بسم الله الرحمن الرحيم

In the Name of God,
Most Gracious, Most Merciful

FIBER OPTICS COMMUNICATION

by

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ABSTRACT

FIBER OPTICS COMMUNICATION

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This thesis is a study of the basic theory of fiber optics communication. The main components in an optical fiber communication link are considered. An introduction of the theory which describes the way each of the components utilizes light signals is presented. The large information carrying capacity of fiber optics links is discussed as one of the most important advantages of fiber optics links over metallic links. Finally, a simple point-to-point optical link was designed as a direct application of the theory.

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CHAPTER 1

INTRODUCTION

1-1 OBJECTIVE

The objective of my thesis is to introduce the theory of optical communication. I will first review the theory of light propagation through a fiber optical cable. Then I will describe the main building blocks in an optical link. These blocks include:

1. light source,
2. fiber cable,
3. photodetector.

Following the theory, a simple short-haul digital point-to-point communication link will be presented. There is no economical justification for building an optical link such as the one at the end of this thesis; it helps greatly in visualizing and understanding the concept of optical communications. The system that will be presented is a digital optical link with data rate of 10 Mbps. The link uses a multimode step index fiber with a light emitting diode as a light source with no regenerative repeaters. For a communication link such as the one described above, a conventional copper link is more economical.

1-2 HISTORICAL BACKGROUND

Communication may be defined as the transfer of information from one point to another. For the information to be conveyed over any distance, a communication system is 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 recovered by demodulation. The use of visible optical carrier waves or light communication has been common for many years. Simple optical communication systems, for example, signal fire and reflecting mirrors, were used long before any of the metallic communication links. Although some investigation of optical communication continued in the early part of the 20th Century, 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. At the same time, light transmission is severely affected by disturbances such as rain, snow, fog and dust. Meanwhile, lower frequency and hence longer wavelength electromagnetic waves (i.e., radio and microwaves) proved suitable carriers for information transfer in the atmosphere.

In theory, the greater the carrier frequency in an ideal link, the larger the available transmission bandwidth, and thus the larger the information-carrying capacity of the communication link. Since optical frequencies are on the order of $5x10^{14}$ Hz, an ideal optical fiber link has a theoretical information carrying capacity (bandwidth) exceeding that of a microwave system by a factor of 10^5. A single telephone channel needs a 4 KHz channel bandwidth to be transmitted with a reasonable fidelity. The 10^5 difference is equivalent to 250 telephone channels. Using time division multiplexing techniques (will be explained in Chapter 6), the number of channels will increase significantly. In the early 1960s, following the invention of the laser, a new interest in optical communication was stimulated. The lasers provided powerful coherent light sources with the possibility of modulation at high frequencies. The proposals for optical communication via dielectric waveguides such as optical fibers manufactured from glass were made by Kao, Hockham and Werts separately in 1966[1]. Initially optical fibers exhibited very high attenuation rates (around 1000 dB Km^{-1}). Because of this high level of attenuation, early fibers could not compete with the coaxial cables (5-10 dB Km^{-1}). At that time, there were also serious problems involved in joining the fiber cables with low loss. Nevertheless, by 1970 optical fibers with low losses (around 20 dB Km^{-1}) and suitable low loss joining techniques were produced. At this attenuation level, repeater spacings for optical fiber links became comparable to those of copper systems making lightwave technology an engineering reality.

At the same time attention was also focused on other optical components which constitute the optical fiber communication system. Semiconductor optical sources (i.e., injection lasers (IL) and light emitting diode (LED)), and photodetectors (i.e., photodiode) compatible in size with optical fiber were designed.

1-3 ADVANTAGES OF OPTICAL FIBER COMMUNICATION

Communication using optical fiber has a number of extremely attractive features. Moreover, the advances in technology to date make optical fiber systems compatible with conventional systems[2]. It is useful to consider features offered by optical fiber communication over the electrical systems.

1-3-1 HIGH BANDWIDTH

Analog information is usually characterized by the power/frequency spectrum content of the electrical signal. On the other hand, information in a discrete or pulsed (digital) form is characterized with respect to the basic unit of information, the bit (1,0). Bandwidth is a measure of the information carrying capacity of a communication link. The greater the bandwidth the greater the information carrying capacity on the link. In a power/frequency graph, bandwidth is the maximum frequency before the signal power is attenuated to the 3 dB level. The optical carrier frequency around 10^{14} Hz has a wavelength in the range of

1.7 to 0.8 μm. Its usual use is in the near infrared between 0.8 and 0.9 μm. More recently this wavelength range has been extended to include the 1.1-1.6 μm range. The optical carrier frequency yields a greater potential transmission bandwidth than the conventional metallic cable systems, i.e., coaxial cable (20 MHz). A measure of the information carrying capacity of an optical fiber is usually specified by the bandwidth-distance product in MHz•Km. The bandwidth of an optical fiber link varies with the fiber used from 20 MHz•Km for step index fibers to 2.5 GHz•Km for graded index fibers. Moreover, a single mode step index fiber has a bandwith that goes up to 400 GHz•Km. This bandwidth is much higher than the 1 MHz limit of twisted-shield wire pair and the 20 MHz limit of coaxial cable. To get a feeling of the optical fiber bandwidth consider Table 1-1. Table 1-1 summarizes the bandwidth requirements of several analog systems. When an analog signal is transmitted digitally, the bit rate depends on the rate at which the analog signal is sampled and the coding scheme used (will be explained in Chapter 6). If the analog signal is sampled instantaneously at regular intervals, f_S, of rates at least twice the highest analog frequency, f_A, (Nyquist rate), i.e.,

$$f_S \geq 2f_A(\max) \tag{1-3-1}$$

then according to the sampling theory, the samples contain all the information in the original analog signal.

Message type	Bandwidth	Comments
Voice	4 KHz	Single telephone channel
Music	10 KHz	AM Radio broadcasting station
Music	200 KHz	FM Radio broadcasting station
Television	6 MHz	Television broadcasting station

Table 1-1 Common analog systems.

From Table 1-1, to transmit a standard telephone channel digitally, it has to be sampled 8000 times a second. If each of these samples is to be coded into 8 bits to describe the amplitude of each sample, a total of 64 Kbps are to be transmitted for a single telephone message. Using time-division multiplexing (TDM) techniques several telephone messages can be sent at the same time. At the receiver the messages are separated (demultiplexed). The telephone network in the United States uses 24 channels, as the basic block, T1 system (transmission at level 1). At this level, 24 voice messages are multiplexed. When digital signaling is used, the combination of these 24 messages gives 24 X 64000 = 1.544 Mbps. This means that the communication link must at least have 1.544 Mbps equivalent bandwidth to be able to transmit at this level. The telephone network in the United States uses 8 different standard rates. These rates start with T1 level where 24 channels are being multiplexed, and go up to 12T3 level where 8064 channels are being multiplexed. Level 12T3 needs 565 Mbps data rate. An exact treatment of the United States telephone system is found in Reference 1.

The need of a larger bandwidth in communication links is clearly demonstrated considering the transmission of a commercial television broadcast. From Table 1-1, the analog signal for TV has a bandwidth of 6 MHz. Digitizing the TV signal by sampling with Nyqust rate, and encoding by 8 bits per sample requires a data rate of (2)•(6 MHz)•(8 bits) = 96 Mbps. If several of these signals were multiplexed onto a single fiber, the total data rate would be several hundred mega bits per second. Several hundred mega bits per second is easily achieved using fiber optic cables.

1-3-2 LOW TRANSMISSION LOSS

Optical fibers have lower transmission loss than copper wires. Fibers have been fabricated with losses as low as 0.1 dB Km^{-1}. This feature has become a major advantage of optical fiber communication. Fiber low loss facilitates their use in long-haul communication links with fewer repeaters. This reduction in equipment and components decreases the system's cost and complexity.

To appreciate the low loss and the wide bandwidth capabilities of optical fibers, consider the curves of

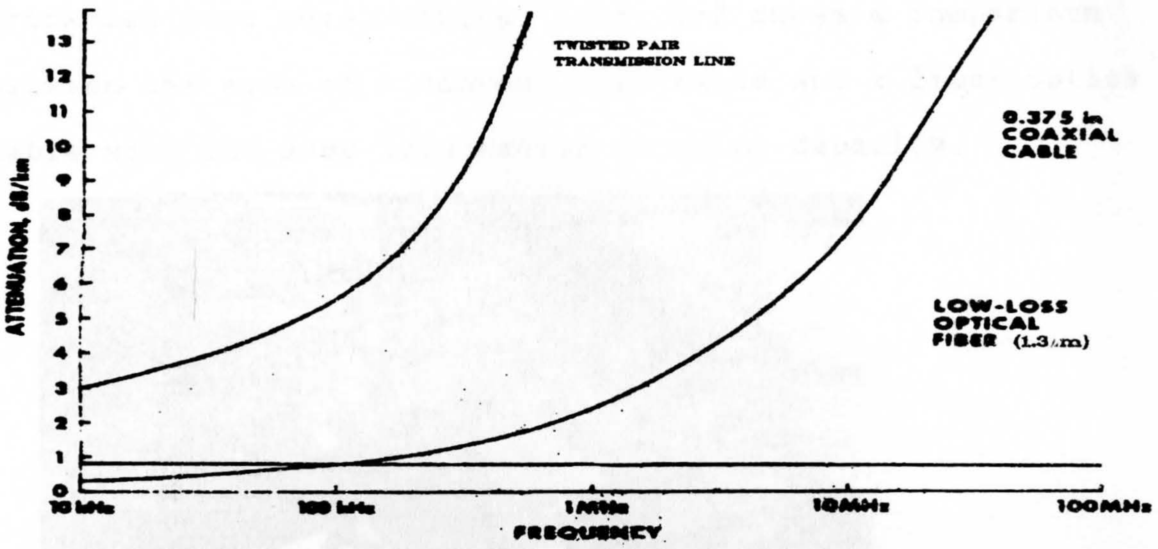

Fig. 1-1 Attenuation as a function of the frequency in three common links, twisted pair line, coaxial cable, and optical fiber link at 1300 nm [Ref. 3].

signal attenuation versus frequency for three different transmission media shown in Fig. 1-1. Optical fibers have a constant attenuation well beyond 100 MHz. When compared with wire pairs or coaxial cables, optical fibers have far less loss for signal frequencies above a few megahertz. This is an important characteristic since it allows the system designer to increase the distance between regenerative repeaters in a communication system.

1-3-3 SMALL SIZE AND WEIGHT

Optical fibers have very small diameters which are often no greater than the diameter of a human hair (2 to 50 μm). This small size leaves us more free space in the crowded underground city duct or in ceiling-mounted cable trays. It is also of great importance in aircraft, satellites, and ships, where small light-weight cables are preferred over metal cables. Fig. 1-2 shows a comparison between the size of a conventional cable and a fiber optics cable with the same information carrying capacity.

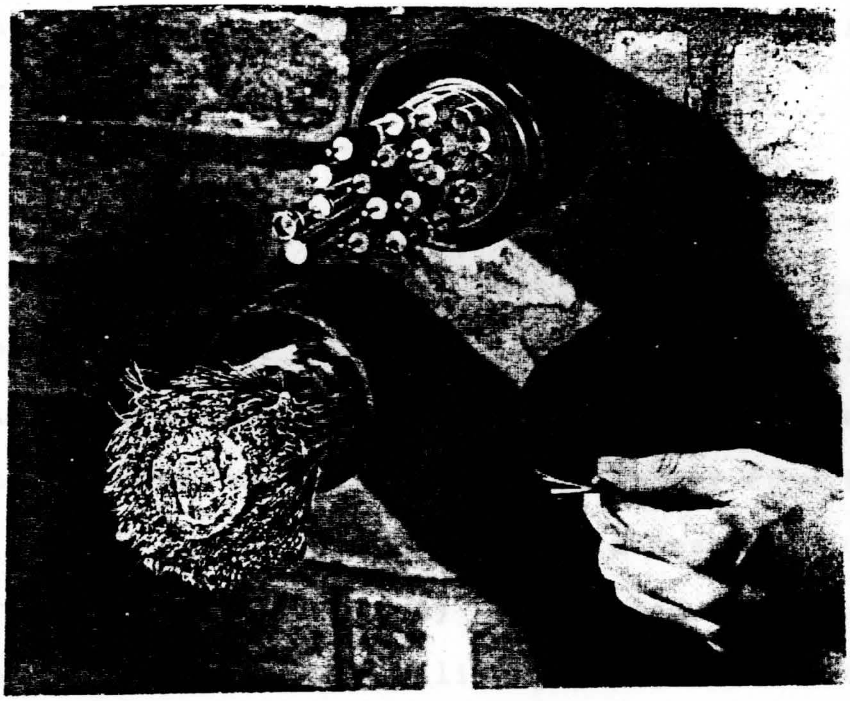

Fig. 1-2 Comparison between optical fiber and metallic telephone cable [Ref. 4].

1-3-4 ELECTRICAL ISOLATION

Since optical fibers are fabricated from glass or sometimes plastic polymers, they are electrical insulators. Therefore, unlike their metallic counterparts, they do not exhibit earth loop and interference problems. Furthermore, this property makes fiber transmission an excellent method for communication in electrically hazardous environments.

1-3-5 IMMUNITY TO INTERFERENCE AND CROSSTALK

Optical fibers form a dielectric waveguide; therefore, they are free from electromagnetic (EMI)and radio frequency interference (RFI). As a result, the operation of an optical fiber communication link is unaffected by transmission through an electrically noisy environment. Moreover, it is fairly easy to ensure the absence of optical interference between fibers. Hence, crosstalk is negligible even when many fibers are cabled together.

1-3-6 SIGNAL SECURITY

The light from optical fibers does not radiate significantly. Therefore, optical fibers provide a high degree of signal security. Unlike the situation with copper cables, a transmitted optical signal cannot be obtained from the fiber without drawing optical power from the fiber. As a result, any attempt to acquire a message signal transmitted optically may be detected. This makes fiber optics attractive for military and general data transmission (computer network) applications.

1-3-7 PROVIDING NATURAL GROWTH CAPABILITY

An engineer using optical fibers has a great deal of flexibility. The engineer can install an optical fiber link and use it initially in a low-capacity (low-bit-rate) system. As the system needs grow, the engineer can take advantage of the broad band capabilities of the optical fibers and convert to a high-capacity (high-bit-rate) system by simply changing the terminal electronics. A comparison of the growth capability of different transmission media is shown in Table 1-2. For the three digital transmission rates (1.544, 6.312, and 44.7 Mbps), the loss of the optical fiber is constant. However, the loss of the metallic transmission lines increases with the transmission rates. This increase in the loss with transmission rates limits the use of metallic links at higher rates. The optical fiber, on the other hand, can be used at all bit rates and can grow naturally to satisfy the system's needs. The same conclusion can be reached by considering the attenuation of the three transmission media as a function of the frequency shown in Fig. 1-1.

Transmission media	Loss in dB/km at different bit rate		
	T1 (1.544 Mbps)	T2 (6.312 Mbps)	T3 (44.736 Mbps)
26 Gauge twisted wire pair	24	48	128
0.375-in.-Diameter coaxial cable	2.1	4.5	11
Low-loss optical fiber	0.75	0.75	0.75

Table 1-2 Growth capability, transmission media comparisons.

1-4 DISADVANTAGES OF FIBER OPTICS COMMUNICATION

There are some potential disadvantages of optical fiber cables.

1-4-1 RADIATION DAMAGE

Optical fibers are subject to damage from strong X rays, γ rays, and neutron radiation that are generated during a nuclear radiation. A great amount of research is concentrated around finding new fiber materials which are less susceptible to radiation damage.

1-4-2 CONNECTORS AND SPLICES

The loss at connectors and splices in fiber optics systems is generally greater than this in conventional systems. Moreover, the connectors for fiber systems, especially single mode, require more precision in fabrication and installation than those of conventional communication systems.

1-4-3 SYSTEM DESIGN

Optical fibers are not considered for the transmission of power. Also, since the fiber is a dielectric material, a separate metal line has to be installed with a long-haul link to supply any repeaters that might be needed along the link.

1-5 DIGITAL VERSUS ANALOG COMMUNICATION SYSTEMS

In communication there is a general trend from analog to digital data transmission. The major requirement of a digital system is an increase in bandwidth, whereas that of an analog system is an improvement in linearity. Fiber optics gives an excellent improvement for both of the above requirements. Still digital operation offers many advantages over analog operation.

1-5-1 NOISE IMMUNITY

The information is carried in an analog signal in the shape that the signal has. If the signal to noise ratio (S/N) is relatively large it will affect the shape of the analog signal significantly. This change in the shape of the signal changes the message carried (i.e., errors are introduced in the signal). Also, when an analog signal is amplified, both the signal and noise are amplified at the same time. In addition to the amplified noise, there will be an additional noise from the amplifier electronics. On the other hand, in a digital signal the information is carried in the kind that the pulses have (i.e., 0 or a 1 is being sent in the channel). As a result, as long as a digital pulse can be determined at the receiver as a 1 or 0, S/N will not affect the bit error rate (BER). Moreover, at a repeater, a digital signal can be regenerated exactly and retransmitted along the link.

1-5-2 USER FLEXIBILITY

Digital systems allow the use of a common language. In a digital channel, voice, video, facsimile, and data can be transmitted by the same network. All it takes is the change of the information source (microphone, VCR, facsimile, and computer) and the receiving terminal (speaker, VCR, facsimile, and computer respectively). This is because the transmitted signals appear the same (1,0) whether originally they are voice, video, facsimile, or data.

