_{\mathrm{sys}} &= \left(t_{tx}^2 + t_{\mathrm{mat}}^2 + t_{\mathrm{mod}}^2 + t_{rx}^2\right)^{1/2} \\
&= [(15\ \mathrm{ns})^2 + (21\ \mathrm{ns})^2 + (3.9\ \mathrm{ns})^2 + (14\ \mathrm{ns})^2]^{1/2} \\
&= 30\ \mathrm{ns}
\end{aligned}
$$

Rise Time Budget Example 2:

Assume that the laser diode together with its drive circuit has a rise time of 0.025 ns (25 ps). Taking a 1550-nm laser diode spectral width of 0.1 nm and an average dispersion of 2 ps/(nm · km) for the fiber, we have a GVD-related rise-time degradation of 12 ps (0.012 ns) over a 60-km long optical cable. Assume the InGaAs-APD-based receiver has a 2.5-GHz bandwidth. Calculate total rise time of the optical

Multichannel Transmission Techniques

The multichannel transmit signal is the sum of several independent subsignals or subchannels. Each subchannel carries a low bit rate, hence helping to solve the problem of intersymbol interference (ISI).

MULTIPLEXING IN OFC

Multiplexing (or muxing) is a way of sending multiple signals or streams of information over a communications link at the same time in the form of a single, complex signal; the receiver recovers the separate signals, a process called demultiplexing (or demuxing).

In fiber optic communication, multiplexing is considered to be the principal means for the expansion of existing fiber network engineering.

Since optical data can be carried by employing different physical dimensions, such as time, frequency, space, polarity, etc., different multiplexing techniques are possible to be used in increasing the data-carrying capacity of a single optical fiber.

Currently, multiplexing technologies have used many dimensions to increase optical transmission system capacity over a fixed bandwidth. Two major methods are WDM and OTDM.

Wavelength Division Multiplexing

WDM is one of the optical multiplexing techniques that increases bandwidth by multiplexing a variety of optical carrier signals onto a single optical fiber by using different wavelengths. Each signal at WDM wavelengths is independent of any protocol and any speed. The WDM technology allows bidirectional communications simultaneously over a single optical fiber.

The foundation of WDM simplifies the network to a single virtual optical fiber network instead of using multiple forms of signals with different fibers and services. In this way, WDM increases the bandwidth and lowers the networking cost by reducing the needed fibers.

The concept of WDM

Wavelength division multiplexing (WDM) is based on the fundamental physical principle which states that many optical rays having different wavelengths can be propagated together over a common optical channel with no interference.

The concept of WDM is analogous to the basic concept of frequency division multiplexing (FDM) in which the available bandwidth of a communications channel in its frequency domain is divided into multiple sub-bands (called user channels). It implies that each user channel occupies only a part of the wide frequency spectrum. In WDM, each user channel is recognized by an optical wavelength.

Remember the relationship between the wavelength and frequency as, which implies that shorter the wavelength of the signal, higher will be its frequency, and vice-versa.

There are two different wavelength patterns of WDM systems, coarse (CWDM) and dense (DWDM). CWDM and DWDM are based on the same concept of using multiple light wavelengths on a single fiber, but differ in the spacing of the wavelengths, numbers of channels, and the ability to amplify the multiplexed signals in the optical space.

In a WDM system, different optical signals are combined (multiplexed) together at one end of the optical fiber and separated (demultiplexed) into different channels at the other end.

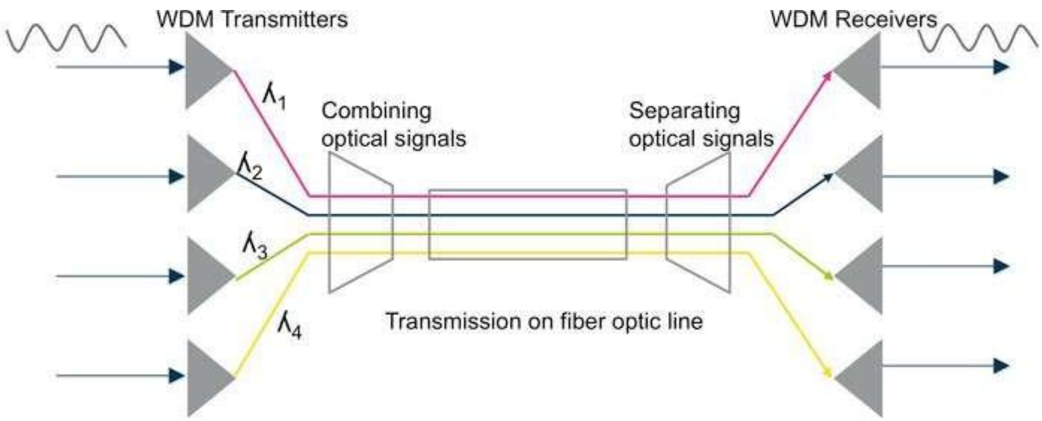


Figure 4.19 Wavelength Division Multiplexing

The optical carrier WDM is often regarded as an analogous technique of frequency division multiplexing, which typically applies to a radio carrier. However, there is no essential difference between them since they communicate the same information.

Principles of Wavelength Division Multiplexing (WDM)

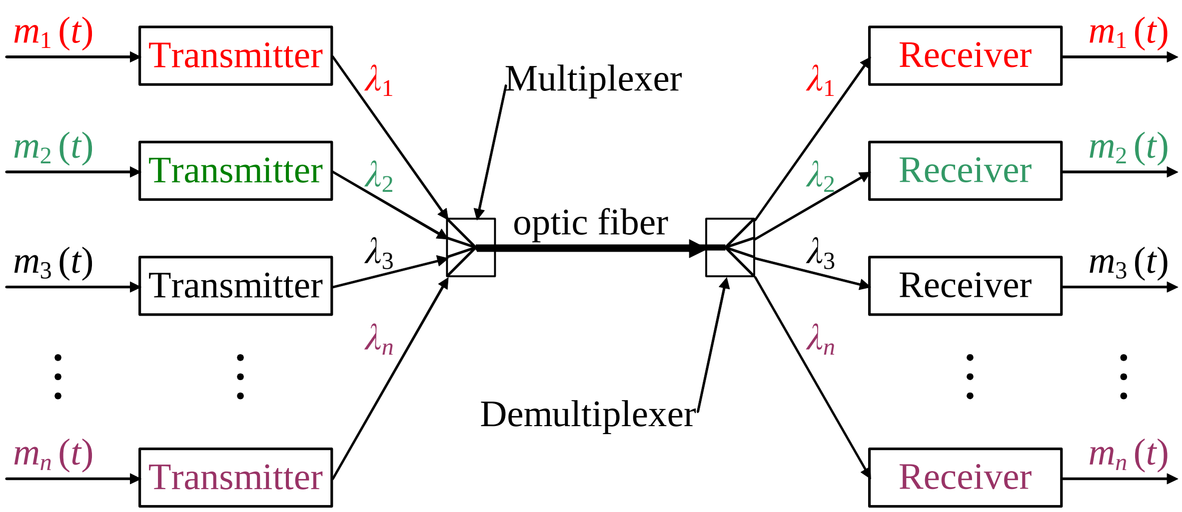


Figure 4.20 Wavelength Division Multiplexing

Key Components for WDM

1. Passive Optical Components
2. Wavelength Selective Splitters

3. Wavelength Selective Couplers
4. Active Optical Components
5. Tunable Optical Filter
6. Tunable Source
7. Optical amplifier
8. Add-drop Multiplexer and De-multiplexer

TDM and WDM

TDM divides a high-bandwidth transmitted signal into time slots. Each time slot carries a different low-bandwidth signal.
In WDM, several high-bandwidth signals travel on the same fiber, in the same time, each using a different light wavelength.
DWDM uses the same principles as a WDM, but with high density of light wavelength allocation.
A common application of multiplexing is in long-distance data and voice communications.