CHAPTER 2

BASIC OPTICAL LAWS

2-1 NATURE OF LIGHT

The nature of light went through several variations during the history of physics. Light was thought of as minute particles. These particles are emitted by the light source and travel in straight lines. Light particles have the ability to penetrate transparent materials, but they are reflected by opaque ones. Although this theory could explain large scale optical phenomena, such as reflection and refraction, it could not explain fine-scale phenomena, such as interference and diffraction. Later, light was considered as wave motion, that theory could explain diffraction fringes. Then Maxwell in his theory dealt with light as electromagnetic waves. Those waves are transverse in nature, i.e., the electric field is perpendicular to the magnetic field in the wave, and both are perpendicular to the direction in which the wave propagates. According to Maxwell's theory (which will be explained later), electromagnetic waves that are radiated from a small optical source can be represented by a train of spherical wave fronts with the source at the center. A wave front is the locus of all points in the wave train that have the same phase. Therefore, wave fronts are separated by one wavelength. The direction in which a wave front propagates is perpendicular to the wave front itself. Hence, light waves can be represented by rays in the direction of propagation. Considering light as rays is called geometrical optics. Geometrical optics is valid and gives good results with an acceptable approximation. If exact results are required, then wave optics should be used. For example, when studying the basic theory of light propagation in a straight fiber cable, geometrical optics is sufficient. On the other hand, studying the loss in a bent fiber requires wave optics.

The interaction of light with material, such as radiation from Light Emitting Diode (LED) or absorption of light by a photo-detector, can not be explained by any of the above theories alone. In these cases, quantum theory gives an exact explanation. (This will be explained later.) Quantum theory considers light as having both particle and wave properties. As a particle, light is always emitted or absorbed in discrete units called photons. As a wave, the energy, E, of the photon is given in (2-1-1).

$$E = h \times \nu \qquad (2\text{-}1\text{-}1)$$

where $h = 6.625 \times 10^{-34}$ J.sec is Plank's constant and ν is the frequency of the wave associated with the photon.

2-2 BASIC OPTICAL LAWS AND DEFINITIONS

Rather than using wave optics, it is easier and more straight-forward to explain the basic theory of light transmission in a straight fiber using geometrical optics.

A fundamental optical parameter of a material is the refractive index or the index of refraction, n. The refractive index of a medium is defined as the ratio of the velocity of light in vacuum c = $3x10^8$ m/sec. to the velocity of light in the medium v, n = c/v. A ray of light travels more slowly in an optically dense medium than in one less dense; the refractive index gives a measure of this effect. Fig. 2-1 shows a light ray incident on the interface between two different materials. When light is incident on the interface between two materials, refraction occurs. Fig. 2-1(a) shows a light ray incident on the interface between two materials from the material with the high refractive index, n_1. The angle of incidence, θ_i, is defined as the angle between the incident ray and the normal to the interface. Refraction occurs at the dielectric interface. The angle of refraction, θ_r, is the angle between the refracted ray and the normal to the interface.

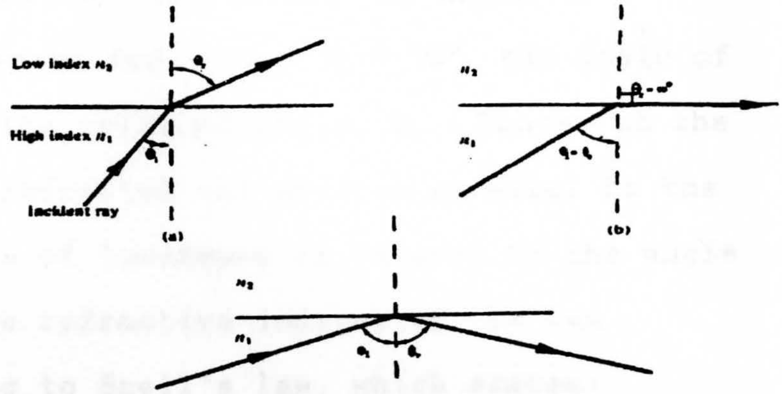

Fig. 2-1 Light ray on high to low refractive index interface: (a) refraction; (b) limiting case, critcal angle; (c) total internal reflection.

As long as $n_1 > n_2$, then $\theta_r > \theta_i$, as shown in Fig. 2-1(a). As the angle of incidence, θ_i, increases, the angle of refraction, θ_r, increases too. When $\theta_r = 90°$, the angle of incidence is called the critical angle, θ_c. Hence, at the critical angle, the refracted ray emerges parallel to the interface. The angle of incidence is related to the angle of refraction and the refractive indices of the two dielectrics according to Snell's law, which states:

$$n_1 \times \sin\theta_i = n_2 \times \sin\theta_r \qquad (2\text{-}2\text{-}1)$$

or

$$\frac{\sin\theta_i}{\sin\theta_r} = \frac{n_2}{n_1} \qquad (2\text{-}2\text{-}2)$$

At the critical angle, $\sin\theta_r = 1$, so we get $\theta_c = \sin^{-1}(n_2/n_1)$. If θ_i is increased above the value of θ_c, then θ_r will be greater than $90°$. In this case, the light ray will be reflected back in the same dielectric (total internal reflection 99.9%). The angle of reflection is the angle between the reflected ray and the normal to the interface surface. The angle of incidence is equal to the angle of reflection. Total internal reflection is the mechanism by which light propagates through a fiber optics cable. To study total internal reflection through an ideal (low loss and no imperfections) fiber optics cable, consider Fig. 2-2.

The light ray shown in Fig. 2-2 is incident from air with the refractive index n_0 (less than the core refractive index) on the core surface. The angle of incidence is θ_{in} at point A. The ray refracts at the air-core interface and propagates inside the core. The refractive index of the core n_1 is greater than n_2 for the cladding. The refracted ray propagates inside the fiber and reaches the core-cladding interface at point C. The angle of incidence at point C is θ_1, shown in Fig. 2-2. If θ_1 is greater than the critical angle at the core-cladding interface, the ray will be reflected back in the core (total internal reflection). The reflected ray at C propagates and reaches the core-cladding interface at point D. From geometry, the angle of incidence at point D will be equal to θ_1, which is less than θ_c at point D so there the ray reflects again. The process of total internal reflection is repeated each time the ray reaches the core-cladding interface, and as a result, the ray propagates through the fiber.

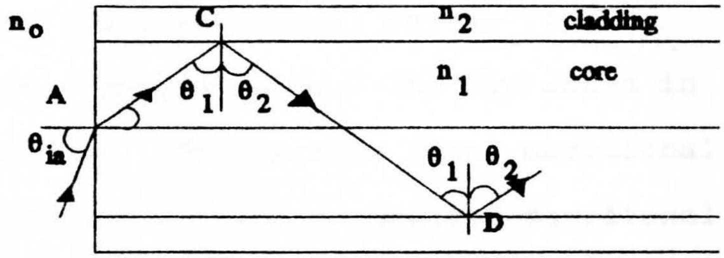

Fig. 2-2 Transmission of light ray in a fiber optics cable.

There are two different kinds of rays that may exist inside a fiber optics cable. The first kind is meridional rays, which are the rays that cross the fiber axis after each reflection. Meridional rays are confined to one plane, which is the plane that contains the fiber axis. Hence, it is relatively easy to follow a meridional ray as it propagates through a fiber optics cable. The ray shown in Fig. 2-2 is a meridional ray. At the same time, meridional rays are divided into two kinds: first, bounded meridional rays, which are trapped in the fiber's core and transmit through the fiber by total internal reflection, and second, unbound meridional rays, which are refracted out of the core and die out. The second kind of rays is called skew rays. Skew rays are not confined to a single plane. They transmit through a fiber cable without passing through the fiber axis. These rays follow a helical path as they are reflected on the core-cladding interface.

2-3 ACCEPTANCE ANGLE

Not all rays incident on the core surface of a fiber optics cable propagate down the fiber. To explain this, consider the fiber cable in Fig. 2-3.

Fig. 2-3 shows a meridional ray, A, incident onto the core surface, making angle θ_1 with the fiber axis. The ray refracts at the air-core interface with the angle of refraction, θ_2. The refracted ray reaches the core-cladding interface at point E, making an angle θ_c with the perpendicular to the interface. This meridional ray propagates through the fiber by total internal reflection as explained before. Any ray with an angle of incidence at the air-core interface greater than θ_a will refract with angle greater than θ_2. As θ_2 increases, the angle of incidence of the refracted ray at the core-cladding interface decreases. As a result, the angle

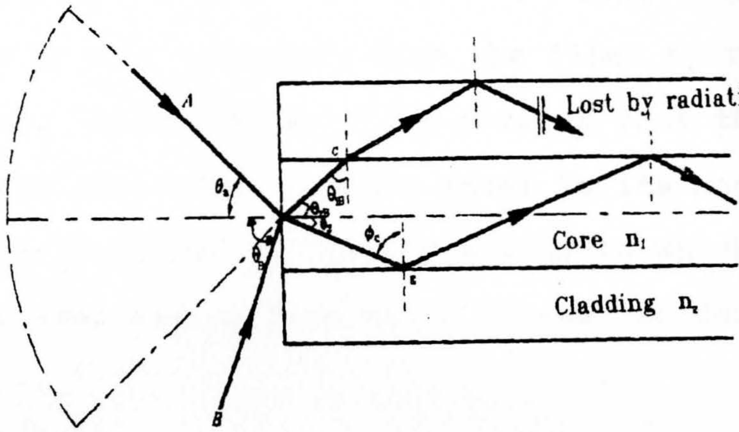

Fig. 2-3 A meridional ray incident onto the core with an angle equal to the acceptance angle.

of incidence at the core-cladding interface will be less than θ_c and the ray will be refracted inside the cladding. Hence, any ray that refracts inside the cladding dies out and will be lost. As an example, consider ray B, shown in Fig. 2-3. Ray B is incident onto the core surface with angle θ_B with the fiber axis where $\theta_B > \theta_a$. This ray will be refracted inside the core with angle of refraction, θ_{rB}, where $\theta_{rB} > \theta_2$. Because $\theta_{rB} > \theta_2$, the angle of incidence of this ray at the core-cladding interface, point C, will be less than the critical angle θ_c or $\theta_{iB} < \theta_c$. Hence, this ray will be refracted into the cladding and will not propagate through the fiber. In the above case, the angle θ_a is called the acceptance angle.

Assuming that a fiber has a regular cross section (i.e., the core-cladding interfaces are parallel and there are no discontinuities), an incident ray (meridional) with an angle less than θ_a will propagate down the fiber by total internal reflection. By symmetry, it is obvious that the ray emerges from the core with an angle equal to its angle of incidence. This is assuming that the medium to which the ray emerges is the same medium from which it was incident onto the fiber.

2-4 NUMERICAL APERTURE

An important term related to the transmission of meridional rays is the numerical aperture (NA).

In Fig. 2-4, a light ray is incident onto the fiber core, with an angle of incidence, θ_1, with the fiber axis. For the ray to propagate, θ_1 must be less than or equal to θ_a,

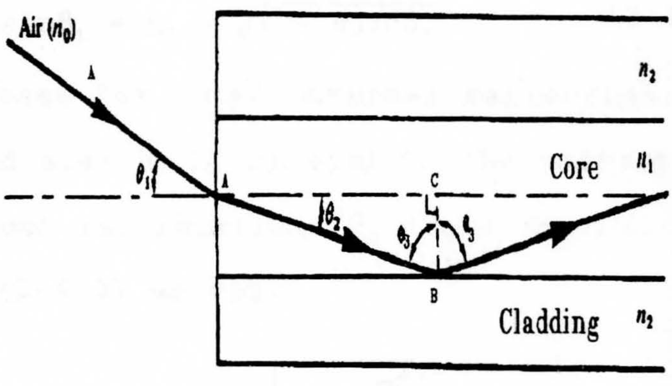

Fig. 2-4 A meridional ray in a fiber cable.

$\theta_1 \leq \theta_a$. Assuming that the refractive index of the medium from which the ray was incident is n_0, and the core refractive index is n_1, which is slightly greater than the cladding refractive index n_2. Also, it is assumed that the entrance face of the fiber is normal to the core axis.

Snell's law for the refracted ray is:

$$n_0 \times \sin\theta_1 = n_1 \times \sin\theta_2 \qquad (2\text{-}4\text{-}1)$$

where θ_2 is the angle of refraction inside the core shown in Fig. 2-4. Considering the right-angled triangle ABC in Fig. 2-4, the angle θ_3 can be written as $\theta_3 = (\pi/2) - \theta_2$ or $\sin\theta_2 = \cos\theta_3$. Here θ_3 is greater than or equal to the critical angle at the core cladding interface. Equation (2-4-1) becomes:

$$n_0 \times \sin\theta_1 = n_1 \times \cos\theta_3 \qquad (2\text{-}4\text{-}2)$$

Using the trigonometrical relationship $\sin^2\theta + \cos^2\theta = 1$ in (2-4-2) we get:

$$n_0 \times \sin\theta_1 = n_1 \times \sqrt{1 - \sin^2\theta_3} \qquad (2\text{-}4\text{-}3)$$

In the limiting case for total internal reflection, $\theta_1 = \theta_a$ and $\theta_3 = \theta_c$, and also θ_c is related to the refractive indices n_1 and n_2 through the relation, $\theta_c = \sin^{-1}(n_2/n_1)$. Substituting this in (2-4-3) we get:

$$n_0 \times \sin\theta_a = n_1 \times \sqrt{1 - \frac{n_2^2}{n_1^2}} \qquad (2\text{-}4\text{-}4)$$

Equation (2-4-4) above relates the refractive indices n_1 and n_2 to the acceptance angle θ_a. The right hand side of (2-4-4) is called the numerical aperture (NA) of the fiber. To derive an expression for NA, (2-4-4) can be written as:

$$n_0 \times \sin\theta_a = n_1 \times \sqrt{\frac{n_1^2 - n_2^2}{n_1^2}} \tag{2-4-5}$$

or

$$NA = n_0 \times \sin\theta_a = \sqrt{n_1^2 - n_2^2} \tag{2-4-6}$$

From the above equations, it is clear that an incident ray with an angle of incidence θ_i such that $0 \le \theta_i \le \theta_a$ will propagate down the fiber. Another way of expressing NA is in terms of the fiber refractive index difference Δ where Δ is defined as[5]:

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$
$$\Delta \approx \frac{n_1 - n_2}{n_1} \qquad for \quad \Delta \ll 1 \tag{2-4-7}$$

As a result, the NA can be expressed as:

$$NA = n_1 \times \sqrt{2 \times \Delta} \tag{2-4-8}$$

NA is a very useful measure of the light-gathering ability of the fiber core.

All the equations that were derived above are independent of the fiber diameter. They are functions of the refractive indices of the core and cladding or the refractive index difference. This suggests that those equations can be used for fibers with different core diameters. The above equations break down only for very small diameters where ray optics does not apply. This is because the ray theory is only a partial description of the character of light. As explained before, ray optics describes the direction of a plane wave component in the fiber, but it does not take into account the interference between such components. When interference phenomenon is considered, it is found that only rays with certain discrete characteristics propagate in the fiber. Hence, the fiber will only support a discrete number of guided modes. A mode is a group of parallel rays with equal angle with the fiber axis. Modes that propagate through the fiber are those which satisfy Maxwell's equations. The number of modes becomes critical in small core diameter fibers that only support one or a few modes. As a result, electromagnetic mode theory must be applied in these cases.

In the previous section meridional rays and their propagation through fiber optics cable were considered. However, there is another kind of ray, the skew ray, that propagates through the fiber without passing through its axis. Because of the path that skew rays follow as they travel through the core, it is not easy to visualize skew rays' path in two dimensions. Although skew rays follow a helical path along the fiber, they obey the laws of reflection and refraction at the core cladding interface. In graded index fiber, skew rays are very difficult to track but they follow the same theory that meridional rays follow.

2-5 REFLECTION AND REFRACTION OF PLANE WAVES

2-5-1 THE LAW OF REFLECTION AND REFRACTION

It will be assumed that the boundary between two media is infinite and that there are no free charges or free surface currents on the boundary surface. The boundary conditions for such systems are:

1. the normal components of D and B fields are continuous across the boundary,
2. the tangential components of E and H fields are continuous across the boundary.

Consider an incident wave traveling in medium 1. This medium has electromagnetic parameters $(\mu_1, \varepsilon_1, \sigma_1)$. This wave is incident on medium 2, which has electromagnetic parameters $(\mu_2, \varepsilon_2, \sigma_2)$. For a fiber optic cable, the core and the cladding are non-conducting, i.e., the σ's equal zero. Consider the interface between two dielectrics (core and cladding in a fiber optic cable), 1 and 2 shown in Fig. 2-5. Fig. 2-5 shows an incident wave in the medium of

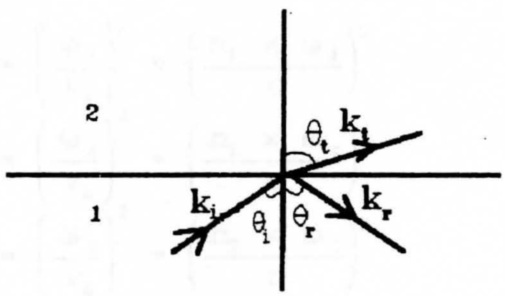

Fig. 2-5 A wave incident on the boundary between two dielectrics.

the refractive index n_i. This wave has an angle of incidence θ_i. At the boundary surface, there will be a reflected wave in medium 1 and a transmitted or refracted wave in medium 2. Considering the electric field in the wave, the E field for the three waves can be written as:

$$\boldsymbol{E}_i = \boldsymbol{E}_{0i} \times \exp(j(\boldsymbol{k}_i \cdot \boldsymbol{r} - \omega_i \times t)) \tag{2-5-1}$$
$$\boldsymbol{E}_r = \boldsymbol{E}_{0r} \times \exp(j(\boldsymbol{k}_r \cdot \boldsymbol{r} - \omega_r \times t)) \tag{2-5-2}$$
$$\boldsymbol{E}_t = \boldsymbol{E}_{0t} \times \exp(j(\boldsymbol{k}_t \cdot \boldsymbol{r} - \omega_t \times t)) \tag{2-5-3}$$

where E_i, E_r, and E_t are the incident, reflected and transmitted (refracted) waves respectively. Also, by definition, the magnitude of the wave propagation vector is given by $k = \omega/v$, and v is the velocity of light in that medium, given by $v = c/n$. The propagation wave vectors k for the three waves are defined in (2-5-4), (2-5-5), and (2-5-6).

$$k_i^2 = \left(\frac{\omega_i}{v_i}\right)^2 = \left(\frac{n_1 \times \omega_i}{c}\right)^2 \tag{2-5-4}$$
$$k_r^2 = \left(\frac{\omega_r}{v_1}\right)^2 = \left(\frac{n_1 \times \omega_r}{c}\right)^2 \tag{2-5-5}$$
$$k_t^2 = \left(\frac{\omega_t}{v_2}\right)^2 = \left(\frac{n_2 \times \omega_t}{c}\right)^2 \tag{2-5-6}$$

Similar equations can be written for the magnetic field in the light wave.