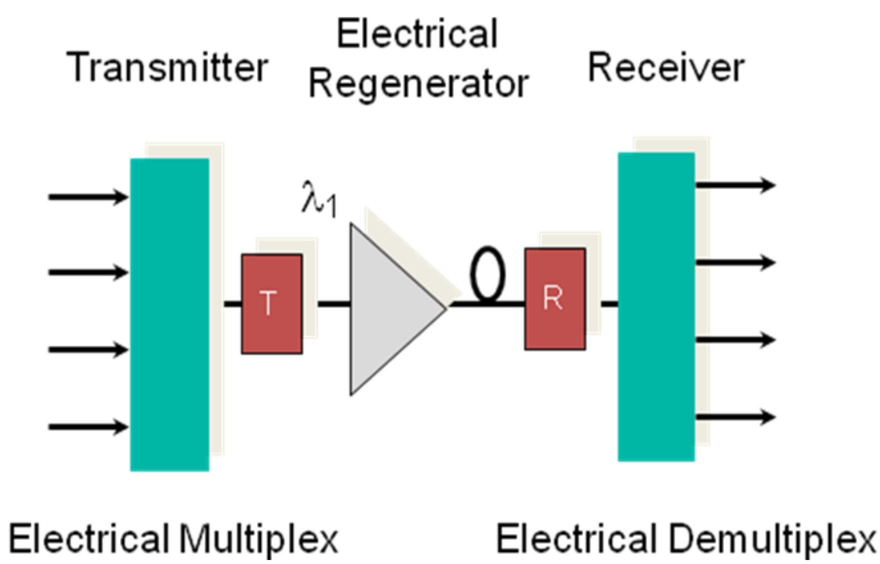
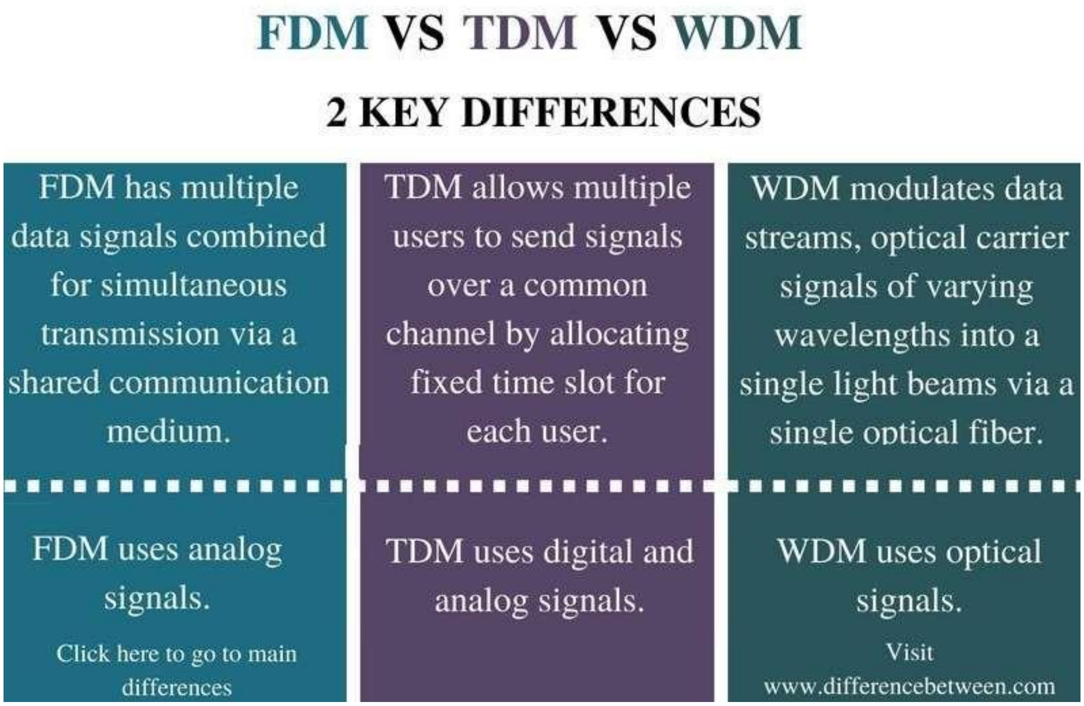


Figure 4.21 Time Division Multiplexing



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SCHOOL OF ELECTRICAL AND ELECTRONICS

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

UNIT – V – OPTICAL COMMUNICATIONS – SEC1403

FDDI

Fiber distributed data interface (FDDI) is a high-performance fiber optic token ring LAN running at 100 Mbps over distances up to 200 km with up to 1000 stations connected. FDDI is used as backbone to connect copper LANs as shown in the figure 5.1

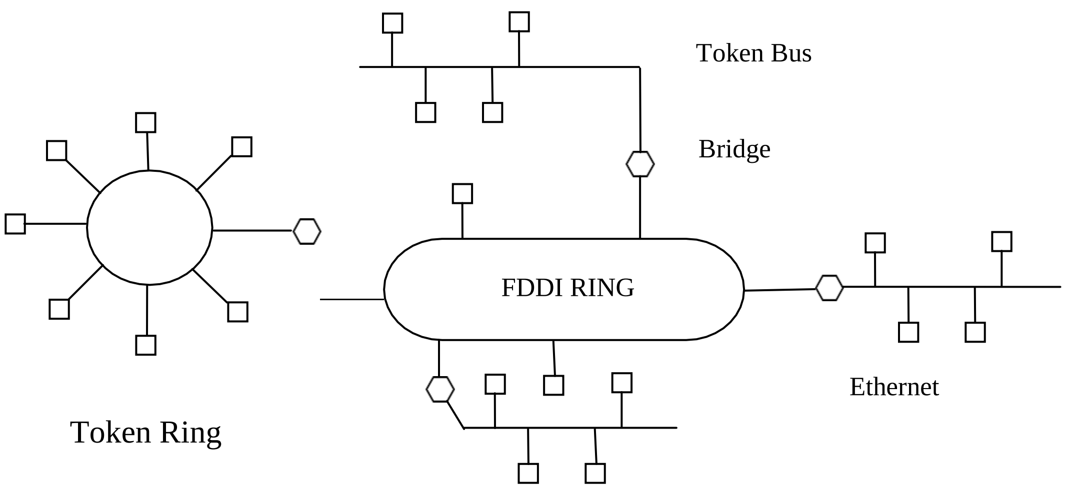

Figure 5.1 FDDI network structure

FDDI uses a multimode fiber because the cost of single mode fiber is not justified for networks running at only 100 Mbps. It also uses LEDs instead of Lasers not only because of the lower cost but also because FDDI may sometimes be used to connect directly to user workstations, and safety against exposure to LASER radiation is difficult to maintain in that case. The minimum BER required to be maintained is 1 in 2.5 x 10^{10}.

The FDDI cabling consists of two fiber rings, one transmitting clockwise and the other transmitting counterclockwise. If either one breaks the other acts as backup. If both the rings break at the same points, the two rings can be joined to format new approximately twice as long. This new ring is formed by relays at the two nodes adjoining the broken link.

FDDI defines two classes of stations A and B. Class A stations connect to both rings. The cheaper class B stations only connect to one of the rings. Depending on how important fault tolerance is, an installation can chose class A or class B stations.

The physical layer in FDDI uses 4 out of 5 encoding scheme. i.e. each group of 4 MAC symbols are encoded as a group of 5 bits on the medium. Sixteen of the 32 combinations are for data, 3 are for delimiters, 2 are for control, 3 are for hardware signaling, and 8 are unused. This scheme saves bandwidth but the self clocking property available with Manchester coding is lost. To compensate a long preamble is used to synchronize the receiver to the sender's clock.

The basic FDDI protocols are modeled on the 802.5 protocols. The station must first capture a token, transmit a frame and remove it when it comes around. In FDDI the time spent in waiting for a frame to circumnavigate is reduced by allowing the station to put a new token back onto the ring as soon as it has finished transmitting its frames. In a large ring, several frames may be on the ring at the same time.

FDDI data frames are similar to 802.5 frames as shown below in figure 5.2. Frame status byte holds acknowledgement bits, similar to those of 802.5. The frame control field tells what kind of frame this is (data, control, etc.)

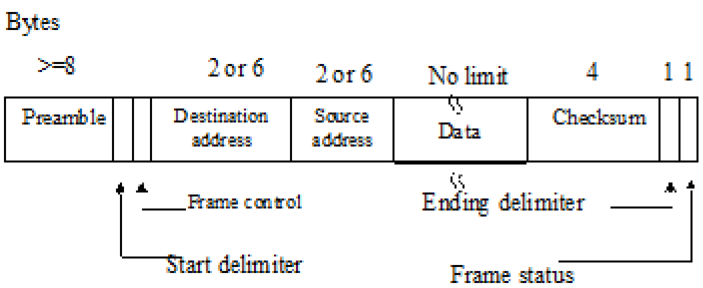

Figure 5.2 FDDI frame structure

In addition to the regular (asynchronous) frames, FDDI also permits special synchronous frames generated every 125 µs by the master for circuit switched PCM or ISDN data. Each of these frames has header, 16 bytes of non circuit- switched data and up to 96 bytes of circuit-switched data (96 = 4x 24 (4 T1 channel) = 3 x 32 (3 E1 channels)).

Once a station has acquired one or more time slots in a synchronous frame, those slots are reserved for it until they are explicitly released. The total bandwidth not used by the synchronous frames is allocated on demand. The non synchronous traffic is divided into classes with the higher priorities getting first shot at the leftover bandwidth.

The FDDI MAC protocol uses three timers. The token holding timer determines how long a station may continue to transmit once it has acquired the token. The token rotation timer is restarted every time the token is seen. If this time expires, it means that the token has probably been lost and the token recovery procedure is initiated. Finally the valid transmission timer is used to time out, and recovers from certain transient ring errors. FDDI also has a priority algorithm similar to 802.4. It determines which priority classes may transmit on a given token pass. If a token is ahead of schedule, all priorities may transmit, but if it is behind schedule, only the highest ones may send.

FDDI is IEEE 802.5 with Optical Fiber Cable

FDDI has two versions - FDDI-I for data only and FDDI-II for voice and data. FDDI very elegantly provides protection against fiber failure. In case of a fault, the traffic is routed through the second fiber in the opposite direction.

FDDI and DQDB led to a rapid evolution of MAN. A MAN can be thought of

- Many LANs together with different physical and logical topologies
- Network spread over larger geographical area.

WAVELENGTH DIVISION MULTIPLEXING

Wavelength division multiplexing (WDM) is a technique of multiplexing multiple optical carrier signals through a single optical fiber channel by varying the wavelengths of laser lights. WDM allows communication in both the directions in the fiber cable.

Concept and Process

In WDM, the optical signals from different sources or (transponders) are combined by a multiplexer, which is essentially an optical combiner. They are combined so that their wavelengths are different.

The combined signal is transmitted via a single optical fiber strand. At the receiving end, a demultiplexer splits the incoming beam into its components and each of the beams is send to the corresponding receivers.

Example

The following diagram conceptually represents multiplexing using WDM. It has 4 optical signals having 4 different wavelengths as shown in figure 5.3. Each of the four senders generates data streams of a particular wavelength. The optical combiner multiplexes the signals and transmits them over a single long-haul fiber channel. At the receiving end, the splitter demultiplexes the signal into the original 4 data streams.

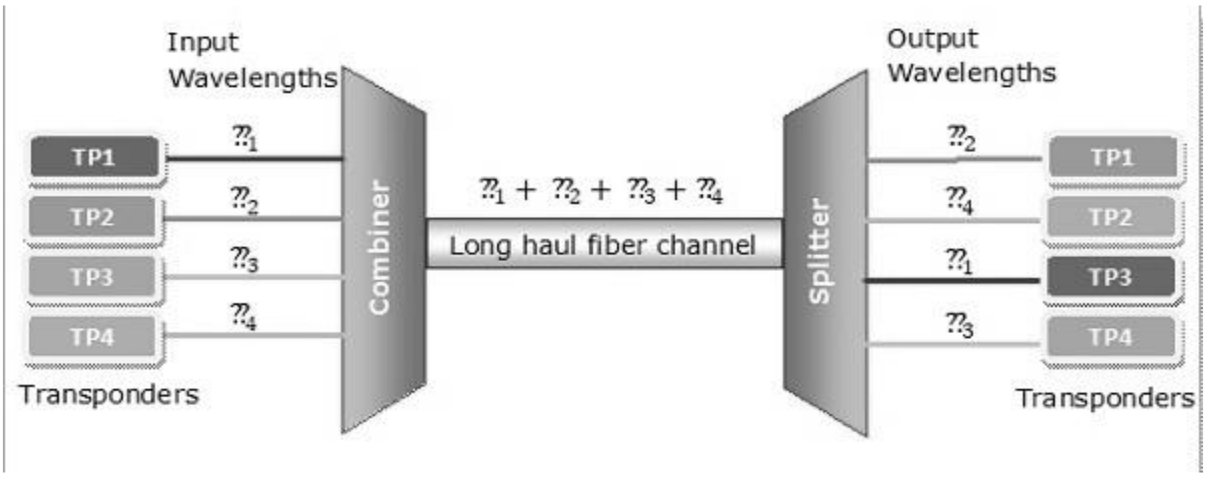

Figure 5.3 Block diagram of Wavelength Division Multiplexing

Categories of WDM

Based upon the wavelength, WDM can be divided into two categories −

- **Course WDM (CWDM)**: CWDM generally operates with 8 channels where the spacing between the channels is 20 nm (nanometers) apart. It consumes less energy than DWDM and is less expensive. However, the capacity of the links, as well as the distance supported, is lesser.
- **Dense WDM (DWDM)**: In DWDM, the number of multiplexed channels much larger than CWDM. It is either 40 at 100GHz spacing or 80 with 50GHz spacing. Due to this, they can transmit the huge quantity of data through a single fiber link. DWDM is generally applied in core networks of telecommunications and cable networks. It is also used in cloud data centers for their IaaS services.

SONET/SDH

Synchronous Optical Network (SONET)

SONET stands for Synchronous Optical Network. SONET is a communication protocol, developed by Bellcore – that is used to transmit a large amount of data over relatively large distances using optical fiber. With SONET, multiple digital data streams are transferred at the same time over the optical fiber.

Key Points:

- Developed by Bellcore
- Used in North America
- Standardized by ANSI (American National Standards Institute)
- Similar to SDH (Synchronous Digital Hierarchy) which is used in Europe and Japan.

A single clock (Primary Reference Clock, PRC) handles the timing of transmission of signals & equipments across the entire network.

SONET Network Elements:

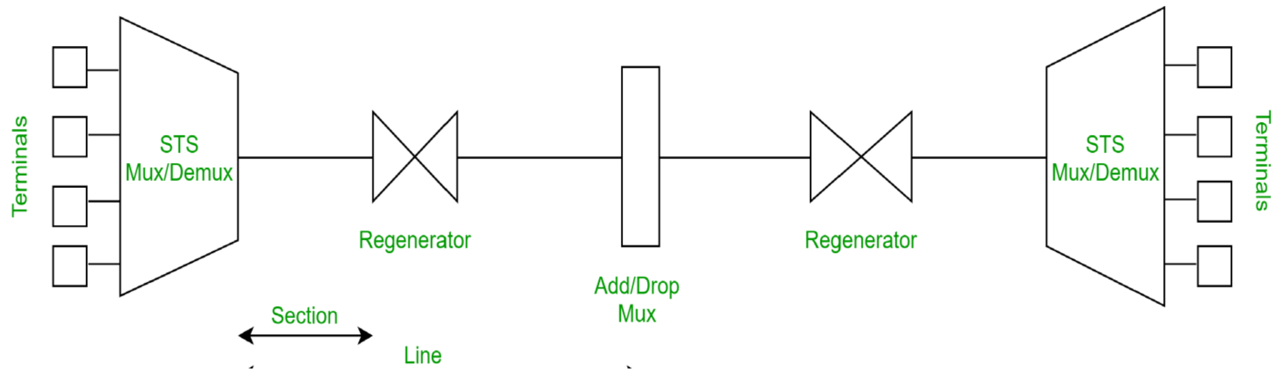

Figure 5.4 Network Elements of SONET

There are four different network elements in SONET are as follows.