In (2-5-1), (2-5-2) and (2-5-3) the origin of the time, t, and the position, r, are arbitrary. For simplicity, the origin is taken to lie in the surface of separation. Hence, the position vector, r_3, of any point on the bounding surface will be on the surface of separation. According to the standard convention, the normal to the surface of separation $\hat{n}$ is taken to be out of medium 1 going into medium 2.

The total electric field at a given point in medium 1 is given by:

$$\boldsymbol{E}_1 = \boldsymbol{E}_i + \boldsymbol{E}_r \tag{2-5-7}$$

The electric field in medium 2 is only the transmitted field. This results in $E_2 = E_t$. Applying the boundary conditions for any point r_3 on the boundary results in:

$$[E_{0i} \exp(j\ (k_i\ .\ r_3 - \omega_i \times t)) + E_{0r} \exp(j\ (k_r\ .\ r_3 - \omega_r \times t))]_{tang.} = [E_{0t} \exp(j\ (k_t\ .\ r_3 - \omega_t \times t))]_{tang.} \tag{2-5-8}$$

Equation (2-5-8) is true for any time t at any arbitrary point r_3 on the boundary surface. To satisfy (2-5-8), we must have equal exponentials regardless of the relative values of the amplitude, E. Thus, we should have $\omega_i = \omega_r = \omega_t = \omega$, i.e., all three waves must have the same frequency. Introducing ω into (2-5-4), (2-5-5) and (2-5-6) results in:

$$k_i^2 = k_r^2 = \left(\frac{n_1 \times \omega}{c}\right)^2 = k_1^2 \tag{2-5-9}$$

$$k_t^2 = \left(\frac{n_2 \times \omega}{c}\right)^2 = k_2^2 \tag{2-5-10}$$

Similarly, to establish the equality in (2-5-8), the following relationships must be true.

$$\mathbf{k}_i \cdot \mathbf{r}_B = \mathbf{k}_r \cdot \mathbf{r}_B = \mathbf{k}_t \cdot \mathbf{r}_B \qquad (2\text{-}5\text{-}11(a))$$

or; $$(\mathbf{k}_i - \mathbf{k}_r) \cdot \mathbf{r}_B = 0 \qquad (2\text{-}5\text{-}11(b))$$

or; $$(\mathbf{k}_i - \mathbf{k}_t) \cdot \mathbf{r}_B = 0 \qquad (2\text{-}5\text{-}11(c))$$

or; $$(\mathbf{k}_r - \mathbf{k}_t) \cdot \mathbf{r}_B = 0 \qquad (2\text{-}5\text{-}11(d))$$

Equation (2-5-11(b)) relates the incident and the reflected wave vectors, so it is called the law of reflection. Similarly, (2-5-11(c)) relates the incident and refracted wave vectors, so it is called the law of refraction.

The plane of incidence is defined as the plane that has $\hat{n}$, the normal unit vector, and $\mathbf{k}_i$. Fig. 2-6 shows the plane of incidence and $\mathbf{k}_i$ for a wave. It also shows the angle of incidence, θ_i.

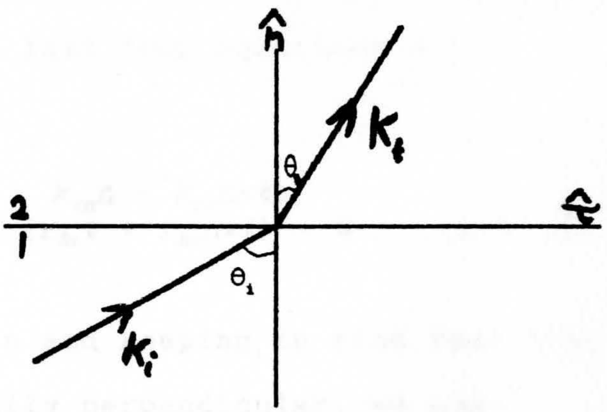

Fig. 2-6 The plane of incidence.

If $\mathbf{k}_i$ is resolved into its components normal and parallel to the surface of the interface by defining a unit tangential vector $\hat{t}$, which is parallel to the surface of interface and to the plane of incidence, then $\mathbf{k}_i$ can be written as:

$$\boldsymbol{k}_i = k_{in}\hat{n} + k_{i\tau}\hat{t} \tag{2-5-12}$$

To complete the three dimensional system, a third vector can be defined as $\hat{n}\times\hat{t}$, which is perpendicular to both $\hat{n}$ and $\hat{t}$. Using the coordinates $\hat{n}$, $\hat{t}$, and $\hat{n}\times\hat{t}$, the wave propagation vector k can be written as:

$$\boldsymbol{k}_r = k_{rn}\hat{n} + k_{r\tau}\hat{t} + k_{rc}\hat{n}\times\hat{t} \tag{2-5-13}$$
$$\boldsymbol{k}_t = k_{tn}\hat{n} + k_{t\tau}\hat{t} + k_{tc}\hat{n}\times\hat{t} \tag{2-5-14}$$

and

$$\boldsymbol{r}_B = r_{B\tau}\hat{t} + r_{Bc}\hat{n}\times\hat{t} \tag{2-5-15}$$

where r lies on the plane of interface so it has no normal component. Substituting the last four equations into (2-5-11(b)) gives:

$$(k_{in}\hat{n} + k_{i\tau}\hat{t} - k_{rn}\hat{n} - k_{rc}\hat{n}\times\hat{t}) \cdot (r_{B\tau}\hat{t} + r_{Bc}\hat{n}\times\hat{t}) = 0 \tag{2-5-16}$$

Simplifying the last equation and keeping in mind that the three unit vectors are mutually perpendicular, we get:

$$(k_{i\tau} - k_{r\tau}) \times r_{B\tau} - k_{rc} \times r_{Bc} = 0 \tag{2-5-17}$$
$$(k_{i\tau} - k_{t\tau}) \times r_{B\tau} + k_{tc} \times r_{Bc} = 0 \tag{2-5-18}$$

Since r_3 is an arbitrary vector in the surface of the boundary, (2-5-17) and (2-5-18) should be true for the special case $r_{3\tau} = 0$ while $r_{3c} \neq 0$. Introducing this in (2-5-17) and (2-5-18) gives:

$$k_{rc} = k_{tc} = 0 \tag{2-5-19}$$

This means that k_r and k_t have no components in the plane of $\hat{n}\times\hat{t}$, i.e., the three propagation vectors lie in the same plane, the plane of incidence. Since $r_{\beta\tau}$ can be different from zero while $r_{\beta c} = 0$, this and (2-5-17) and (2-5-18) give:

$$k_{r\tau} = k_{i\tau} \qquad (2\text{-}5\text{-}20)$$
$$k_{t\tau} = k_{i\tau} \qquad (2\text{-}5\text{-}21)$$

Equations (2-5-20) and (2-5-21) mean that all the three propagation vectors have the same tangential components.

After getting the relation between the tangential components of the E field, the relation between the normal components will be derived. It was found that $k_{rc} = k_{tc} = 0$; using this in (2-5-13) and (2-5-14) we get:

$$\boldsymbol{k}_r = k_{rn}\hat{n} + k_{r\tau}\hat{t} \qquad (2\text{-}5\text{-}22)$$

and

$$\boldsymbol{k}_t = k_{tn}\hat{n} + k_{t\tau}\hat{t} \qquad (2\text{-}5\text{-}23)$$

From (2-5-22), (2-5-9), (2-5-12) and the relation $k_{r\tau} = k_{i\tau}$ we get:

$$\begin{aligned} k_r^2 &= (k_{rn}\hat{n} + k_{r\tau}\hat{t})^2 = k_i^2 \\ k_r^2 &= k_{rn}^2 + k_{r\tau}^2 = k_i^2 \\ k_{rn}^2 &= k_r^2 - k_{r\tau}^2 = k_i^2 - k_{r\tau}^2 \\ k_{rn}^2 &= k_r^2 - k_{r\tau}^2 = k_i^2 - k_{r\tau}^2 = k_i^2 - k_{i\tau}^2 = k_{in}^2 \end{aligned} \qquad (2\text{-}5\text{-}24)$$

From (2-5-24) the relation between the normal components of the refracted and the incident fields can be written as $k_{rn} = \pm k_{in}$. If the plus sign is considered, this means that the incident and the refracted waves move in the same direction. This contradicts the experimental fact that both waves move in opposite directions. As a result, the minus sign should be used (i.e., $k_{rn} = -k_{in}$). Using (2-5-23) in (2-5-10), we get $k^2_{tn} = k^2_t - k^2_{t\tau} = k^2_2 - k^2_{i\tau}$, where k_2 is the same as k_t. The above results can be summarized in the following two formulas:

$$k_{rn} = -k_{in} \tag{2-5-25}$$
$$k_{tn}^2 = k_2^2 - k_{i\tau}^2 \tag{2-5-26}$$

From (2-5-9), it is obvious that the magnitude of the vector k_i is k_1. If the incident wave vector k_i is resolved into the tangential and the normal components, Fig. 2-6 gives:

$$k_{in} = k_1 \times \cos\theta_i \tag{2-5-27}$$
$$k_{i\tau} = k_1 \times \sin\theta_i \tag{2-5-28}$$

Equations (2-5-25) and (2-5-27) give (2-5-29) and (2-5-21), (2-5-20), and (2-5-28) give (2-5-30).

$$k_{rn} = -k_1 \times \cos\theta_i \tag{2-5-29}$$
$$k_{r\tau} = k_1 \times \sin\theta_i \tag{2-5-30}$$

Since k_r also has the magnitude k_1, we can define the angle of reflection θ_r as:

$$k_{rn} = -k_1 \times \cos\theta_r \qquad (2\text{-}5\text{-}31)$$
$$k_{r\tau} = k_1 \times \sin\theta_r \qquad (2\text{-}5\text{-}32)$$

By comparing the expressions of k_{rn} in (2-5-29) and (2-5-31), we conclude that $\theta_r = \theta_i$. This means that the angle of incidence equal to the angle of refraction (the well known law of optics) is a direct consequence of Maxwell's equations.

Considering the transmitted wave, (2-5-21) and (2-5-28) give (2-5-33), (2-5-25) and (2-5-28) give (2-5-34), finally (2-5-9), (2-5-10) and (2-5-34) give (2-5-35):

$$k_{t\tau} = k_1 \times \sin\theta_i \qquad (2\text{-}5\text{-}33)$$
$$k_{tn}^2 = k_2^2 - k_1^2 \times \sin^2\theta_i \qquad (2\text{-}5\text{-}34)$$
$$k_{tn}^2 = k_2^2 \times \left[1 - \left(\frac{n_1}{n_2}\right)^2 \times \sin^2\theta_i\right] \qquad (2\text{-}5\text{-}35)$$

If we define the angle of refraction θ_t for the vector k_t of magnitude k_2 by:

$$k_{t\tau} = k_2 \times \sin\theta_t \qquad (2\text{-}5\text{-}36)$$
$$k_{tn} = k_2 \times \cos\theta_t \qquad (2\text{-}5\text{-}37)$$

From (2-5-36) and (2-5-30), keeping in mind that $k_{t\tau} = k_{r\tau}$, we get:

$$k_2 \times \sin\theta_r = k_1 \times \sin\theta_i \qquad (2\text{-}5\text{-}38)$$

If we substitute the expressions for k_1 and k_2 from (2-5-9) and (2-5-10), we get:

$$n_1 \times \sin\theta_i = n_2 \times \sin\theta_t \qquad (2\text{-}5\text{-}39)$$

Equation (2-5-39) is the well known Snell's law of reflection, which is, as shown above, a direct consequence of Maxwell's equations.

2-6 FIBER OPTICS TYPES

After introducing the concept of total internal reflection, it is time to explain how it applies to fiber optics cable with their three main different types. As explained before, an optical fiber is a dielectric waveguide which operates at the optical frequency (10^{14}-10^{15} Hz). The transmission properties of an optical fiber is dictated by its structural properties. These properties establish the information-carrying capacity of the fiber. Although there are many different configurations that an optical fiber may take, the most widely accepted structure is a single solid dielectric cylinder of radius a and index of refraction n_1. This cylinder is called the core. The core is surrounded by the cladding, which is another dielectric with index of refraction $n_2<n_1$. Although in theory the cladding is not necessary for light to propagate along the core, it serves many purposes:

1. it reduces scattering loss resulting from the discontinuities of the core surface,
2. it adds mechanical strength to the cable,
3. it protects the core from absorbing surface contaminants which might come in contact with it.

The properties of the core divide fibers into two major groups, step index and graded index fiber. Also, step index fibers are divided to single mode and multimode step index fibers.

2-6-1 STEP INDEX FIBER

The optical fiber used in the previous sections to explain the main theory of total internal reflection is considered a step index fiber. This is because the refractive index profile for this type of fiber makes a step change at the core-cladding interface. The refractive index profile for a step index fiber may be defined as:

$$n(r) = \begin{cases} n_1 & r<a \\ n_2 & r\geq a \end{cases} \qquad (2\text{-}6\text{-}1)$$

Fig. 2-7 illustrates the major types of step index fiber. Fig. 2-7(a) shows a multimode step index fiber with a diameter of 50 μm or greater. The radius of a multimode fiber is larger than that of a single mode fiber. For

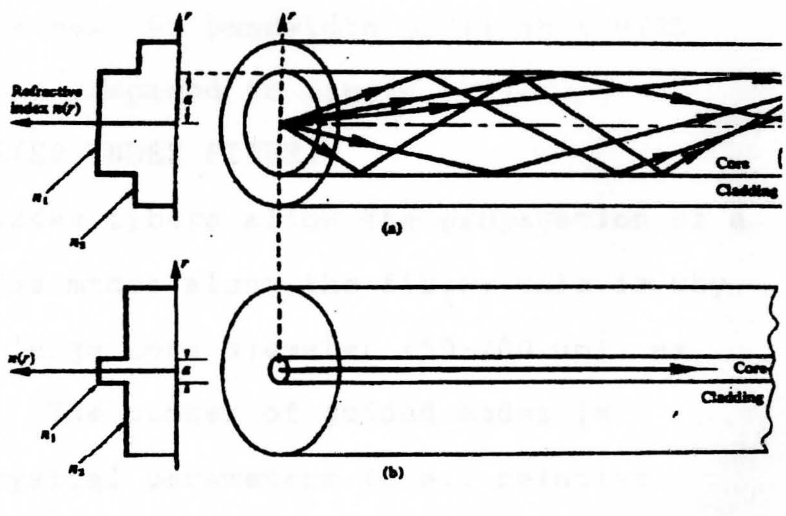

Fig. 2-7 The refractive index profile and ray transmission in step index fiber; (a) multimode step-index fiber; (b) single mode step-index.

this reason, a multimode fiber allows more than one mode to propagate through it. Fig. 2-7(b) shows a single mode or monomode step index fiber which allows the propagation of only one transverse electromagnetic mode and hence the core diameter must be small, of the order of 8-10 μm. The propagation of a single mode is usually shown by a single ray path only (usually shown as the axial ray) through the fiber.

The single mode step index fiber has the advantage of low intermodal dispersion (broadening of transmitted light pulses). This is because only one mode is transmitted through the fiber. In multimode step index fiber, a considerable dispersion may occur due to the fact that there are many modes propagating through the fiber. (This will be explained in Chapter 3.) Modal dispersion in multimode step index fiber limits the maximum bandwidth attainable with multimode step index as compared to single mode.

2-6-1(a) MULTIMODE STEP INDEX FIBER.

Multimode step index fibers allow the propagation of a finite number of guided modes along the fiber; this is why it has comparatively large core diameter (50-200 μm), as shown in Fig. 2-7(a). 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. These wavelengths are included in the normalized frequency V, where V is given by[6]:

$$V = \frac{2\pi}{\lambda} \times a \times (NA) \qquad (2\text{-}6\text{-}2)$$

where a is the core radius. The normalized frequency in (2-6-2) is a dimensionless number that determines the number of modes a multimode fiber can support and it is referred to as the V value. Although modes may propagate as unguided or leaky modes which can travel considerable distances along the fiber, it is the guided modes which are of paramount importance in optical fiber communications. This is because these modes are confined to the fiber over its full length. It is shown[6] that the total number of guided modes or the mode volume, M_s, for a step index fiber is related to the V value for the fiber by the approximate expression:

$$M_s \approx \frac{V^2}{2} \qquad (2\text{-}6\text{-}3)$$

which allows an estimate of the number of guided modes propagating along a step index fiber.

The optical power that is launched into a fiber optics cable will be distributed among the allowable modes in the core. Each of these modes will have a different spatial field distribution, propagation constant, etc. In an ideal multimode step index fiber with properties that are independent of the distance, there will be no mode coupling, and the optical power launched into a particular mode remains in that mode and travels independently of the power launched into other guided modes.

2-6-1(b) SINGLE MODE STEP INDEX FIBER

The core diameter in a single mode step index fiber is very small (8-10 μm) compared to that of a multimode fiber, as shown in Fig 2-7(b). Because of its small diameter size, only one mode can propagate along a single mode fiber; all other modes are attenuated by leakage or absorption. Single mode fibers do not suffer either mode coupling or modal dispersion; hence, there is only one mode in the core, and this is why single mode fibers have high band width.