1. **STS Multiplexer:**
   - Performs multiplexing of signals
   - Converts electrical signal to optical signal
2. **STS Demultiplexer:**
   - Performs demultiplexing of signals

- Converts optical signal to electrical signal

3. **Regenerator:**

   It is a repeater, that takes an optical signal and regenerates (increases the strength) it.

4. **Add/Drop Multiplexer:**

   It allows adding signals coming from different sources into a given path or removing a signal.

SONET is used to convert electrical signal into optical signal so that it can travel longer distances.

SONET Connections:

There are three connections in SONET are

- **Section:** Portion of network connecting two neighbouring devices.
- **Line:** Portion of network connecting two neighbouring multiplexers.
- **Path:** End-to-end portion of the network.

SONET Layers:

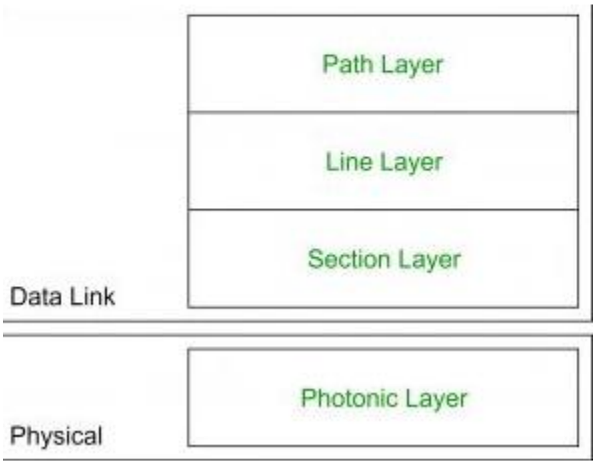

Figure 5.5 Functional Layers in SONET

SONET includes four functional layers are given in figure 5.5.

1. **Path Layer:**
   - It is responsible for the movement of signal from its optical source to its optical destination.
   - STS Mux/Demux provides path layer functions.

-

2. **Line Layer:**
   - It is responsible for the movement of signal across a physical line.
   - STS Mux/Demux and Add/Drop Mux provide Line layer functions.
3. **Section Layer:**
   - It is responsible for the movement of signal across a physical section.
   - Each device of network provides section layer functions.
4. **Photonic Layer:**
   - It corresponds to the physical layer of the OSI model.
   - It includes physical specifications for the optical fiber channel (presence of light = 1 and absence of light = 0).

Advantages of SONET:

- Transmits data to large distances
- Low electromagnetic interference
- High data rates
- Large Bandwidth

Synchronous optical networking (SONET) and synchronous digital hierarchy (SDH) are standardized protocols that transfer multiple digital bit streams synchronously over optical fiber using lasers or highly coherent light from light-emitting diodes (LEDs). At low transmission rates data can also be transferred via an electrical interface. The method was developed to replace the plesiochronous digital hierarchy (PDH) system for transporting large amounts of telephone calls and data traffic over the same fiber without the problems of synchronization.

SONET and SDH, which are essentially the same, were originally designed to transport circuit mode communications (e.g., DS1, DS3) from a variety of different sources, but they were primarily designed to support real-time, uncompressed, circuit-switched voice encoded in PCM format. The primary difficulty in doing this prior to SONET/SDH was that the synchronization sources of these various circuits were different. This meant that each circuit was actually operating at a slightly different rate and with different phase. SONET/SDH allowed for the simultaneous transport of many different circuits of differing origin within a single framing protocol. SONET/SDH is not a complete communications protocol in itself, but a transport protocol (not a 'transport' in the OSI Model sense).

Due to SONET/SDH's essential protocol neutrality and transport-oriented features, SONET/SDH was the obvious choice for transporting the fixed length Asynchronous Transfer Mode (ATM) frames also known as cells. It quickly evolved mapping structures and concatenated payload containers to transport ATM connections. In other words, for ATM (and eventually other protocols such as Ethernet), the internal complex structure previously used to transport circuit-oriented connections was removed and replaced with a large and concatenated frame (such as STS-3c) into which ATM cells, IP packets, or Ethernet frames are placed.

Both SDH and SONET are widely used today: SONET in the United States and Canada, and SDH in the rest of the world. Although the SONET standards were developed before SDH, it is considered a variation of SDH because of SDH's greater worldwide market penetration. SONET is subdivided into four sub-layer with some factor such as the path, line, section and physical layer.

The SDH standard was originally defined by the European Telecommunications Standards Institute (ETSI), and is formalized as International Telecommunication Union (ITU) standards G.707, G.783, G.784, and G.803. The SONET standard was defined by Telcordia and American National Standards Institute (ANSI) standard T1.105 which define the set of transmission formats and transmission rates in the range above 51.840 Mbit/s.

SDH differs from PDH:

SDH differs from Plesiochronous Digital Hierarchy (PDH) in that the exact rates that are used to transport the data on SONET/SDH are tightly synchronized across the entire network, using atomic clocks. This synchronization system allows entire inter-country networks to operate synchronously, greatly reducing the amount of buffering required between elements in the network. Both SONET and SDH can be used to encapsulate earlier digital transmission standards, such as the PDH standard, or they can be used to directly support either Asynchronous Transfer Mode (ATM) or so-called packet over SONET/SDH (POS) networking. Therefore, it is inaccurate to think of SDH or SONET as communications protocols in and of themselves; they are generic, all-purpose transport containers for moving both voice and data. The basic format of a SONET/SDH signal allows it to carry many different services in its virtual container (VC), because it is bandwidth-flexible.

SONET and SDH often use different terms to describe identical features or functions. This can cause confusion and exaggerate their differences. With a few exceptions, SDH can be thought of as a superset of SONET.

SONET is a set of transport containers that allow for delivery of a variety of protocols, including traditional telephony, ATM, Ethernet, and TCP/IP traffic. SONET therefore is not in itself a native communications protocol and should not be confused as being necessarily connection-oriented in the way that term is usually used.

Protocol Overview

The protocol is a heavily multiplexed structure, with the header interleaved between the data in a complex way. This permits the encapsulated data to have its own frame rate and be able to "float around" relative to the SDH/SONET frame structure and rate. This interleaving permits a very low latency for the encapsulated data. Data passing through equipment can be delayed by at most 32 microseconds (μs), compared to a frame rate of 125 μs; many competing protocols buffer the data during such transits for at least one frame or packet before sending it on. Extra padding is allowed for the multiplexed data to move within the overall framing, as the data is clocked at a different rate than the frame rate. The protocol is made more complex by the decision to permit this padding at most levels of the multiplexing structure, but it improves all-around performance.

Framing

In packet-oriented data transmission, such as Ethernet, a packet frame usually consists of a header and a payload. The header is transmitted first, followed by the payload (and possibly a trailer, such as a CRC). In synchronous optical networking, this is modified slightly. The header is termed the *overhead*, and instead of being transmitted before the payload, is interleaved with it during transmission. Part of the overhead is transmitted, then part of the payload, then the next part of the overhead, then the next part of the payload, until the entire frame has been transmitted.

In the case of an STS-1, the frame is 810 octets in size, while the STM-1/STS-3c frame is 2,430 octets in size. For STS-1, the frame is transmitted as three octets of overhead, followed by 87 octets of payload. This is repeated nine times, until 810 octets have been transmitted, taking 125 μs. In the case of an STS-3c/STM-1, which operates three times faster than an STS-1, nine octets of overhead are transmitted, followed by 261 octets of payload. This is also repeated nine times until 2,430 octets have been transmitted, also taking 125 μs. For both SONET and SDH, this is often represented by displaying the frame graphically: as a block of 90 columns and nine rows for STS-1, and 270 columns and nine rows for STM1/STS-3c. This representation aligns all the overhead columns, so the overhead appears as a contiguous block, as does the payload.