2-6-2 GRADED INDEX FIBER

Graded index fibers do not have a constant refractive index in the core. They have 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. The refractive index for a graded index fiber can be expressed as:

$$n(r) = \begin{cases} n_1 \sqrt{\left(1 - 2\,\Delta \left(\frac{r}{a}\right)^{\alpha}\right)} & r<a \quad (core) \\ n_1 \sqrt{1 - 2\Delta} = n_2 & r \geq a \quad (cladding) \end{cases} \tag{2-6-4}$$

where Δ is the relative refractive index difference and α is the profile parameter. α gives the characteristic refractive index profile of the fiber core. Equation (2-6-4) is a convenient method of expressing the refractive index profile of the fiber core. Fig. 2-8 shows the refractive index profile as α varies. For α = 1 in (2-6-4), a triangular profile results, for $\alpha = 2$ a parabolic profile results. As α approaches ∞, the profile becomes more like a step index one as shown in Fig. 2-8.

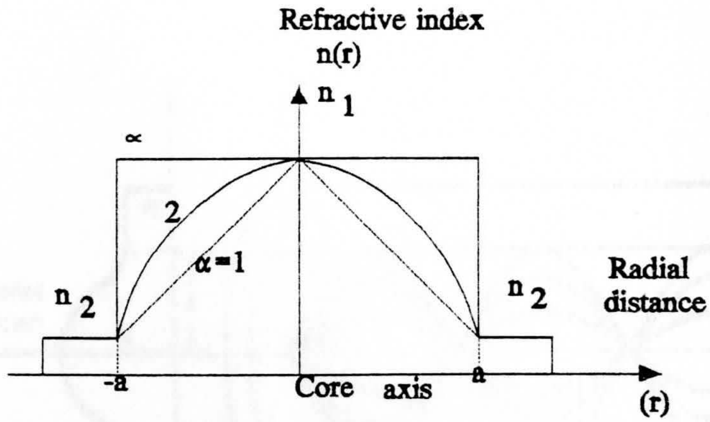

Fig. 2-8 Possible fiber refractive index profiles for different values of α.

A multimode graded index fiber with parabolic index profile core is shown in Fig. 2-9. It may be observed that the meridional rays shown appear to follow a curved path through the fiber core. Using the concepts of geometric optics, the gradual decrease in the refractive index from the center of the core creates many refractions of the rays as they transmit through the core.

This mechanism is illustrated in Fig. 2-9 where the ray is shown to be gradually curved. The angle of incidence on each layer will increase as the ray travels towards the cladding. Finally, the angle of incidence will reach the critical angle where total internal reflection occurs. The ray then travels back towards the axis, again being continuously refracted. Fig. 2-10 illustrates roughly the way in which a graded index fiber transmits light. In

Fig. 2-10, it is assumed that the graded index consists of a finite number of layers with different refractive indices, n_1, n_2, n_3,.. . Those indices decrease

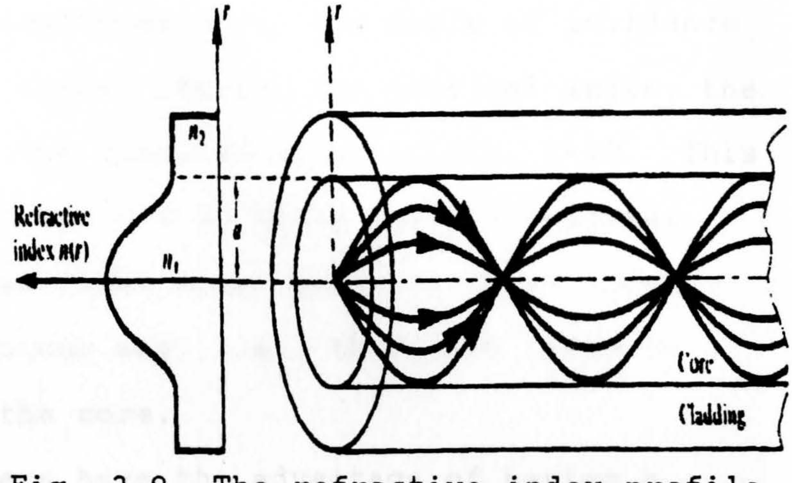

Fig. 2-9 The refractive index profile and ray transmission in a multimode graded index fiber.

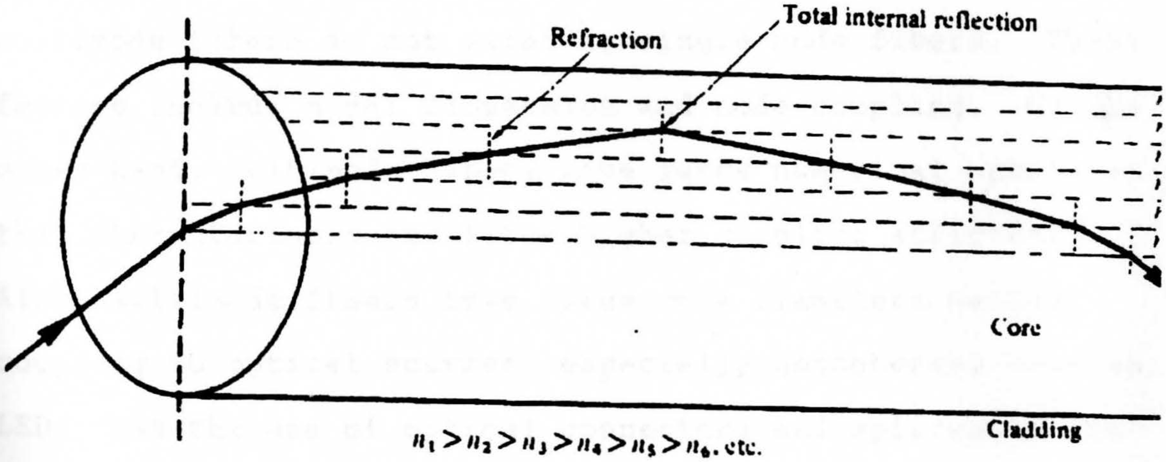

Fig. 2-10 An expanded diagram showing refraction at various high to low index interface within a graded index fiber.

as the distance from the cladding decreases. When a light ray reaches the interface between two layers, it refracts at the boundary and propagates through the second layer. Then the ray reaches the interface between the subsequent two layers, the angle of incidence at this interface will be greater than that at the first interface. The ray refracts again, this process continues until the angle of incidence reaches the critical angle. Beyond the critical angle, the ray reflects back in the core, as shown in Fig. 2-10. This process is similar to the one by which light propagates through a graded index fiber where the refractive index decreases in a continuous way, i.e., there are infinite number of layers in the core.

Single mode fibers have the advantage of having a relatively higher bandwidth compared to multimode fibers. Also, since only one mode propagates in a single mode fiber, many of the signal degradation factors that exist in multimode fibers do not exist in single mode fibers. These factors include modal dispersion and mode coupling. On the other hand, multimode fibers have large numerical apertures, that characteristic facilites higher coupling efficiency. Also, multimode fibers have large core diameters making coupling to optical sources, especially noncoherent sources, LEDs, and the use of optical connectors and splices, a lot easier. It will be shown in Section 3-5-2 that graded index fibers reduce signal dispersion in a multimode fiber which increases the fiber bandwidth significantly. The high bandwidth required nowadays in most of the optical communication links, especially the digital links, and the many advances in light sources manufacturing techniques make single mode fiber more attractive than multimode fiber links.

CHAPTER 3

TRANSMISSION CHARACTERISTICS OF OPTICAL FIBERS

In Chapter 2, the basic transmission mechanisms of the optical signal along fiber cable were discussed. In this chapter, the factors that affect the performance of optical fiber as a transmission medium will be discussed. The transmission characteristics of most interest for an optical communication link are those of attenuation (or loss) and bandwidth.

3-1 ATTENUATION

Attenuation or transmission loss of optical fibers is one of the most important factors which brought their wide acceptance in telecommunications. Channel attenuation determines the maximum transmission distance before signal restoration becomes necessary. Optical fiber communications became attractive when the transmission losses of fibers were reduced below those of the competing metallic conductors (less than 5dB km^{-1}).

Signal attenuation within optical fibers, as with metallic conductors, is usually expressed in the logarithmic unit of the decibel, which is defined as:

$$\textit{number of decibels (dB)} = 10 \log_{10}\left(\frac{P_i}{P_o}\right) \qquad (3\text{-}1\text{-}1)$$

In optical fiber communications, the attenuation is usually expressed in decibels per unit length (i.e., dB km^{-1}) following:

$$\alpha_{dB}L = 10 \log_{10}\left(\frac{P_i}{P_o}\right) \tag{3-1-2}$$

where α_{dB} is the signal attenuation per unit length in decibels and L is the fiber length.

A number of mechanisms are responsible for the signal attenuation within optical fibers. These mechanisms are results of the material composition, the preparation and purification techniques, and the waveguide structure. Attenuation may be categorized within several major areas which include material absorption, material scattering (linear and nonlinear), and curve and microbending losses due to leaky modes. Also, there are losses at connectors and splices which may be used along a fiber link.

3-1-1 MATERIAL ABSORPTION LOSSES

Material absorption is a loss mechanism related to material composition, and the fabrication process for the fiber. This results in some power dissipation as heat in the waveguide. Light absorption may be intrinsic (caused by the interaction with one or more of the major components of the fiber) or extrinsic (caused by impurities within the fiber).

3-1-2 INTRINSIC ABSORPTION

Although absolutely pure glass has little intrinsic absorption due to its basic material structure in the near infrared region, it has two major intrinsic absorptions at optical wavelength in the interval 0.8-1.7 μm. Also, "strong absorption bands occur due to oscillations of structural units such as Si-O (9.2 μm), P-O (8.1 μm), and Ge-O (11.0 μm) within the glass. Hence, above 1.5 μm absorption is largely infrared absorption which causes most of pure glass losses[8]".

3-1-3 EXTRINSIC ABSORPTION

Extrinsic absorption is a result of impurity in the fiber. These impurities are produced during the preparation of the fiber. A major source of signal attenuation is extrinsic absorption from transition metal elements impurities. As an example, it is found that chromium and copper in their worst valence state can cause attenuation in excess of 1 dB km^{-1} in the near infrared region. The modern techniques in preparing the fiber could reduce the impurity in

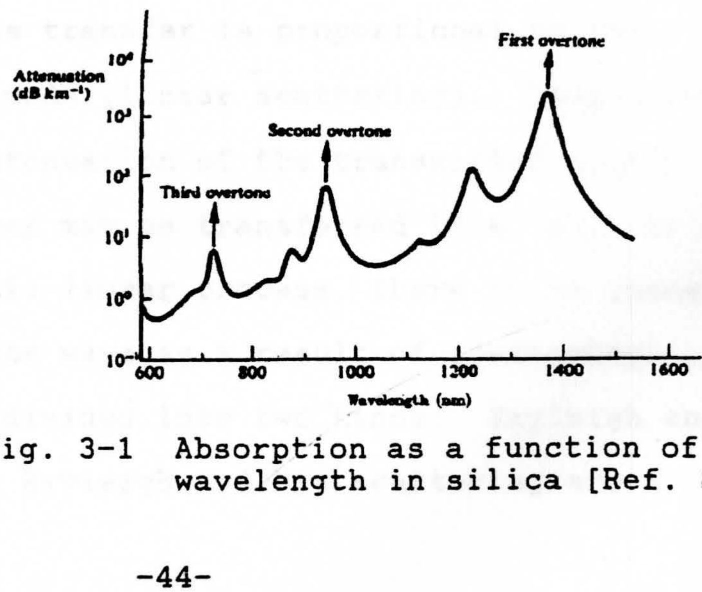

Fig. 3-1 Absorption as a function of wavelength in silica [Ref. 8].

the fiber to a very low level that makes extrinsic absorption negligible. However, another major extrinsic absorption mechanism is caused by absorption due to water (OH ions) dissolved in the glass. These hydroxyl groups are bonded into the glass structure and have fundamental stretching vibrations which occur at wavelengths between 2.7 and 4.2 μm depending on the group position in the glass network. The fundamental vibrations give rise to overtones appearing almost harmonically at 1.38, 0.95, and 0.72 μm as shown in Fig. 3-1. Furthermore, combinations between the overtones and the fundamental SiO_2 vibration occur at 1.24, 1.13, and 0.88 μm completing the absorption spectrum shown in Fig. 3-1. A detaled discussion about extrinsic absorption is found in Referrence 9 or in a good Solid State Physics book.

3-2 LINEAR SCATTERING LOSSES

Linear scattering mechanisms cause the transfer of some or all the optical power contained within one propagating mode to another. This transfer is proportional to the optical power of the mode (linear scattering). This process tends to result in attenuation of the transmitted light since the optical power may be transferred to a leaky or a radiated mode. In this linear process, there is no change in the frequency of the wave as a result of scattering. Linear scattering is divided into two kinds: Rayleigh and Mie scattering. Both Rayleigh and Mie scattering are a result of nonideal physical properties of the fiber which cannot be eliminated during the manufacture of the fiber.

3-2-1 RAYLEIGH SCATTERING

Rayleigh scattering results from inhomogeneities of random nature occurring on a small scale compared with the wavelength of the light. These inhomogeneities appear as fluctuations in the refractive index of the fiber that arise due to density and composition variations which are frozen into the glass lattice during the cooling process. These fluctuations can be reduced by improving the manufacturing techniques, but total elimination of these fluctuations cannot be achieved. It was found that Rayleigh scattering happens in all directions and is proportional to λ^{-4} and is given by[10]:

$$\alpha = \frac{8\pi^3}{4\lambda^4} n^8 p^2 k_B T_f \beta_f \qquad (3\text{-}2\text{-}1)$$

where α is Rayleigh scattering coefficient, λ is the optical wavelength, n is the core refractive index, p is the average photoelastic coefficient, β_f is the isothermal compressibility at a fictive temperature T_f, and k_B is Boltzmann's constant. The fictive temperature is defined as the temperature at which the glass can reach a state of thermal equilibrium. It is clear from (3-2-1) that Rayleigh scattering is strongly reduced by operating at the largest possible wavelength.

3-2-2 MIE SCATTERING

Mie scattering is only in the forward direction and is caused by inhomogeneities which are comparable in size to the guided wavelength. These inhomogeneities result from the nonperfect cylindrical structure of the waveguide caused by imperfections such as irregularities in the core-cladding interface, core-cladding refractive index difference along the fiber length, diameter fluctuations, and strains and bubbles in the core. Mie scattering can be reduced to an acceptable level by:

1. removing imperfections due to the glass manufacturing process,
2. carefully controlling extrusion and coating of the fiber,
3. increasing the fiber guidance by increasing the refractive index difference.

3-3 NONLINEAR SCATTERING LOSSES

In many cases, optical waveguides do not behave as completely linear channels. Several nonlinear effects occur, which in the case of scattering cause disproportionate attenuation. These cases usually occur at high optical power levels. This nonlinear scattering causes the optical power from one mode to transfer to another mode either in the forward or the backward direction at different frequency. Nonlinear scattering depends critically upon the optical power density within the fiber, and hence only becomes significant above certain threshold power levels.

The most important types of nonlinear scattering are stimulated Brillouin and Roman scattering. These scattering mechanisms give optical gain, but with a shift in frequency; thus, they contribute to attenuation for light transmission at a specific wavelength.

3-4 FIBER BEND LOSS

Optical fibers suffer radiation losses at bends or curves in their paths. The origin of those losses is the evanescent field at the bend. To explain this phenomenon consider the bent fiber shown in Fig. 3-2. For simplicity, a low order mode will be considered. Although most of the energy in the mode will propagate through the core, there will be a small part of the energy that propagates through the cladding. This part is shown as a small tail in the cladding. The amount of energy in the cladding decays exponentially as a function of the distance from the core when a fiber is bent. At a certain distance X_c from the

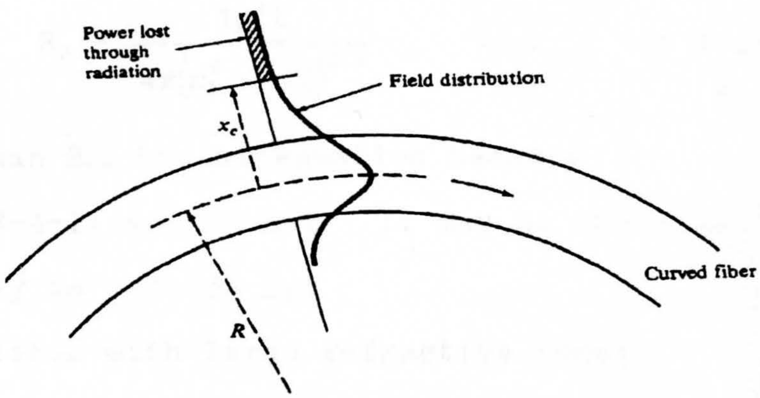

Fig. 3-2 Sketch of the fundamental mode in a curved optical fiber.

fiber axis, the field tail would have to move faster than the speed of light to keep up with the core field. Since this cannot happen, the energy of the field tail of distance greater than X_c from the center will be lost, and part of the mode radiates out of the fiber. The loss can generally be represented by a radiation attenuation coefficient given by[6]:

$$\alpha_T = c_1 \times \exp(-\ c_2 R) \tag{3-4-1}$$

where c_1 and c_2 are constants and R is the radius of curvature. It is found that bending losses increase as R decreases, the maximum loss occurs at the critical radius of curvature R_c. R_c is given by[6]:

$$R_c \approx \frac{3 n_1^2 \lambda}{4\pi\left(n_1^2\ -\ n_2^2\right)^{3/2}} \tag{3-4-2}$$

If R becomes less than R_c, the attenuation becomes noticeable. From (3-4-1) and (3-4-2), it may be observed that bending loss may be reduced by:

1. designing fiber with large refractive index difference,
2. operating at the shortest wavelength possible.

Another form of radiation loss in optical waveguide results from mode coupling caused by random microbends of the optical fiber. Microbends are small fluctuations in the radius of curvature of the fiber axis that may occur in the fiber manufacture and/or cabling process. These fluctuations cause some energy coupling between modes. Since energy may transfer to a leaky mode, loss will result as a direct consequence of microbends.

3-5 DISPERSION

As mentioned before, dispersion limits the bandwidth of the optical link. Dispersion causes distortion for both digital and analog transmission along the optical fiber, and also causes broadening of the transmitted light pulses as they travel along the channel.