The internal structure of the overhead and payload within the frame differs slightly between SONET and SDH, and different terms are used in the standards to describe these structures. Their standards are extremely similar in implementation, making it easy to interoperate between SDH and SONET at any given bandwidth.

In practice, the terms STS-1 and OC-1 are sometimes used interchangeably, though the OC designation refers to the signal in its optical form. It is therefore incorrect to say that an OC-3 contains 3 OC-1's: an OC-3 can be said to contain 3 STS-1's.

SDH Frame

The Synchronous Transport Module, level 1 (STM-1) frame is the basic transmission format for SDH the first level of the synchronous digital hierarchy. The STM-1 frame is transmitted in exactly 125 μs, therefore, there are 8,000 frames per second on a 155.52 Mbit/s OC-3 fiber-optic circuit. The STM-1 frame consists of overhead and pointers plus information payload. The first nine columns of each frame make up the section overhead and administrative unit pointers, and the last 261 columns make up the information payload. The pointers (H1, H2, H3 bytes) identify administrative units (AU) within the information payload. Thus, an OC-3 circuit can carry 150.336 Mbit/s of payload, after accounting for the overhead.

Carried within the information payload, which has its own frame structure of nine rows and 261 columns, are administrative units identified by pointers. Also within the administrative unit are one or more virtual containers (VCs). VCs contain path overhead and VC payload. The first column is for path overhead; it is followed by the payload container, which can itself carry other containers. Administrative units can have any phase alignment within the STM frame, and this alignment is indicated by the pointer in row four.

The section overhead (SOH) of a STM-1 signal is divided into two parts: the regenerator section overhead (RSOH) and the multiplex section overhead (MSOH). The overheads contain information from the transmission system itself, which is used for a wide range of management functions, such as monitoring transmission quality, detecting failures, managing alarms, data communication channels, service channels, etc.

The STM frame (Figure 5.6) is continuous and is transmitted in a serial fashion: byte-by-byte, row-by-row.

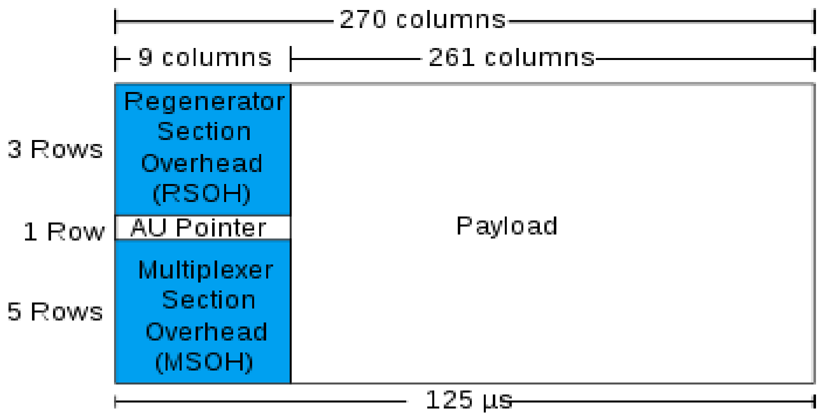

Figure 5.6 SDH Frame

Another type of high-speed data networking circuit is 10 Gigabit Ethernet (10GbE). The Gigabit Ethernet Alliance created two 10 Gigabit Ethernet variants: a local area variant (LAN PHY) with a line rate of 10.3125 Gbit/s, and a wide area variant (WAN PHY) with the same line rate as OC-192/STM-64 (9,953,280 kbit/s).The WAN PHY variant encapsulates Ethernet data using a lightweight SDH/SONET frame, so as to be compatible at a low level with equipment designed to carry SDH/SONET signals, whereas the LAN PHY variant encapsulates Ethernet data using 64B/66B line coding.

However, 10 Gigabit Ethernet does not explicitly provide any interoperability at the bit stream level with other SDH/SONET systems. This differs from WDM system transponders, including both coarse and dense wavelength-division multiplexing systems (CWDM and DWDM) that currently support OC-192 SONET signals, which can normally support thin-SONET–framed 10 Gigabit Ethernet.

SONET/SDH Data Rates:

SONET Optical Carrier level	SONET frame format	SDH level and frame format	Payload bandwidth (kbit/s)	Line rate (kbit/s)
OC-1	STS-1	STM-0	50,112	51,840
OC-3	STS-3	STM-1	150,336	155,520
OC-12	STS-12	STM-4	601,344	622,080
OC-24	STS-24	–	1,202,688	1,244,160
OC-48	STS-48	STM-16	2,405,376	2,488,320
OC-192	STS-192	STM-64	9,621,504	9,953,280
OC-768	STS-768	STM-256	38,486,016	39,813,120

Table 5.1 SONET/SDH Data Rates

User throughput must not deduct path overhead from the payload bandwidth, but path-overhead bandwidth is variable based on the types of cross-connects built across the optical system.

Note that the data-rate progression starts at 155 Mbit/s and increases by multiples of four. The only exception is OC-24, which is standardized in ANSI T1.105, but not a SDH standard rate in ITU-T G.707.Other rates, such as OC-9, OC-18, OC-36, OC-96, and OC-1536, are defined but not commonly deployed; most are considered orphaned rates.

ATM

ATM stands for Asynchronous Transfer Mode. It is a switching technique that uses time division multiplexing (TDM) for data communications as shown in figure 5.7.

ATM networks are connection oriented networks for cell relay that supports voice, video and data communications. It encodes data into small fixed - size cells so that they are suitable for TDM and transmits them over a physical medium.

The size of an ATM cell is 53 bytes: 5 byte header and 48 byte payload. There are two different cell formats - user-network interface (UNI) and network-network interface (NNI). The below image represents the Functional Reference Model of the Asynchronous Transfer Mode.

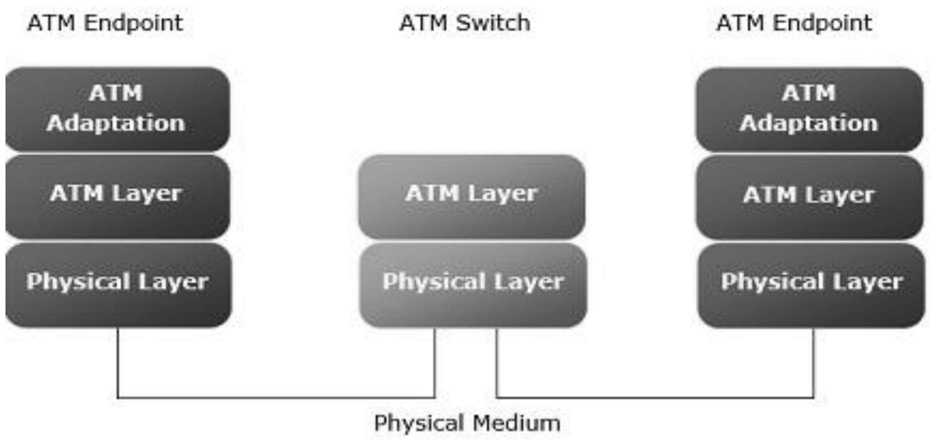

Figure 5.7 ATM Networks

Benefits of ATM Networks are

- It provides the dynamic bandwidth that is particularly suited for bursty traffic.
- Since all data are encoded into identical cells, data transmission is simple, uniform and predictable.
- Uniform packet size ensures that mixed traffic is handled efficiently.
- Small sized header reduces packet overload, thus ensuring effective bandwidth usage.
- ATM networks are scalable both in size and speed.