Fig. 3-3 shows the effect of dispersion on the shape of an optical pulse. It may be observed that each pulse broadens and overlaps with its neighbors. As the length of the optical link increases, the broadening of each pulse increases; eventually the pulses overlap and become indistinguishable at the receiver input. Fig. 3-3(a) shows the input pulse of the digital signal 1011. After traveling distance L_1 along the fiber, the signal broadens. This is shown in

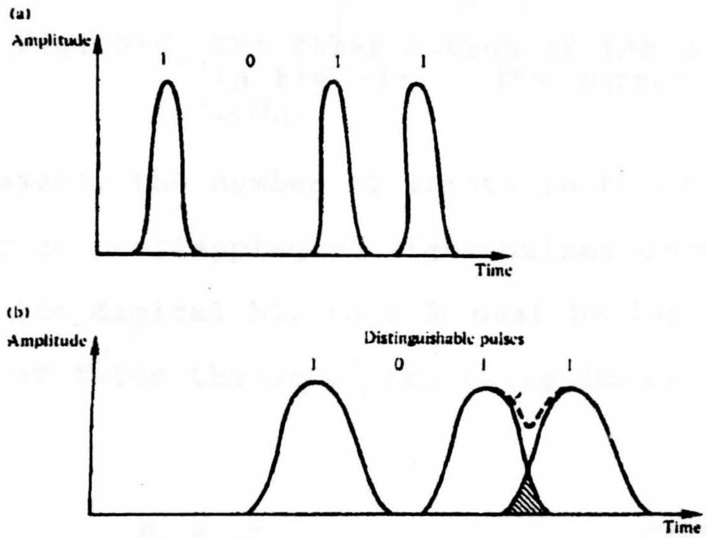

Fig. 3-3 An illustration of dispersion in the digital signal 1011; (a) fiber input; (b) fiber output.

Fig. 3-3(b). If the length of the link is increased to L_2, the signal broadening increases too, and the pulses become indistinguishable as shown in Fig. 3-4. These effects determine the maximum distance before a repeater is needed to reshape the signal while it is distinguishable.

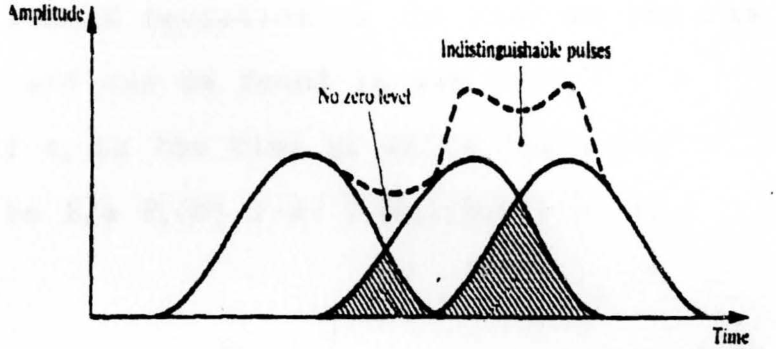

Fig. 3-4 The fiber output of the signal in Fig. 3-3. The output at $L_2 > L_1$.

As the overlap increases, the number of errors in the signal also increases. For no overlapping of light pulses down an optical fiber link, the digital bit rate B_T must be less than the reciprocal of twice the broadened pulse duration. Hence:

$$B_T \leq \frac{1}{2\tau} \tag{3-5-1}$$

where τ is the pulse broadening due to dispersion on the channel.

Another more accurate estimate of the maximum bit rate for an optical channel considering dispersion may be obtained by considering Gaussian shape output pulses with an rms width of σ. A Gaussian distribution output power with time may be described as:

$$P_o(t) = \frac{1}{\sqrt{2\pi}} \exp\left(-\left(\frac{t^2}{2\sigma^2}\right)\right) \tag{3-5-2}$$

where σ and σ^2 are the standard deviation and the variance of the distribution respectively. For the Gaussian distribution, the standard deviation is the same as the rms value of the signal, and can be found in any good statistical book. If t_e is the time at which the pulse width becomes equal to $1/e\ P_0(0)$ i.e. $P_0(t_e)/P_0(0) = 1/e$, then (3-5-2) gives:

$$t_e = \sqrt{2}\ \sigma \tag{3-5-3}$$

If the full width of the pulse at 1/e point is denoted by τ_e, then:

$$\tau_e = 2t_e = 2\sqrt{2}\ \sigma \tag{3-5-4}$$

Taking the Fourier transform of (3-5-2) gives:

$$P(w) = \frac{1}{2\sqrt{\pi}} \exp\left(-\left(\frac{\omega^2\sigma^2}{2}\right)\right) \tag{3-5-5}$$

The 3 dB optical bandwidth is defined as the modulation frequency at which the received optical power has fallen to one-half of its input at t = 0 value, $1/(2\pi)^{½}$. Using (3-5-5), it gives:

$$\frac{1}{2\sqrt{(2\pi)}} = \frac{1}{\sqrt{2\pi}} \exp\left[\frac{[-(-\omega\,(3dB\ opt)]^2}{2} \times \sigma^2\right]$$

$$.693 = \frac{[\omega\,(3dB\ opt)]^2}{2} \times \sigma^2 \tag{3-5-6}$$

It is given that:

$$\omega(3\ dB\ opt) = 2\pi\ B_{opt} = \frac{0.8326\ \sqrt{2}}{\sigma} \qquad (3\text{-}5\text{-}7)$$

From the above equations B_{opt} is given by:

$$B_{opt} = \frac{0.8326\sqrt{2}}{2\pi\sigma} = \frac{0.530}{\tau_e} = \frac{0.187}{\sigma} \qquad (3\text{-}5\text{-}8)$$

When employing the return to zero pulse (will be explained later) where the maximum bite rate $B_T(\max) = B_{opt}$, then:

$$B_T(\max) \simeq \frac{0.2}{\sigma} \qquad bits/sec \qquad (3\text{-}5\text{-}9)$$

Equation (3-5-9) gives a reasonably good approximation for the maximum bit rate that can be achieved considering a Gaussian distribution.

The conversion of bit rate to bandwidth in Hertz depends on the digital coding format used (it will be discussed later).

The number of optical signal pulses which may be transmitted through a fiber optics link in a given period of time, and, therefore, the link information carrying capacity is restricted by the amount of pulse dispersion per unit length. In an ideal optical link (no mode coupling or filtering), the pulse dispersion increases with the link length. In general, dispersion is divided into two kinds:

1. intramodal dispersion,
2. intermodal dispersion.

3-5-1 INTRAMODAL DISPERSION

Intramodal or chromatic dispersion is a direct result of the fact that a light pulse has a finite spectral linewidth. Since an optical source does not emit just a single frequency but a band of frequencies, then there will be propagation delay differences between the different components of the transmitted signal. In the case of an injection laser source, the spectral width is very narrow as compared to an LED. Hence, intramodal dispersion in systems with laser sources is less than those with LED source. The delay differences may be caused by the dispersive properties of the waveguide material, $n(\omega)$, or by waveguide effects within the fiber structure, material dispersion and waveguide dispersion respectively.

3-5-1(a) MATERIAL DISPERSION

Material dispersion occurs when the phase velocity of a plane wave propagating in the dielectric medium varies with wavelength. This is a direct result of the fact that the materials which form ordinary fibers are dispersive in nature, i.e., their refractive indices vary as a function of the wavelength. It will be shown at the end of this section that a material is said to exhibit material dispersion when the second differential of the refractive index with respect to wavelength is not zero (i.e., $d^2n/d\lambda^2 \neq 0$). The pulse spread due to material dispersion is given by considering the group velocity V_g, which is defined as:

$$V_g = \frac{d\omega}{d\beta}$$

$$= \frac{d\lambda}{d\beta} \cdot \frac{d\omega}{d\lambda} = \left[\frac{d}{d\lambda}\left(n_1 \frac{2\pi}{\lambda}\right)\right]^{-1}\left(\frac{-\omega}{\lambda}\right)$$

$$= \frac{-\omega}{2\pi\lambda}\left(\frac{1}{\lambda}\frac{dn_1}{d\lambda} - \frac{n_1}{\lambda^2}\right)^{-1}$$

$$= \frac{c}{\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right)} \qquad (3\text{-}5\text{-}10)$$

group delay τ_g, which gives the pulse spread due to material dispersion. Hence, from (3-5-10), τ_g is given by:

$$\tau_g = \frac{1}{V_g} = \frac{1}{c}\left(n_1 - \lambda \frac{dn_1}{d\lambda}\right) \qquad (3\text{-}5\text{-}11)$$

where n_1 is the refractive index of the core material. The pulse delay, τ_m, due to material dispersion in a fiber of length L, is therefore given by:

$$\tau_m = \frac{L}{c}\left(n_1 - \lambda \frac{dn}{d\lambda}\right) \qquad (3\text{-}5\text{-}12)$$

The pulse broadening due to material dispersion, σ_m, for a source with rms spectral width, σ_λ and average wavelength λ, can be obtained as follows. Consider σ_m which may be written in the form shown in (3-5-13).

$$\sigma_m = \sigma_\lambda \frac{d\tau_m}{d\lambda} + \sigma_\lambda \frac{d^2\tau_m}{d\lambda^2} + \ldots\ldots \qquad (3\text{-}5\text{-}13)$$

As the first term in (3-5-13) usually dominates, especially for sources operating over 0.8-0.9 μm wavelength range[6], this gives:

$$\sigma_m \approx \sigma_\lambda \frac{d\tau_m}{d\lambda} \tag{3-5-14}$$

Hence, the pulse spread may be evaluated by considering the dependence of τ_1 on λ, from (3-5-12) we get:

$$\begin{aligned} \frac{d\tau_m}{d\lambda} &= \frac{L}{c}\left(\frac{dn_1}{d\lambda} - \frac{dn_1}{d\lambda} - \lambda\frac{d^2n_1}{d\lambda^2}\right) \\ &= -\frac{L\lambda}{c}\frac{d^2n_1}{d\lambda^2} \end{aligned} \tag{3-5-15}$$

From (3-5-14) and (3-5-15), the rms pulse broadening due to material dispersion is given by:

$$\sigma_m \approx \frac{\sigma_\lambda L}{c}\left|\lambda\frac{d^2n_1}{d\lambda^2}\right| = D_{mat}(\lambda)L\sigma_\lambda \tag{3-5-16}$$

where $D_{mat}(\lambda)$ is the material dispersion. Material dispersion for optical fibers is sometimes quoted as a value for $\left|\lambda^2(d^2n_1/d\lambda^2)\right|$ or simply $\left|d^2n_1/d\lambda^2\right|$. This means that if $d^2n_1/d\lambda^2 = 0$ for a material, it will suffer no material dispersion.

At the same time, material dispersion may be given in terms of the material dispersion parameter, M, which is defined as:

$$M = \frac{1}{L}\frac{d\tau_m}{d\lambda} = \frac{\lambda}{c}\left|\frac{d^2n_1}{d\lambda^2}\right| \tag{3-5-17}$$

which is often expressed in units of ps nm^{-1} km^{-1}. Material dispersion can be reduced by using sources with smaller bandwidth i.e., coherent emitters.

3-5-1(b) WAVEGUIDE DISPERSION

Waveguide dispersion results from the fact that the group velocity of a wave varies with the wavelength for a particular mode. Considering ray theory approach, it is equivalent to the angle between the ray and the fiber axis varying with the wavelength, and this leads to a variation in the transmission time delay for the rays. This delay produces pulse dispersion for the light pulse.

3-5-2 INTERMODAL DISPERSION

Pulse broadening due to intermodal dispersion (modal or mode dispersion) results from the propagation delay differences between modes within a multimode fiber. Higher order modes travel more distance than lower order modes as they propagate along a fiber. As a result of this path difference, lower order modes reach the fiber end before higher order modes which causes pulse broadening. Single mode fiber does not suffer modal dispersion since it only supports one mode. To reduce the effect of modal dispersion, graded index fiber is used. In graded index fiber, higher order modes travel faster than lower order modes. At the same, higher order modes travel longer distance in the core than lower order modes. This causes both kinds modes to reach the fiber end at the same time so reducing modal dispersion.

CHAPTER 4

PHOTOEMITTERS AND PHOTODETECTORS

Photoemitters and photodetectors are devices designed to generate and detect light, respectively. In theory, light emitters and light detectors utilize light in exactly the reverse manner from one another.

Light emitters, or sources, convert electrical energy or heat to light and can be either coherent or incoherent. Coherent light sources, such as a gas laser, radiate optical energy over a very narrow band. On the other hand, incoherent sources, such as light emitting diodes (LED) and incandescent lights, radiate optical energy over a broad range of wavelengths. "The photoemission process (luminescence) can be classified, according to the nature by which it occurs, into three types: photoluminescence, cathodoluminescence, and electroluminescence[11]". In the case of LEDs, electroluminescence plays the most effective role in the emission of light.

A photodetector, or light sensor, converts optical energy to an equivalent response that is easily measurable. A typical light detector used in an optical communication system converts the incoming light energy to an equivalent electrical response. Light sensors are divided into two types: thermal and quantum sensors. Thermal sensors are those in which the absorbed light is converted to heat.

This produces a detectable change in the device temperature. Meanwhile, quantum sensors are those in which the absorbed light generates free carriers. Those free carriers can easily be detected and measured. Quantum sensors are the kind used in optical communication, and they are called photovoltaic detectors.

4-1 LIGHT EMITTING DIODE (LED)

The principal light source used for an optical fiber communication system is the light emitting diode. An LED is basically a heterostructure p-n junction. A p-n junction is two adjoining semiconductor materials with different band-gap energies. A perfect semiconductor material with no impurity is called intrinsic semiconductor. The band structure is shown in Fig. 4-1.

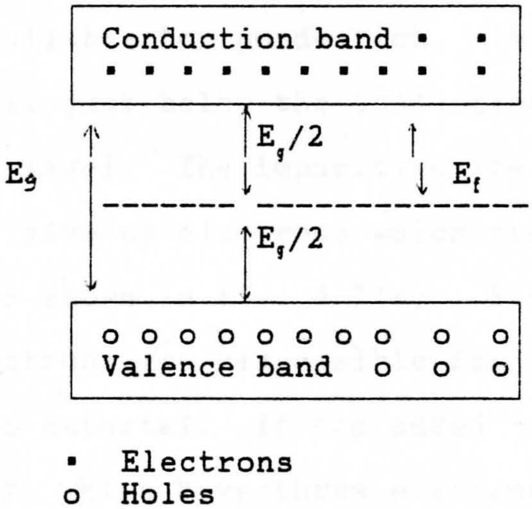

Fig. 4-1 The band structure of a perfect semiconductor.

In Fig. 4-1, the two energy bands are separated by a forbidden gap or a band-gap, E_g. The width of the forbidden gap varies for different semiconductor materials. Figure 4-1 shows the situation in a semiconductor at a temperature above absolute zero. Thermal excitation raises some electrons from the valence band to the conduction band leaving empty holes in the valence band. These thermally excited electrons in the conduction band and the holes in the valence band allow conduction through the material.

Conduction can be greatly increased by adding impurities from group V elements through a process called doping. The semiconductor after doping is called extrinsic semiconductor. Elements of the V column of the periodic table have five electrons in the outer shell. Four of these five electrons are used in four covalent bonds with the four electrons of the semiconductor; the fifth electron remains loose and available for conduction. This gives rise to an occupied level just below the conduction band which is called donor level. The impurities are called donors because they give up electrons which are responsible for conduction as shown in Fig. 4-2(a). Since in this type of material electrons are responsible for conduction, it is called n-type material. If the added impurities were from the III group, which have three electrons in their outer shell, the three electrons make covalent bonds with the semiconductor and a hole is created. This raises the unoccupied level of the valence band to the acceptor level as shown in Fig. 4-2(b). This free hole is responsible for conduction and the material is called a p-type semiconductor. If a n-type material and a p-type material

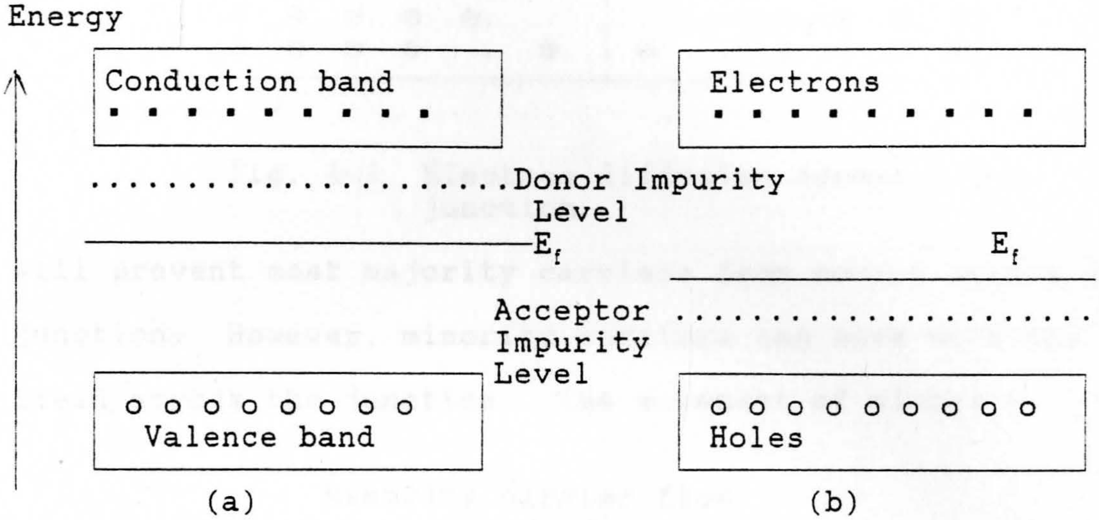

Fig. 4-2 Energy band diagram: (a) n-type; (b) p-type.

were used to make a single crystal, the junction between them is called a p-n junction. When a p-n junction is created, the majority carriers diffuse across it, which causes the electrons to fill holes in the p side of the junction. As a result of this diffusion, an electric field appears across the junction. This field opposes further movement of the carriers. The junction area will be free of any mobile carriers, and this region is called the depletion region, shown in Fig. 4-3.

When p-n junction is in the reverse-bias condition, the width of the depletion region will increase as shown in Fig. 4-4. The increase of the width of the depletion region

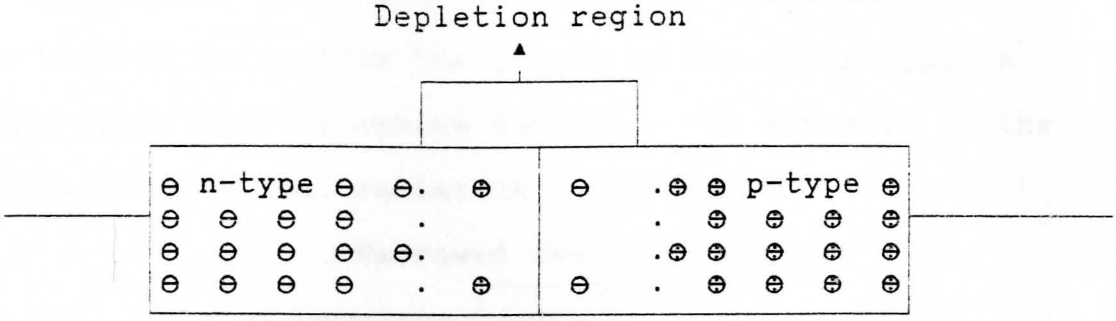

Fig. 4-3 Electron diffusion across a p-n junction.

will prevent most majority carriers from moving across the junction. However, minority carriers can move with the field across the junction. The movement of minority

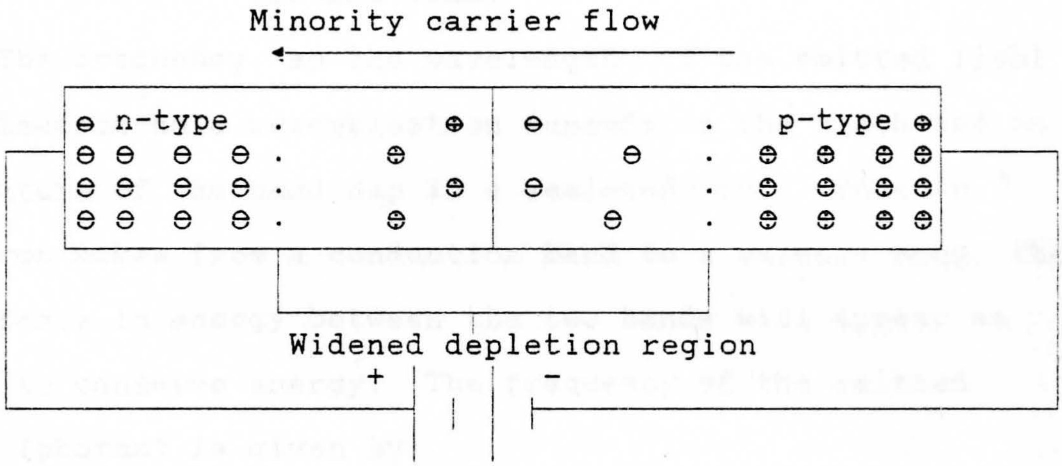

Fig. 4-4. A reverse bias widens the depletion region.

carriers is small and negligible in normal conditions, but it increases and becomes more significant when excess carriers are created, as in an illuminated photodiode.

If the junction is in the forward bias condition, the width of the depletion region decreases as shown in Fig. 4-5. In the forward-bias case, the depletion region width is reduced, and the movement of the electrons from the n-type and the holes from the p-type to the other type is possible where they recombine together. As a result of the recombination, optical radiation is generated.

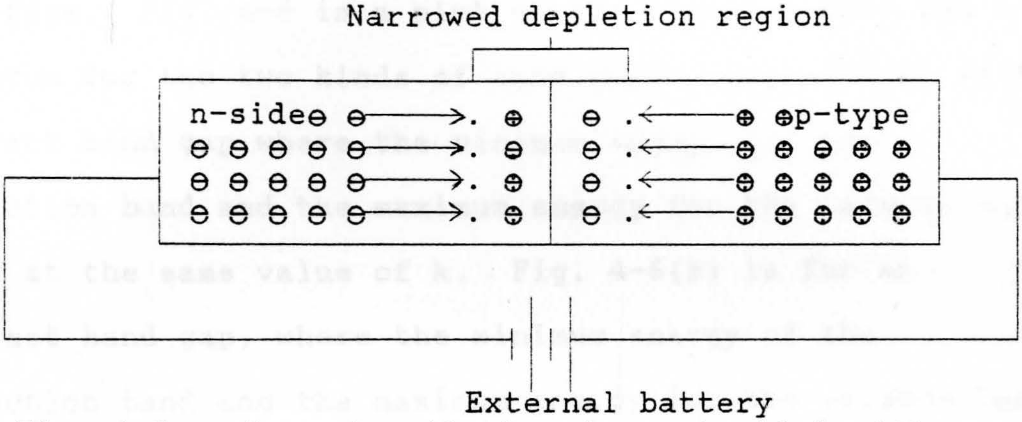

Fig. 4-5. Lowering the barrier potential with a forward bias.

The frequency, so the wavelength, of the emitted light due electron-hole recombination depends on the width and on the nature of the band gap in a semiconductor. When an electron moves from a conduction band to a valence band, the difference in energy between the two bands will appear as light to conserve energy. The frequency of the emitted light (photon) is given by:

$$\nu = \frac{E_g}{h} \qquad (4\text{-}1\text{-}1)$$

Electron-hole recombination may be radiative or irradiative. To conserve energy in a radiative recombination, a photon with energy equal to E_g will result. On the other hand, conservation of energy for an irradiative recombination is achieved by the emission of a phonon. This phonon will dissipate as heat. The product of an electron-hole recombination depends on the characteristics of the energy gap in the semiconductor. In semiconductors, there are two different kinds of energy gaps: direct and indirect band gaps. Fig. 4-6 is a plot of the energy versus the momentum for the two kinds of band gaps. Fig. 4-6(a) is for a direct band gap where the minimum energy for the conduction band and the maximum energy for the valance band occur at the same value of k. Fig. 4-6(b) is for an indirect band gap, where the minimum energy of the conduction band and the maximum energy for the valence band occur at different value of k. In the first case, an electron-hole recombination occurs, and only a photon is required to establish energy conservation. On the other hand, a phonon is required to establish energy conservation in the second case.

For an efficient LED, a direct band semiconductor is preferred, where the emitted photon will have enough energy for transmission. Also, because there is no phonon emission, the source temperature will stay almost fixed.

4-2 LED STRUCTURES

There are four major types of LED structures: surface emitters or Burrus LEDs, edge emitters, planar, and dome LEDs. While the first two structures are used exclusively in fiber optics communication, the other structures find more application as cheap plastic encapsulated visible

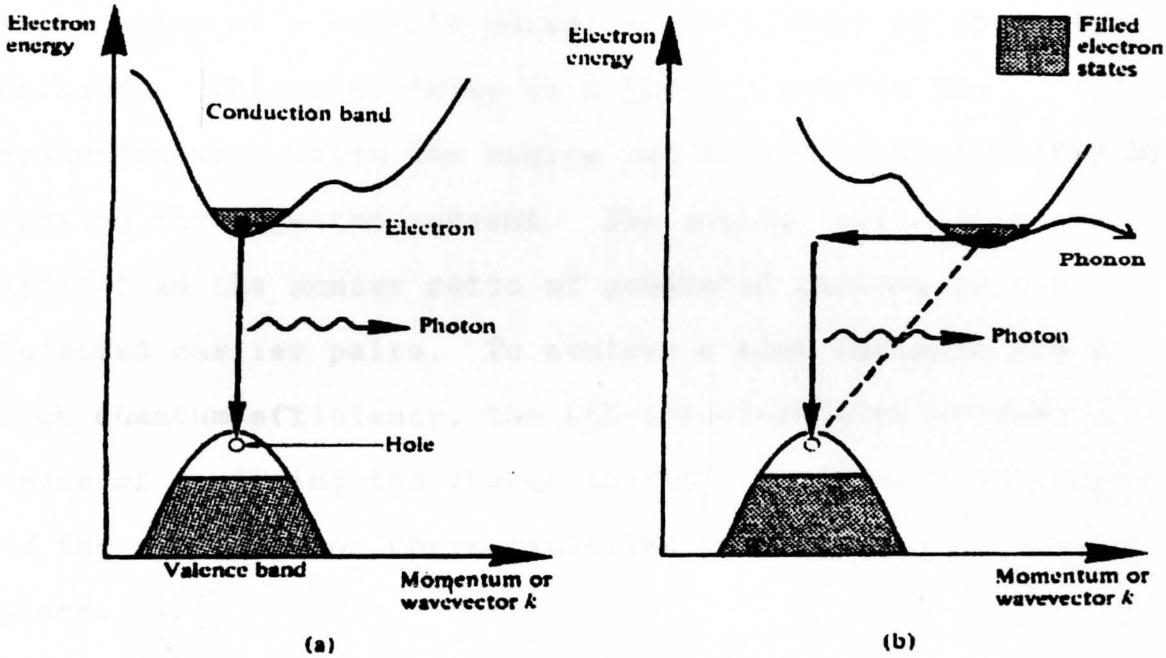

Fig. 4-6 Energy-momentum diagrams showing the types of transition: (a) direct bandgap; (b) indirect bandgap semiconductor [Ref. 11].

devices for use in other areas, such as, TV channel changers and industrial counting. For optical communication systems requiring bit rates less than approximately 100 to 200 Mb/s with multimode fiber-coupled optical power in tens of microwatts, LEDs are usually the best light source choice. To be useful in fiber transmission applications, an LED must have a high radiance output, a fast emission response time, and a high quantum efficiency. An LED radiance or brightness is a measure in watts of the optical power radiated into a unit solid angle per unit area of the emitting surface. High radiance is necessary to couple sufficiently high optical power levels into a fiber. The emission response time is the time delay between the application of a current pulse, and the onset of optical emission. This time delay is a factor limiting the bandwidth with which the source can be modulated directly by varying the injected current. The quantum efficiency is defined as the number ratio of generated photons to the injected carrier pairs. To achieve a high radiance and a high quantum efficiency, the LED structure must provide a means of confining the charge carriers to the active region of the p-n junction where radiative recombinations take place.

4-2-1 SURFACE EMITTER LED

A surface emitter LED obtains high radiance by restricting the emission to a small active region within the device. In the surface emitter LED, the plane of the active light-emitting region is oriented perpendicularly to the axis of the fiber, as shown in Fig. 4-7.

In this structure, a well is attached through the substrate of the device, to which a fiber is centered in order to accept the emitted light. This method prevents heavy absorption of the emitted radiation and physically accommodates the fiber. "The circular active area in practical surface emitters is normally 50 μm in diameter and up to 2.5 μm thick. The emission pattern is essentially

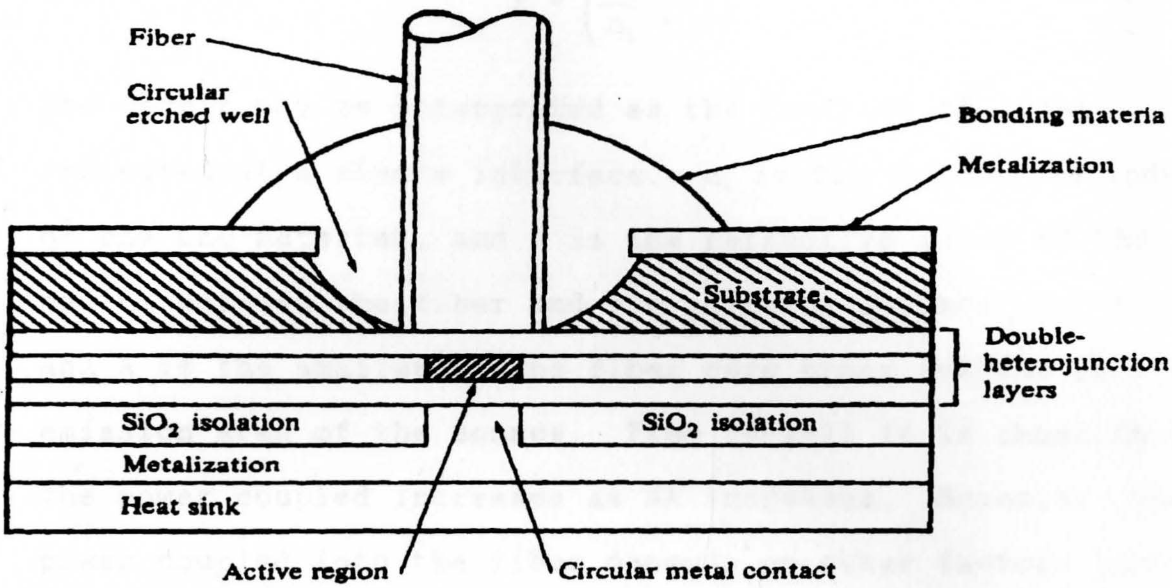

Fig. 4-7 Schematic (not to scale) of high-radiance surface-emitting LED. The active region is limited to a circular section having an area compatible with the fiber-core end face [Ref. 7].

isotropic with a 120° half-power beam width[10]". This pattern is called a Lambertain pattern, where the source is equally bright when viewed from any direction. Moreover, the source power diminishes as cos θ, where θ is the angle between the viewing direction and the normal to the surface. Hence, the power is down 50% of its peak when θ = 60° giving total half-power beam width of 120°.

The power coupled P_c into a step index fiber is given by the relation:

$$P_c = \pi(1-r) \times A \times R_D \times (NA)^2 \qquad (4\text{-}2\text{-}1)$$

where r is the Fresnel reflection coefficient given by:

$$r = \left(\frac{n_1 - n}{n_1 + n}\right)^2 \qquad (4\text{-}2\text{-}2)$$

The term r may be interpreted as the fraction of light reflected at a single interface. n_1 is the refractive index of the LED material, and n is the refractive index of the medium between the fiber and the emitting surface i.e. air, and A is the smaller of the fiber core cross section or the emission area of the source. From (4-2-1) it is shown that the power coupled increases as NA increases. Moreover, the power coupled into the fiber depends on other factors such as the distance, and the alignment between the emission area and the fiber, and the LED emission pattern. The dependence of the coupled power to a fiber on the emission patter makes the radiance of an LED an important factor.

4-3 OPTICAL DETECTORS

The detector is an essential component of an optical fiber link. Its function is to convert the changes in the received optical signal to corresponding changes in an electrical signal. Since the optical power that reaches the photodetector is usually weak and distorted with a relatively high noise level, the photodetector should have very high performance requirements. These requirements are:

1. high response or sensitivity in the operating wavelength range,
2. minimum addition of noise to the system,

3. fast response to handle the desired data rate,
4. to be insensitive to variations in temperature,
5. to be compatible with the physical dimensions of the fiber,
6. to have a reasonable cost in relation to the other components of the system,
7. to have a relatively long operating life.

As mentioned earlier, a photodetector utilizes light on a reverse way from the way an LED does. According to their structures, photodetectors are divided into many types. These types are: PN photodetector, PIN photodetector, avalanche photodetector, and photomultiplers. PIN and avalanche photodetectors are used most in fiber optics communication systems.

4-4 PHYSICAL PRINCIPLES OF PHOTODETECTORS

4-4-1 PN PHOTODETECTOR

A PN photodetector (photodiode) is simply a p-n junction in the reverse bias condition, as shown in Fig. 4-8. Fig. 4-8 shows the depletion, the diffusion, and the absorption regions in a typical PN photodiode. The width of the depletion region depends upon doping concentrations for a given applied reverse bias. The lower the doping, the wider the depletion region.

Photons incident on the PN photodiode may be absorbed in both the depletion and the diffusion regions. The position and the width of the absorption region depends upon

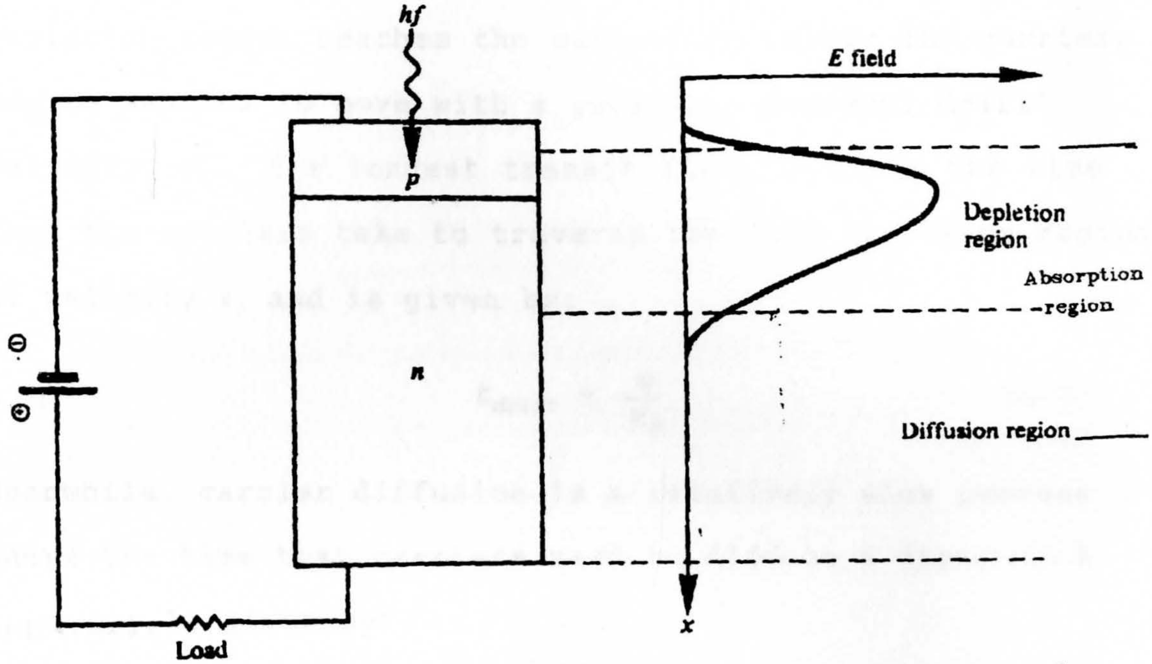

Fig. 4-8 PN photodiode shwoing depletion, diffusion, and absorption regions [Ref. 7].

both the energy of the incident photons and the material from which the photodiode is made. This region may extend completely throughout the device in the case of weak absorption of photons. As a result, the electron-hole pairs are generated in both the depletion and the diffusion regions. In the depletion region, the carrier pairs separate and drift under the influence of the electric field. On the other hand, outside the depletion region the holes diffuse towards the depletion region in order to be collected. The diffusion process is very slow compared to the drift process, so diffusion limits the response of the photodiode. The speed of response of a photodiode is limited by the time it takes photogenerated carriers to drift across the depletion region. When the field in the depletion region reaches the saturation value, the carriers may be assumed to move with a constant (maximum) drift velocity, v_d. The longest transit time, t_{drift}, is the time that the carriers take to traverse the full depletion region at velocity v_d and is given by:

$$t_{drift} = \frac{W}{V_d} \qquad (4-4-1)$$

Meanwhile, carrier diffusion is a relatively slow process where the time that carriers need to diffuse a distance d, t_{diff}, may be given by[11]:

$$t_{diff} = \frac{d^2}{2D_c} \qquad (4-4-2)$$

where D_c is the minority carrier diffusion coefficient.