ATM reference model comprises of three layers

- **Physical Layer −** This layer corresponds to physical layer of OSI model. At this layer, the cells are converted into bit streams and transmitted over the physical medium. This layer has two sub layers: PMD sub layer (Physical Medium Dependent) and TC (Transmission Convergence) sub layer.
- **ATM Layer −**This layer is comparable to data link layer of OSI model. It accepts the 48 byte segments from the upper layer, adds a 5 byte header to each segment and converts into 53 byte cells. This layer is responsible for routing of each cell, traffic management, multiplexing and switching.
- **ATM Adaptation Layer (AAL) −**This layer corresponds to network layer of OSI model. It provides facilities to the existing packet switched networks to connect to ATM network and use its services. It accepts the data and converts them into fixed sized segments. The transmissions can be of fixed or variable data rate. This layer has two sub layers − Convergence sub layer and Segmentation and Reassembly sub layer.
- **ATM endpoints −** It contains ATM network interface adaptor. Examples of endpoints are workstations, routers, CODECs, LAN switches, etc.
- **ATM switch −**It transmits cells through the ATM networks. It accepts the incoming cells from ATM endpoints (UNI) or another switch (NNI), updates cell header and retransmits cell towards destination.

IP Over WDM

Expanding Internet-based services are driving the need for evermore bandwidth in the network backbone. These needs will grow further as new real-time multimedia applications become more feasible and pervasive. Currently, there is no other technology on the horizon that can effectively meet such a demand for bandwidth in the transport infrastructure other than WDM technology.

This technology enables incremental and quick provisioning up to and beyond two orders of magnitude of today's fiber bandwidth levels. This precludes the need to deploy additional cabling and having to contend with right-of-way issues, a key advantage. Hence, it is only natural that over time optical/WDM technology will migrate closer to the end users, from core to regional, metropolitan, and ultimately access networks.

At present, WDM deployment is mostly point-to-point and uses SONET/SDH as the standard layer for interfacing to the higher layers of the protocol stack. However, large-scale efforts are underway to develop standards and products that will eliminate one or more of these intermediate layers (e.g., SONET/SDH, ATM) and run IP directly over the WDM layer.

IP over WDM has been envisioned as the winning combination due to the ability of the IP to be the common revenue-generating convergence sub layer and WDM as a bandwidth-rich transport sub layer. Various important concerns still need to be addressed regarding IP-WDM integration. These include light path routing coupled with tighter interworking with IP routing and resource management protocols, survivability provisioning, framing/monitoring solutions, and others.

OPTICAL LAN STANDARDS – IEEE 802.3

Ethernet, IEEE 802.3 defines the frame formats or frame structures that are developed within the MAC layer of the protocol stack.

Essentially the same frame structure is used for the different variants of Ethernet, although there are some changes to the frame structure to extend the performance of the system should this be needed.

With the high speeds and variety of media used, this basic format sometimes needs to be adapted to meet the individual requirements of the transmission system, but this is still specified within the amendment / update for that given Ethernet variant.

Ethernet MAC data frame format

The basic Ethernet frame in use today is referred to as the Ethernet type II frame. This is the frame format developed by the layer 2 elements of the stack, and this is then passed to the layer 1 physical layer to put it into the format for sending.

The layer 2 format consists of the main elements of the data frame, but without some headers needed for the actual sending of the overall data.

Its format can be seen in the diagram below.

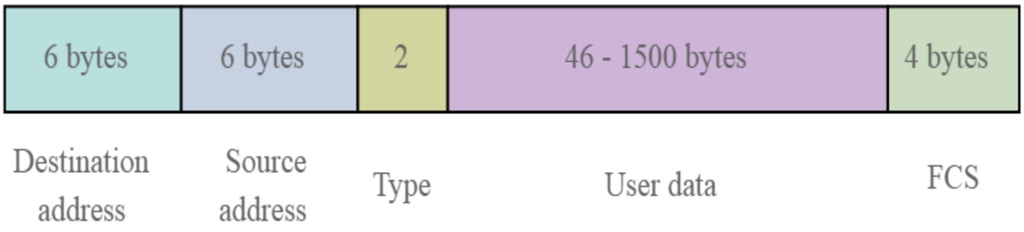

Figure 5.8 Basic Ethernet layer 2 frame format

The basic frame consists of seven elements split between three main areas:-

Header

- Preamble / SFD: - this element within the header is added by the layer 1 part of the protocol stack. It enables the receiver to synchronise and know that a data frame is about to be sent.

- Preamble (PRE) - This is seven bytes long and it consists of a pattern of alternating ones and zeros, and this informs the receiving stations that a frame is starting as well as enabling synchronization.
- Start of Frame Delimiter (SFD) - This consists of one byte and contains an alternating pattern of ones and zeros but ending in two ones.
- Destination Address (DA) - This field contains the address of station for which the data is intended. The left most bit indicates whether the destination is an individual address or a group address. An individual address is denoted by a zero, while a one indicates a group address. The next bit into the DA indicates whether the address is globally administered, or local. If the address is globally administered the bit is a zero, and a one of it is locally administered. There are then 46 remaining bits. These are used for the destination address itself.
- Source Address (SA) - The source address consists of six bytes, and it is used to identify the sending station. As it is always an individual address the left most bit is always a zero.
- Length / Type - This field is two bytes in length. It provides MAC information and indicates the number of client data types that are contained in the data field of the frame. It

may also indicate the frame ID type if the frame is assembled using an optional format.(IEEE 802.3 only).

Payload

- Data - This block contains the payload data and it may be up to 1500 bytes long. If the length of the field is less than 46 bytes, then padding data is added to bring its length up to the required minimum of 46 bytes.

  Later implementations allowed for so-called 'jumbo' frames up to 9,000 bytes long to facilitate certain types of large traffic flows such as file transfers and video links.

Trailer

- Frame Check Sequence (FCS) - This field is four bytes long. It contains a 32 bit Cyclic Redundancy Check (CRC) which is generated over the DA, SA, Length / Type and Data fields.

After the Ethernet data frame itself there is an interframe gap of a minimum of 12 bytes of data. This acts as a delimiter to ensure that the receiver knows the frame is complete before any further data is sent.

Half-duplex transmission

This access method involves the use of CSMA/CD and it was developed to enable several stations to share the same transport medium without the need for switching, network controllers or assigned time slots. Each station is able to determine when it is able to transmit and the network is self organizing.

The CSMA/CD protocol used for Ethernet and a variety of other applications falls into three categories. The first is Carrier Sense. Here each station listens on the network for traffic and it can detect when the network is quiet. The second is the Multiple Access aspect where the stations are able to determine for themselves whether they should transmit. The final element is the Collision Detect element. Even though stations may find the network free, it is still possible that two stations will start to transmit at virtually the same time. If this happens then the two sets of data being transmitted will collide. If this occurs then the stations can detect this and they will stop

transmitting. They then back off a random amount of time before attempting a retransmission. The random delay is important as it prevents the two stations starting to transmit together a second time.
Note: According to section 3.3 of the IEEE 802.3 standard, each octet of the Ethernet frame, with the exception of the FCS, is transmitted low-order bit first.

Full duplex

Another option that is allowed by the Ethernet MAC is full duplex with transmission in both directions. This is only allowable on point-to-point links, and it is much simpler to implement than using the CSMA/CD approach as well as providing much higher transmission throughput rates when the network is being used. Not only is there no need to schedule transmissions when no other transmissions are underway, as there are only two stations in the link, but by using a full duplex link, full rate transmissions can be undertaken in both directions, thereby doubling the effective bandwidth.

Ethernet addresses

Every Ethernet network interface card (NIC) is given a unique identifier called a MAC address. This is assigned by the manufacturer of the card and each manufacturer that complies with IEEE standards can apply to the IEEE Registration Authority for a range of numbers for use in its products.

The MAC address comprises of a 48-bit number. Within the number the first 24 bits identify the manufacturer and it is known as the manufacturer ID or Organizational Unique Identifier (OUI) and this is assigned by the registration authority. The second half of the address is assigned by the manufacturer and it is known as the extension of board ID.

The MAC address is usually programmed into the hardware so that it cannot be changed. Because the MAC address is assigned to the NIC, it moves with the computer. Even if the interface card moves to another location across the world, the user can be reached because the message is sent to the particular MAC address.

Fast Ethernet was able to deliver data at a rate of 100 Mbps which was a significant improvement over the original 10 Mbps Ethernet systems. It was released under IEEE 802.3u in 1995.