To see how t_{drift} compares to t_{diff}, it is found[6] that a field strength above $2x10^4$ V cm^{-1} in silicon gives maximum (saturated) carrier velocity of approximately 10^7 cm s^{-1}. This gives a transit time through a depletion layer of width 10 mm of around 0.1 ns. On the other hand, hole diffusion time over a similar distance of the same layer is around 40 ns, and electron diffusion time is around 8 ns. It is noticed that the drift process of the carriers is much faster than their diffusion. As a result, it is important that the photons are absorbed in the depletion region. This is why the depletion region is made as long as possible by

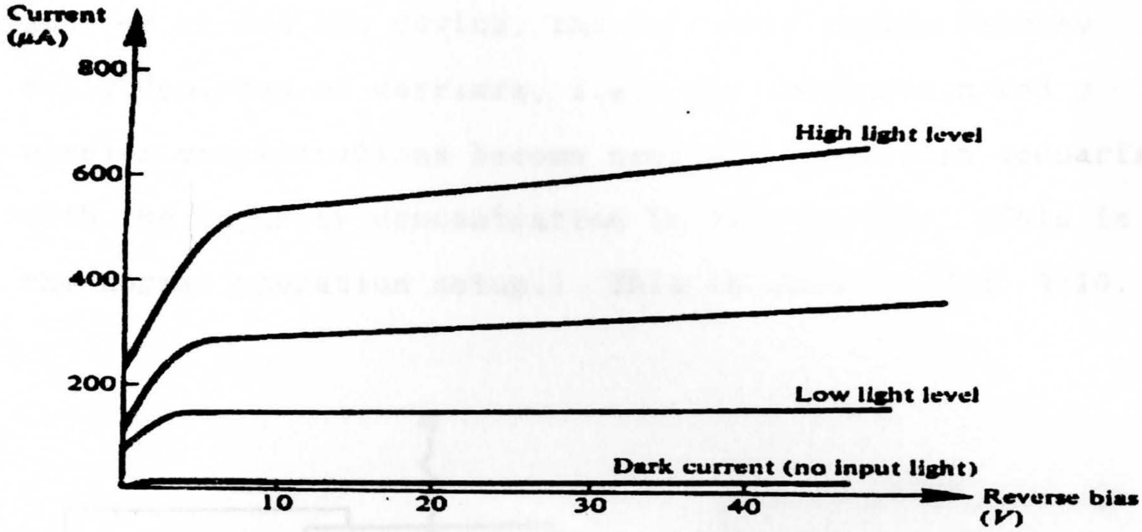

Fig. 4-9 Typical PN photodiode output characteristics [Ref. 6].

decreasing the doping in the n type material.

Typical output characteristics for a reverse-biased PN photodiode are shown in Fig. 4-9. The different operating conditions may be noted moving from no light input to a high light level.

4-4-2 PIN PHOTODETECTOR

Light with long wavelengths penetrates more deeply into the semiconductor material. In this case, a wider depletion region is necessary for light to be effectively absorbed in the photodiode. To achieve this, the n-type material is doped so lightly that it may be considered intrinsic. This structure is known as P-I-N (or PIN) structure. In a PIN photodiode, photon absorption takes place in the depletion region. Because of its performance, the most common semiconductor photodetector is the pin photodiode.

If a sufficiently large reverse-bias voltage is applied across the device, the intrinsic region becomes fully depleted of carriers, i.e., the intrinsic n and p carrier concentrations become negligibly small in comparison with the impurity concentration in that region. (This is the normal operation setup.) This is shown in Fig. 4-10.

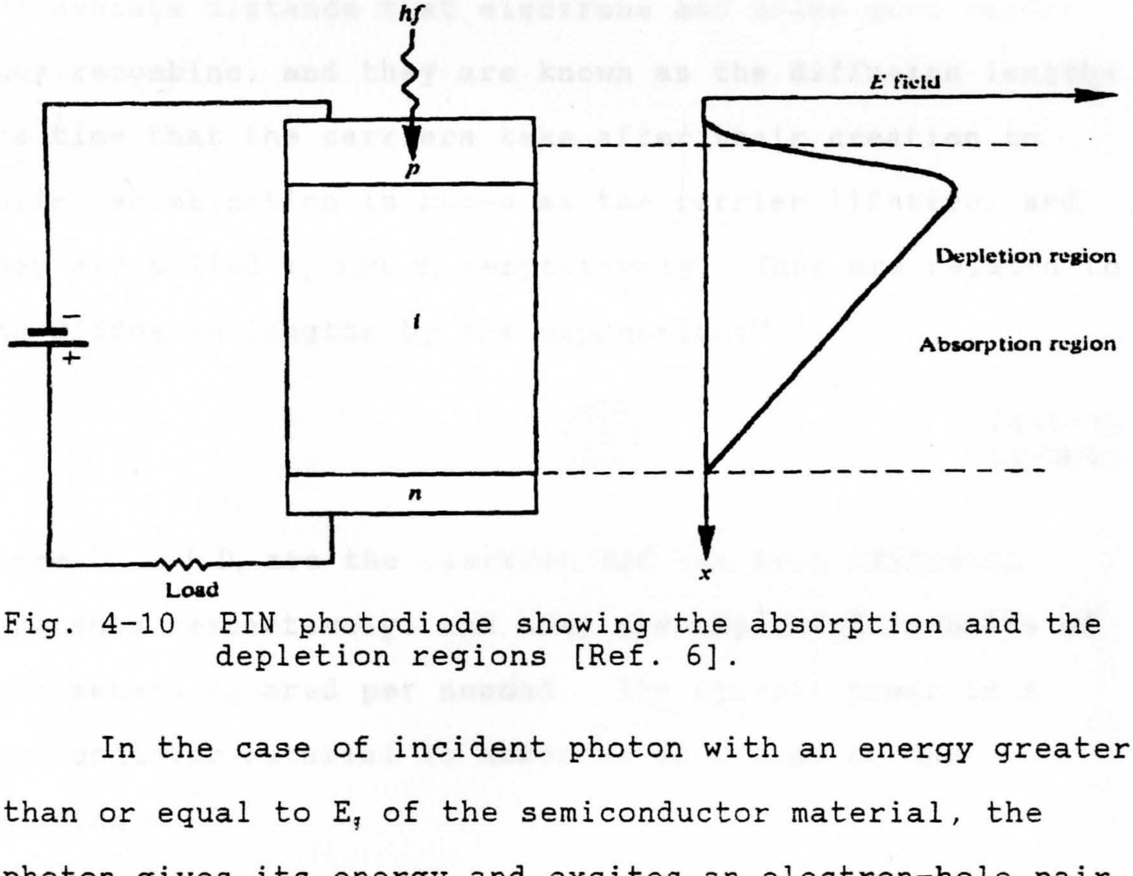

Fig. 4-10 PIN photodiode showing the absorption and the depletion regions [Ref. 6].

In the case of incident photon with an energy greater than or equal to E_g of the semiconductor material, the photon gives its energy and excites an electron-hole pair. This electron-hole pair are known as photocarriers because they carry the charge through the circuit. The photodetector is normally designed so that photocarriers are generated mainly in the depletion region where most of the incident light is absorbed. The electric field present in the depletion region causes the carriers to separate and to move away from the reverse-biased junction. This causes a current called the photocurrent to flow in the exterior circuit.

As the charge carriers move through the material, some electron-hole pairs recombine again before they reach the junction sides and disappear. L_n and L_p are respectively the average distance that electrons and holes move before they recombine, and they are known as the diffusion lengths. The time that the carriers take after their creation to their recombination is known as the carrier lifetime, and they are called τ_n and τ_p respectively. They are related to the diffusion lengths by the expressions[11]:

$$L_n = \sqrt{D_n \tau_n} \quad (4\text{-}4\text{-}3)$$
$$L_p = \sqrt{D_p \tau_p} \quad (4\text{-}4\text{-}4)$$

where D_n and D_p are the electron and the hole diffusion constants respectively, and they are expressed in units of centimeters squared per second. The optical power in a semiconductor material is absorbed according to the equation[6]:

$$P(x) = P_0\left(1 - e^{-\alpha_s(\lambda)x}\right) \quad (4\text{-}4\text{-}5)$$

where P_0 is the incident optical power level, $\alpha_s(\lambda)$ is the absorption coefficient at the used wavelength, and $P(x)$ is the optical power absorbed in a distance x. α_s depends strongly on the wavelength; hence, a particular semiconductor material can only be used over a limited wavelength range where α_s is large.

The quantum efficiency η, and the response speed for a photodetector are two important factors that must be considered in choosing a photodetector for a communication system. These parameters depend on the material band gap, the operating wavelength, the doping, and the thickness of the p, i, and n regions of the device. η is defined as the number of electron-hole pairs generated per incident photon of energy $h\upsilon$, and it is given by:

$$\eta = \frac{\textit{number of electron-hole pairs generated}}{\textit{number of incident photons}}$$

$$= \frac{I_p/q}{P_o/h\nu} \qquad (4\text{-}4\text{-}6)$$

In (4-4-6), I_p is the average photocurrent generated by the average optical power P_0 incident on the photodetector.

To achieve a high quantum efficiency, the depletion layer must be thick enough to permit a large fraction of the incident light to be absorbed. At the same time, the thicker the depletion layer, the longer it takes for the photo-generated carriers to drift across the reverse-biased junction. Since the carrier drift time determines the response speed of the photodiode, a compromise has to be made between the response time and η.

4-4-2(a) RESPONSE TIME

The response time of a photodiode and its output circuit depends mainly on:

1. the transit time of the photocarriers in the depletion region,
2. the diffusion time of the photocarriers generated outside the depletion region, and
3. the RC time constant of the photodiode and its associated circuit.

The absorption coefficient α_s, the depletion region width w, the photodiode junction and the package capacitance, the amplifier capacitance, the detector load resistance, the amplifier input resistance and, the photodiode series resistance are the photodiode parameters responsible for the above three factors[11]. As mentioned earlier, the response speed of a photodiode is fundamentally limited by the time it takes the photogenerated carriers to travel across the depletion region.

4-4-3 AVALANCHE PHOTODETECTOR

The photodiodes introduced before are very successful in their applications in the background-limited photodetection. However, their lack of internal gain in many cases requires an amplifier to provide noticeable signal currents. Avalanche photodiodes (APDs) internally multiply the primary signal (photocurrent) before it enters the input circuitry of the following amplifier. This process increases the sensitivity of the system, since the photocurrent is multiplied before it encounters the thermal noise associated with the receiver circuit. In order for the carriers to multiply, they must traverse an area with high electric field. In the case of an electron in a high electric field area, it will gain enough energy so that it ionizes bound electrons in the valence band upon colliding with them. This carrier multiplication mechanism is known as impact ionization. The newly created carriers find themselves in an area with high electric field; they gain energy, and each may ionize another bonded carrier and so on. This phenomenon is known as the avalanche effect. Below the diode breakdown voltage a finite number of carriers are created, whereas above that voltage, in theory, that number is infinite. In practice, the avalanche mechanism is a statistical process since not every carrier pair generated in the diode ionizes another pair[6].

CHAPTER 5

FIBER CONNECTORS AND SPLICES

Connecting individual segments of fibers either at the source or receiver ends, during splicing while being installed, or at a fiber to fiber joint, requires considerable attention in order to obtain a relatively low loss fiber system. If efficient methods of interconnection did not exist, transmission of data for relatively long distances would become a more costly and complex process. In this case, a very long uncut cable would be required, or detection and reamplification of the signal at every break in the cable would have to be performed. Since long cables are hard to handle during installation and reamplification is a costly method of attaining long-distance data transmission, efficient interconnecting devices are an economical necessity. Repeaters are active devices which need energy to operate. Meanwhile, connectors are passive devices; the reduction of number of repeaters in a system increases the reliability, and decreases the energy requirement of the system. In addition, efficient interconnection components are cost effective.

5-1 CONNECTORS

If an optical fiber system is to be traced from beginning to end, three different types of connectors would be encountered. At the transmitting end of the communication link, source-to-fiber connectors would be used. Along the link, if the fiber cable is shorter than the link length required, fiber-to-fiber connector(s) or splice(s) would be used. Finally, at the other end of the link, fiber to detector connector is required. Each of the three connector types requires different design criteria; hence, each type will be discussed separately.

5-1-1 SOURCE-TO-FIBER CONNECTORS

A typical light source that will be considered is an LED. The brightness or the radiance of a light source is defined as the power radiated into a unit solid angle per unit emission area and it has the dimensions of watt/[cm^2 steradian]. An LED is a lambertain source, where the brightness or radiance of the source is the same looking into the source from any direction, and the off-axis radiance varies as:

$$B = B_0 \times \cos\theta \qquad (5\text{-}1\text{-}1)$$

where B_0 is the radiance or brightness of the source at the fiber axis, and θ is the angle between the fiber axis and the direction from which the radiance is measured. To explain this, consider a spherical coordinate system with the source at the center and facing the positive z-axis. In a lambertain source the power radiated from the source will be a function of both of the R, θ, and φ. If the radiance is to be viewed in a direction θ, the power will vary as $\cos\theta$. At the same time, the emission area will have $\cos\theta$

dependence leaving the radiance unchanged.

When coupling light into optical fibers, it is usually desirable to maximize one of the following two quantities:

1. the total power coupled into the fiber, or
2. the coupling efficiency, η.

η is defined as $\eta = P_i/P_{LED}$ where P_i is the power injected into (coupled to) the fiber, and P_{LED} is the power emitted by the LED. Since P_i can be written as $P_i = \eta \times P_{LED}$, P_i may be increased by using a more powerful or more directional (less half-power width angle) source and leaving η unchanged. For a typical LED η is usually small, around 5%.

In the case of a lambertain source (LED) coupled to a step index fiber with a core area A_{core} and numerical aperture NA, the simplest method of transferring light energy is to butt-couple them. When the diode and the fiber are properly butt-coupled, the power injected into the fiber is given by[13]:

$$P_i = \pi \times T \times B \times A\ (NA)^2 \qquad (5\text{-}1\text{-}2)$$

where T is the transmissivity and its value is between 0.95 and 1.0, and A is the area of the core or the emitting surface, whichever is smaller. The transmissivity of a fiber depends on the configuration and the number of single fibers in fiber cable. For a single fiber T = 1. The optical coupling efficiency is given by[6]:

$$\eta = \frac{P_i}{P_{LED}} = T\left(\frac{A}{A_{LED}}\right)(NA)^2 \qquad (5\text{-}1\text{-}3)$$

If $A \geq A_{LED}$ then (5-1-3) can be written as:

$$\eta = T\,(NA)^2 \qquad (5\text{-}1\text{-}4)$$

From (5-1-3) and (5-1-4) the power coupled from an LED to a single multimode step-index fiber (T = 1) can be written as:

$$P_i = P_{LED} \times (NA)^2 \qquad (5\text{-}1\text{-}5)$$

Equations (5-1-2), (5-1-3) and (5-1-5) show that substituting a large and bright source for a smaller and less radiant one leads to an increase in the injected power but a decrease in coupling efficiency. The above discussion gives an accurate analysis of power coupling from a lambertain source to a step index fiber considering meridional rays only. If skew rays are to be considered, a more complicated analysis is required. A complete discussion considering skew rays is found in Reference 10.

In the case of a nonlambertain light source, the intensity or brightness may be approximated by a power law variation of the form:

$$B = B_0 \cos^{\sigma}\theta \qquad (5\text{-}1\text{-}6)$$

where B_0 is defined the same as for lambertain source and σ is a numerical value characteristic of the source. A more detailed discussion is found in Reference 10.