Although technology has moved on significantly to standards like 1000Mbps or 1 Gb Ethernet and even 10 Gb Ethernet, but still the old Fast 100 Mbps Ethernet its seen, especially in the guise of 100BASE-T which was for Ethernet over copper and used with Cat5 cables.100 Mbps Ethernet / Fast Ethernet can still be seen on legacy equipment like old computers, Ethernet switches and Ethernet routers, printers etc.

At the time of its release, Fast Ethernet represented a very fast medium for data transfer, and it was widely used for local area networks and many other applications including local and wide area networks, especially when using the fiber based media.

However it was the 100BASE-T version that took off for home and local area networking, and it laid the foundations for the use of future releases of the Ethernet standard. As 100 Mbps Ethernet was backwards compatible with 10 Mbps ports, computers, printers, Ethernet routers and Ethernet switches, etc were marked with 10/100 Mbps to indicate that both standards could be used.

Fast Ethernet / 100 Mbps Ethernet versions

There are several versions of 100 Mbps Ethernet and these are designated using the 100BASE-xx configuration where 100 indicate the speed in Mbps, BSE indicates it is Baseband and the suffix indicates the medium as shown in the table 5.2.

100MBPS ETHERNET VERSION	**DETAILS**
100 Mbps Ethernet over copper wire	
100BASE-TX *	uses two pairs of Category 5 UTP (Unshielded Twisted Pairs) - Cat 6 or Cat 7 would also work, but it was not available when 100BASE-T was launched
1000BASE-T4	This is a form of 100BASE-T used four pairs of Category 3 (now obsolete)
1000BASE-TX	This is a form of 100BASE-T used two pairs of Category 3 (now obsolete)
100 Mbps Ethernet over Fiber	
100BASE-FX	This version uses two strands of multi-mode optical fibre for receive and transmit. Maximum length is 400 metres for half-duplex connections (to ensure collisions are detected) or 2 kilometres for full-duplex and is primarily intended for backbone use.

100BASE-SX	This uses two strands of multi-mode optical fibre for receive and transmit. It is a lower cost alternative to using 100Base-FX, because it uses short wavelength optics which are significantly less expensive than the long wavelength optics used in 100Base-FX. 100Base-SX: can operate at distances up to 300 metres.
100Base-BX	This version of 100 Mbps Ethernet uses a single strand of optical fibre (unlike 100BASE-FX, which uses a pair of fibres). Single-mode fibre is used, along with a special multiplexer which splits the signal into transmit and receive wavelengths.

Table 5.2 Ethernet Version

The segment length for a 100Base-T cable is limited to 100 metres.

100Base -T overview

100BASE-T Ethernet, also known as Fast Ethernet is defined under the 802.3 family of standards under 802.3u. Like other flavours of Ethernet, 100Base-T, Fast Ethernet is a shared media LAN. All the nodes within the network share the 100 Mbps bandwidth. Additionally it conforms to the same basic operational techniques as used by other flavours of Ethernet. In particular it uses the CSMA/CD access method, but there are some minor differences in the way the overall system operates.

The designation for 100Base-T is derived from a standard format for Ethernet connections. The first figure is the designation for the speed in Mbps. The base indicates the system operates at baseband and the following letters indicate the cable or transfer medium.

Fast Ethernet data frame format

Although the frame format for sending data over an Ethernet link does not vary considerably, there are some changes that are needed to accommodate the different physical requirements of the various flavours. The format adopted for Fast Ethernet, 802.3u is given below:

PRE	SOF	DA	SA	Length / type	Data payload	FCS
7	1	6	6	2	46 - 1500	4

Figure 5.9 Ethernet data format

Fast Ethernet (802.3u) Data Frame Format

It can be seen from the figure 5.9 above that the data can be split into several elements:

PRE: This is the Preamble and it is seven bytes long and it consists of a series of alternating ones and zeros. This warns the receivers that a data frame is coming and it allows them to synchronize to it.

SOF: This is the Start of Frame delimiter. This is only one byte long and comprises a pattern of alternating ones and zeros ending with two bits set to logical "one". This indicates that the next bit in the frame will be the destination address.

DA: This is the Destination Address and it is six bytes in length. This identifies the receiver that should receive the data. The left-most bit in the left-most byte of the destination address immediately follows the SOF.

SA: This is the Source Address and again it is six bytes in length. As the name implies it identifies the source address.

Length /Type: This two byte field indicates the payload data length. It may also provide the frame ID if the frame is assembled using an alternative format.

Data: This section has a variable length according to the amount of data in the payload. It may be anywhere between 46 and 1500 bytes. If the length of data is below 46 bytes, then dummy data is transmitted to pad it out to reach the minimum length.

FCS: This is the Frame Check Sequence which is four bytes long. This contains a 32 bit cyclic redundancy check (CRC) that is used for error checking.

Data transmission speed

Although the theoretical maximum data bit rate of the system is 100 Mbps. The rate at which the payload is transferred on real networks is far less than the theoretical maximum. This is because additional data in the form of the header and trailer (addressing and error-detection bits) on every packet, along with the occasional corrupted packet which needs to be re-sent slows the data transmission. In addition to this time is lost time waiting after each sent packet for other devices on the network to finish transmitting.

Fast Ethernet Applications

Fast Ethernet in the form of 100Base-T, IEEE 802.3u has become one of the most widely used forms of Ethernet. It became almost universally used for LAN applications in view of the ease of its use and the fact that systems could sense whether 10Base-T or 100Base-T speeds should be used. In this way 100Base-T systems could be incorporated steadily and mixed with existing 10Base-T equipment. The higher specification standard would be used once the two communicating elements were both 100Base-T. In addition to this the fiber based version is also used, but in view of the fact that Cat5 cable is so cheap and easy to use, the wired version is more common. However the fiber version has the advantage of being able to communicate over greater distances.

BROADCAST AND SELECT NETWORKS

A broadcast-and-select network consists of a passive star coupler connecting the nodes in the network as shown in Fig. 5.10(a). Each node is equipped with one or more fixed-tuned or tunable optical transmitters and one or more fixed-tuned or tunable optical receivers. Different nodes transmit messages on different wavelengths simultaneously. The star coupler combines all these messages and then broadcasts the combined message to all the nodes. A node selects a desired wavelength to receive the desired message by tuning its receiver to that wavelength. Note that the star coupler offers an optical equivalent to radio systems: each transmitter broadcasts its signal or message on a different wavelength and the receivers are tuned to receive the desired signal. An $N \times N$ star coupler can be realized using a multistage interconnection network which has $\log_2 N$ stages of 2×2 couplers with $N/2$ couplers per stage (assuming N is a power of 2) or directly in integrated optics form with a common coupling region. Integrated optics refers to integration of optical components with fiber interconnections onto a single optical substrate, similar to the way in which electrical components (such as resistors, capacitors, and inductors) are combined in an electronic integrated circuit.

In single-hop broadcast-and-select networks, a message, once transmitted as light, reaches its final destination directly, without being converted to electronic form in between. In order to support packet switching in these networks, we need to have optical transmitters and receivers that can tune rapidly. This is because, in a packet-switched network, a node must be able to transmit (receive) successive packets to (from) different nodes on different wavelengths. The main networking challenge in these networks is the coordination of transmissions between various nodes. In the absence of coordination or efficient medium access control (MAC) protocol, collisions occur when two or more nodes transmit on the same wavelength at the same time. Also, destination conflicts occur if two or more nodes transmit on different wavelengths to the same destination when the destination has only one tunable optical receiver. Moreover, the destination must know when to tune to the appropriate wavelength to receive a packet. Several MAC protocols have been proposed to prevent such collisions/conflicts for single-hop broadcast-and-select networks, assuming the availability of rapidly tunable transmitters and/or receivers.

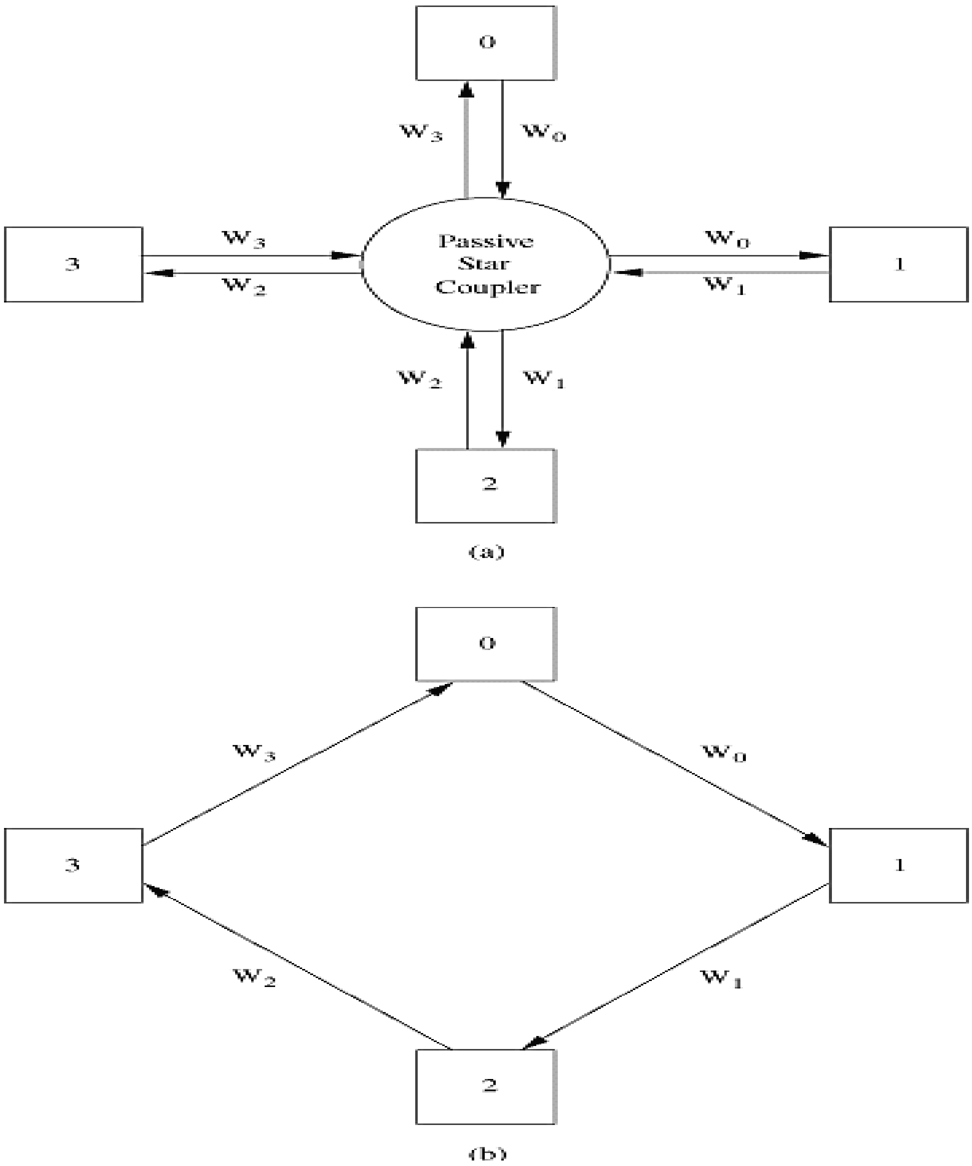

Figure 5.10 (a) Broadcast-and-select network. (b) Logical topology.

To support packet switching efficiently in broadcast-and-select networks, a multihop approach, which avoids rapid tuning altogether, can be used. Each node has a small number of fixed-tuned optical transmitters and fixed-tuned optical receivers. Each transmitter is at a different wavelength. We can represent the network as a graph, wherein a node corresponds to a network node and an edge corresponds to a transmitter–receiver pair on the same wavelength. Thus we obtain a virtual or logical topology over the physical broadcast topology. Figure 5.10(a) shows a four-node broadcast-and-select network. Each node transmits at one fixed wavelength and receives on one fixed wavelength. For example, node 0 can transmit directly to node 1 using wavelength w_0, but not to node 2. To transmit to node 2, node 0 sends a packet to node 1 on wavelength w_0, which receives it, converts it to electronic form, and retransmits it on wavelength w_1. The packet then reaches node 2. The virtual topology of the network in Fig. 5.10(a) is shown in Fig. 5.10(b). In these networks, a packet may have to go through more than one hop before reaching its destination. This leads to an increase in propagation delay in addition to queuing delays at intermediate nodes, and wastage of network capacity.

Advantage of broadcast and select networks

- Simplicity
- Natural multicasting capability (ability to transmit a message to multiple destinations).

Limitations of broadcast and select networks

- They require a large number of wavelengths, typically at least as many as there are nodes in the network, because there is no wavelength reuse in the network. Thus the networks are not scalable beyond the number of supported wavelengths.
- They cannot span long distances since the transmitted power is split among various nodes and each node receives only a small fraction of the transmitted power, which becomes smaller as the number of nodes increases. For these reasons, the main application for broadcast-and-select is high-speed local area networks (LANs) and metropolitan area networks (MAN).

APPLICATIONS OF MILITARY IN OPTICAL NETWORKS

Given that fiber optic technologies are now regularly used for utilities such as telephone and internet communications, it goes without saying that the military uses fiber optic products throughout their land-based facilities. However, perhaps even more importantly, there are many military-specific purposes for which fiber optic cables and products are ideally suited with their fiber optic cable internet.

For instance, some applications for which fiber optic products can provide unrivalled security and stability include shipboard communications, ship to shore communications, and deployable tactical communications. The increased speed of data transmissions allowed by fiber optic products, for example, can be a very major factor contributing to their use for military purposes. When every second counts, and every piece of data is invaluable, it's necessary to use the product which provides the highest and most consistent level of performance and when it comes to data transmission, that level can only be provided by fiber optic.

Additionally, fiber optic cables have been found in many cases to be physically stronger than most alternatives, and more resistant to the kinds of hazards and traffic which might be present in a military space. It's just one more reason, among many others, that the defense sector was an early adopter of fiber optic technologies, with its usage only becoming more integral in the years since.

Since many of the benefits they offer are ideal for military purposes, it stands to reason that fiber optic products would be made specifically for use in those sectors. And indeed, at Interconnect Systems, we offer various fiber optic-related products that are custom-made specifically for a particular military use. One example is the MIL-PRF-28876 shipboard connector, an interconnect that has become truly standard for Navy shipboard applications.

Offering precise optical alignment for ideal performance, environmental protection that ensures connectivity no matter the circumstances, and corrosion resistance to ensure that functionality remains constant in the long term, the MIL-PRF-28876 has been proven to provide high performance without ever faltering.

It's that rare level of steadiness which has led military services, both nationally and abroad, to adopt fiber optic technologies as a baseline. And as military services themselves continue to evolve, innovate, and grow in their own right, their utilization of fiber optic technologies is only likely to grow further: "Growth in the fiber optic cables market for military and aerospace can be attributed to the increasing commercial adoption of fiber optics and growth in platforms, such as unmanned systems, space launch vehicles, and satellites," according to a study of the industry published last month by ResearchandMarkets.com. "Modernization programs of armies and increasing adoption of fiber optic cables for C4ISR applications for high-speed communication are expected to drive the market for fiber optic cables for military and aerospace."

The MIL-DTL-3899 is an excellent example of the fiber optic products available for military usage because, like so many others within that category, it has been made available with an extremely wide range of customizable options. It is currently available in many forms, with various options available for both materials (such as aluminum alloy, composite, and stainless steel) and finishes (including electro less nickel, cadmium, and passivated, among many others).

There are also many different backshells and accessories available for the product, as well as test probes and test adaptors, and turnkey cable assemblies. A wide range of customization options has been made available to ensure these fiber optic products are an ideal fit for an equally wide range of military purposes.

Interconnect Systems has a comprehensive background in aerospace and defense engineering, and has helped to outfit military ships, vehicles, and facilities with fiber optic products throughout its 20-year history.

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