Figures (5-1) and (5-2) show two possible designs for source-to-fiber connectors. The longitudinal separation,

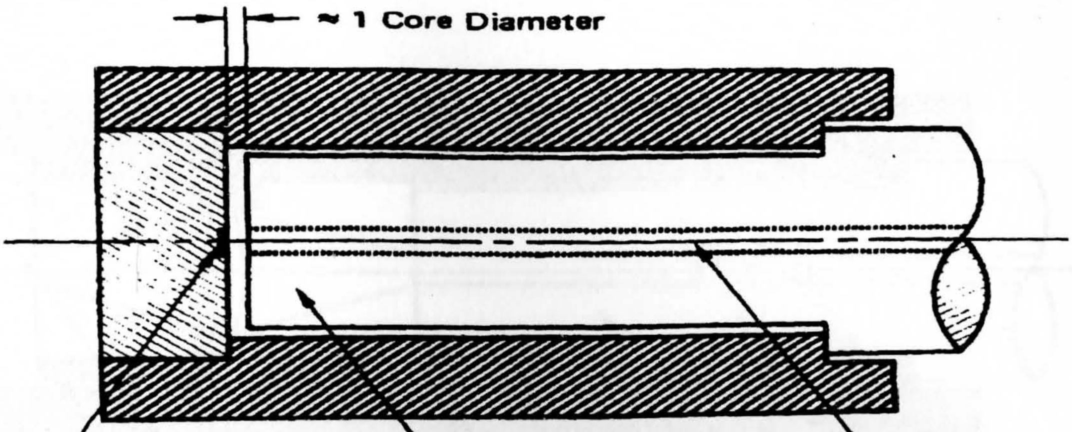

Fig. 5-1 Illustration of source-to-fiber connector, butt-coupling.

the angular misalignment, and the lateral misalignment strongly affect the coupling efficiency. Similarly, the length, and the outer diameter of the fiber termination are also critical dimensions. By precisely controlling those four quantities, a high power coupling efficiency can be achieved. In Fig. (5-2), the lens is used to increase the coupling efficiency of the system. The function of the lens is to magnify the emitting area of the source as seen by the fiber core. The magnification is designed to let the emission area of the source match the core area of the fiber. If the emitting area is increased by a magnification factor, M, the solid angle within which optical power is coupled to the fiber from the LED is increased by the same factor. This magnification leads to better power coupling efficiency.

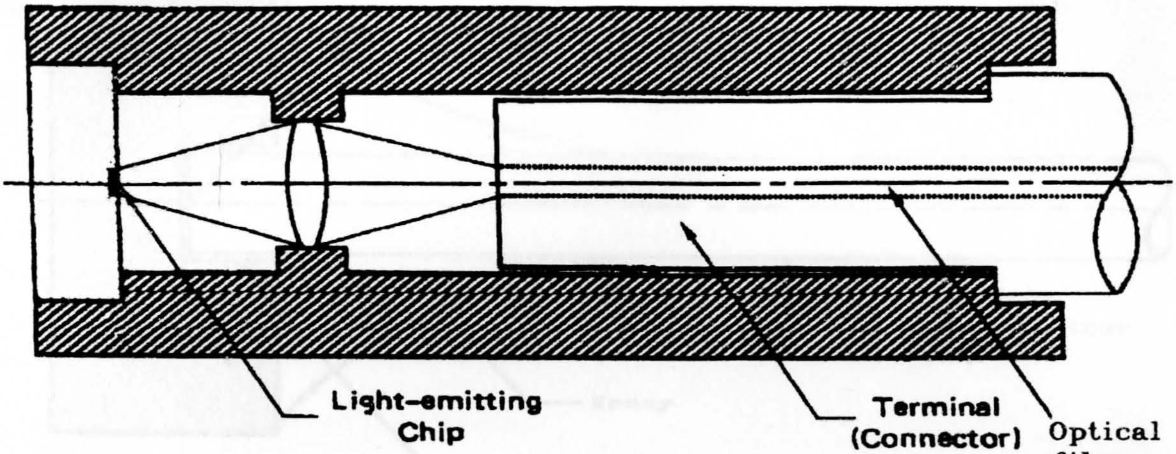

Fig. 5-2 Illustration of a source-to-fiber connector using lens coupling.

In practice, to increase the coupling efficiency, η, many source suppliers provide devices with a short length of fiber already attached in an optimum power-coupling configuration. This section of fiber is generally referred to as a flylead or a pigtail. As Fig. 5-3 shows, a pigtailed device is simply a source and fiber combination that has been aligned and permanently locked into place. The manufacturers of such devices usually specify the amount of power emitted by the fiber. At the other end of a pigtail, a fiber-to-fiber connector would be used.

5-1-2 FIBER-TO-FIBER CONNECTORS

A wide variety of optical fiber connectors exist for different kinds of applications. Their uses range from simple single-channel fiber-to-fiber connectors to multichannel connectors. There are some principal requirements

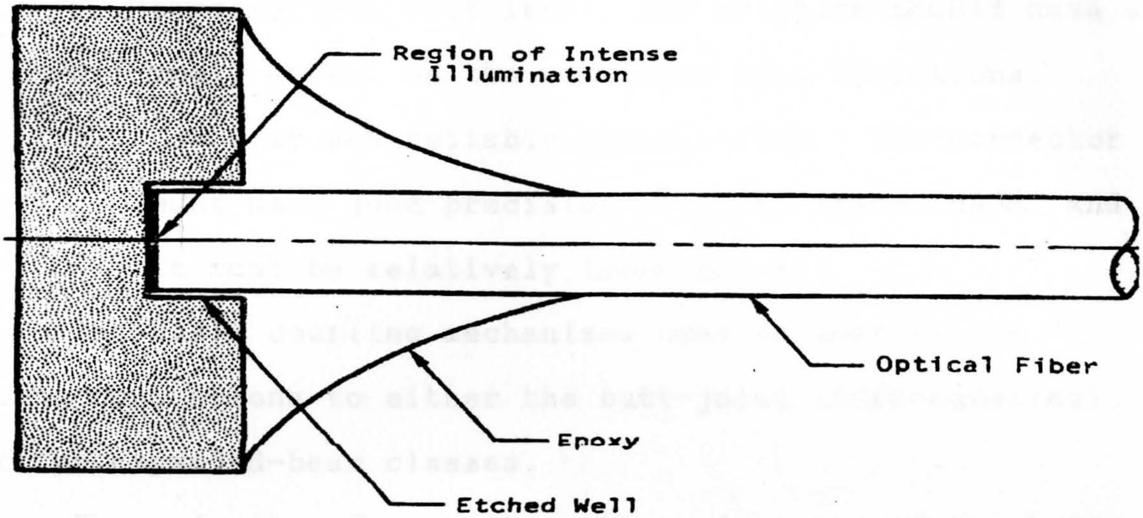

Fig. 5-3 Illustration of an optical fiber pigtailed to an LED chip.

that a good connector should have to be considered as an efficient connector. Following is a list of these requirements.

1. Low coupling losses. The connector must have and maintain low mating losses. These losses must not change significantly during the operation or after many uses.
2. Interchangeability. Each connector must be compatible with the same kind of connectors made by another manufacturer.
3. Ease of assembly and connection. A connector should not be difficult to be installed by a service technician in the field environment. Also, the connector losses should not depend largely on the assembly skills of the technician.

4. Low environmental sensitivity. Changes in the temperature, dust level, and moisture should have a small effect on the connector loss variations.
5. Low cost and reliable construction. The connector must have good precision with the system used, and it must be relatively inexpensive.

The basic coupling mechanisms used in most of the connectors belong to either the butt-joint (butt-coupling), or the expanded-beam classes.

The majority of connectors these days are of the butt-joint type. These connectors use a ceramic, metal, or molded-plastic ferrule for each fiber, and a precision sleeve into which the ferrule fits as shown in Fig. 5-4.

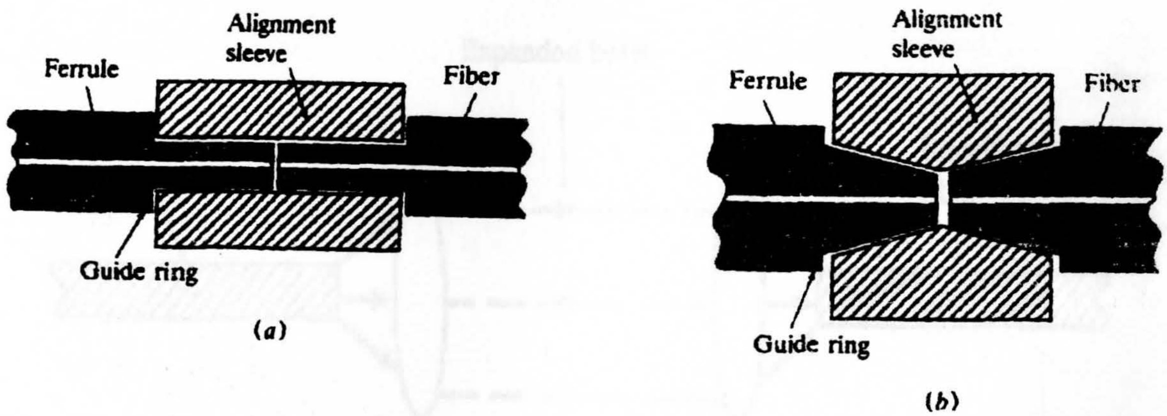

Fig. 5-4 Examples of two popular schemes used in fiber optics connectors: (a) straight sleeve; (b) tapered sleeve.

Fig. 5-4 shows two popular butt-joint alignment designs, the straight-sleeve and the tapered-sleeve. In the straight-sleeve design, both the length of the sleeve and a guide ring on the ferrule determine the end separation of the fibers as shown in Fig. 5-4(a). The tapered-sleeve design uses a tapered sleeve to accept and guide tapered ferrules as shown in Fig. 5-4(b). As in the straight sleeve, both the sleeve length and the guide ring determine the end separation of the fibers.

On the other hand, the expanded-beam connector uses lenses on the ends of the fibers as shown in Fig. 5-5. These lenses either collimate the light emerging from the transmitting fiber, or focus the expanded beam onto the core of the receiving fiber. It is important that the separation

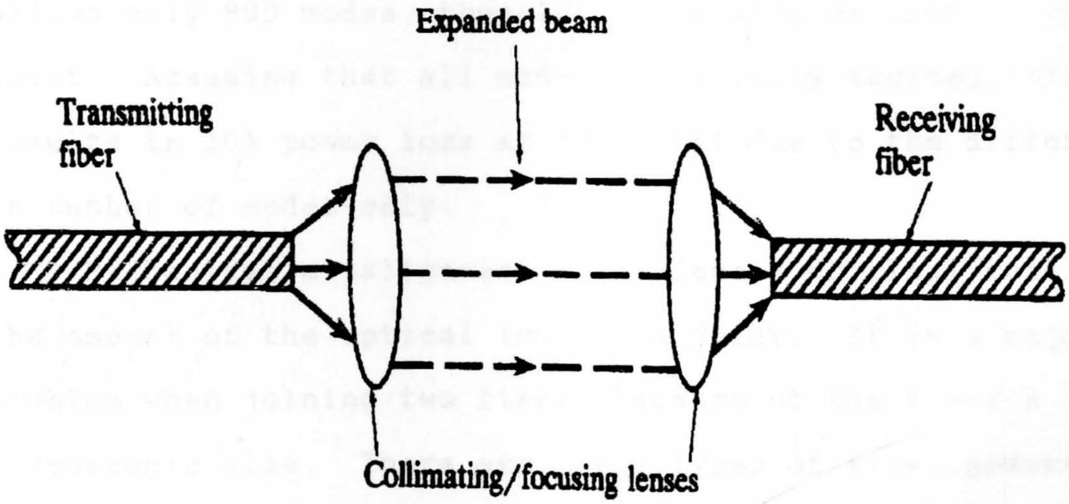

Fig. 5-5 Schematic representation of an expanded-beam fiber optic connector.

between the end of the fiber and the corresponding lens be equal to the focal length of that lens. Since the beam is collimated, separation of the fibers ends may take place within the connector. In this case, connectors are less dependent on longitudinal alignments.

Several conditions affect the amount of optical power lost at any joint (splice or connector). These losses depend on parameters such as the power distribution among the propagating modes at the connector, the length of the fiber between the optical source and the joint (power level), the geometrical and waveguide characteristics of the two fiber ends at the joint, and the fiber end face qualities. The optical power that can be coupled from one fiber to another depends on the number of modes that can propagate through each fiber. For example, if the source fiber propagates 1000 modes while the destination fiber allows only 900 modes, then 100 modes will be lost at the joint. Assuming that all modes are equally excited, this results in 10% power loss at the joint due to the difference in number of modes only.

Mechanical misalignment also plays a critical rule in the amount of the optical loss at a joint. It is a major problem when joining two fibers because of the fiber's microscopic size. There are three types of misalignments which may exist at fiber-to-fiber connectors. These types are described below.

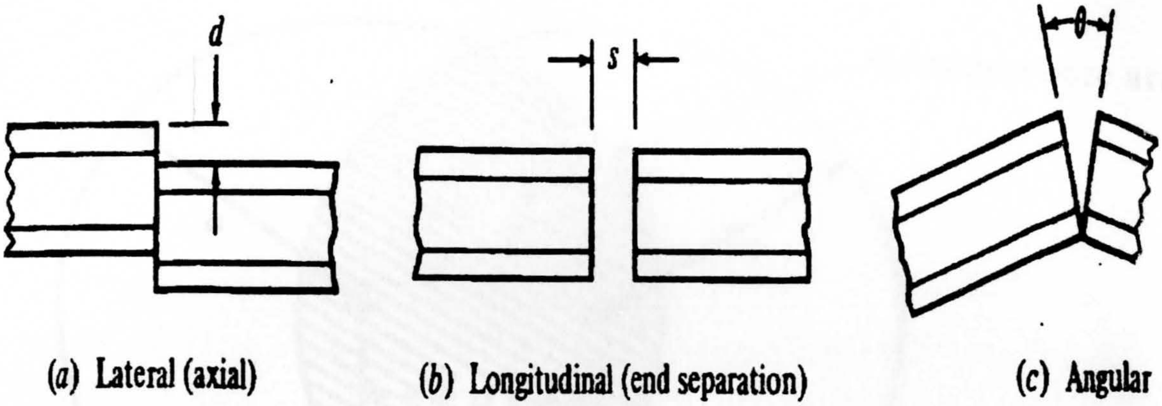

Fig. 5-6 Three types of mechanical misalignments that occur between two joined fibers.

1. Axial displacement or lateral displacement. This displacement results when the axes of the two fibers are separated by a distance d, as shown in Fig. 5-6(a).
2. Longitudinal separation. This occurs when the fibers have the same axis but have a gap, S, between their faces, as shown in Fig. 5-6(b).
3. Angular misalignment which results when the two axis form an angle so the fibers ends faces are no longer parallel, as shown in Fig. 5-6(c).

The most common misalignment occurring in practice which causes the greatest power loss is axial displacement. Axial displacement reduces the common area between the two fiber ends. The reduction in the common area results in corresponding reduction in the optical power that could be

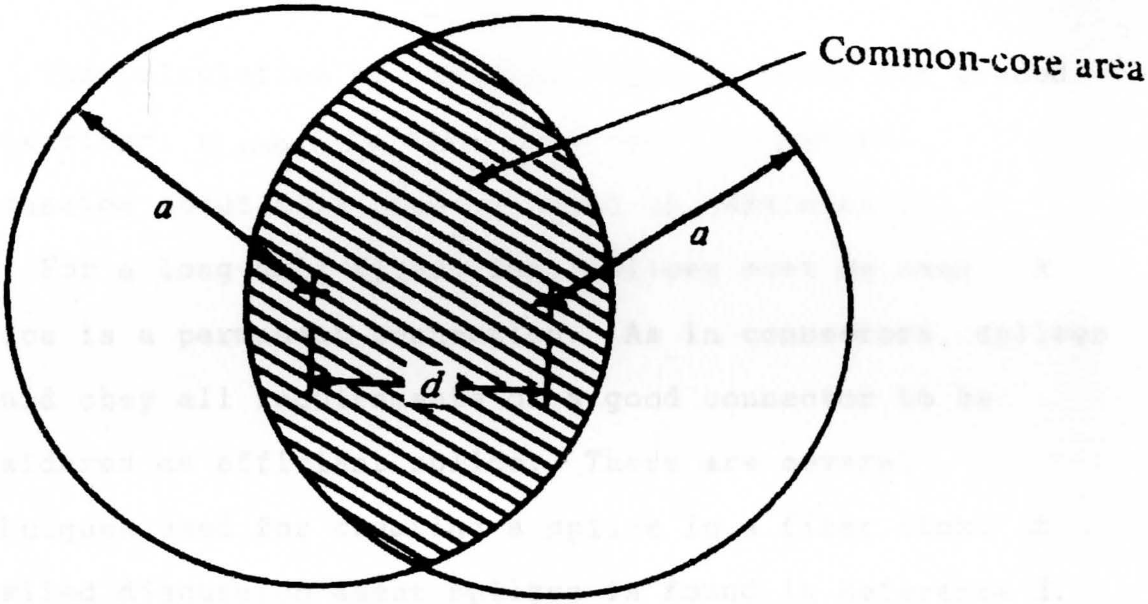

Fig. 5-7 Axial offset reduces the common core area of the two fiber end faces.

coupled at the connector. Fig. 5-7 shows two fiber ends; it is assumed that the fiber cores have the same radius, a. The common core area, A_{comm}, of the fibers in Fig. 5-7 is given by[6]:

$$A_{comm} = 2a^2 \times \arccos\left(\frac{d}{2a}\right) - d\left(a^2 - \frac{d^2}{4}\right)^{1/2} \qquad (5\text{-}1\text{-}7)$$

where d is the separation distance of the two fibers axis, and a is the radius of the fiber cores.

For step-index fiber, the coupling efficiency is simply the ratio of the common area to the core end face area, and it is given by[10]:

$$\eta_{F,step} = \frac{A_{comm}}{\pi a^2}$$

$$= \frac{2}{\pi}\arccos\left(\frac{d}{2a}\right) - \frac{d}{\pi a}\left[1 - \left(\frac{d}{2a}\right)^2\right]^{1/2} \qquad (5\text{-}1\text{-}8)$$

The calculation of the coupling efficiency for graded index fiber, $\eta_{F,graded}$, is more involved. A complete discussion about this case is found in Reference 10.

For a long-hall fiber link, splices must be used. A splice is a permanent connection. As in connectors, splices should obey all requirements of a good connector to be considered an efficient splice. There are several techniques used for creating a splice in a fiber link. A detailed discussion about splices is found in Reference 2.

5-1-3 FIBER-TO-DETECTOR CONNECTORS

The coupling of optical power to an optical detector is a lot easier than coupling the optical power to the fiber from the source or from fiber-to-fiber by a connector. This is because in the former case, the geometry of the components used is more favorable than in either of the latter cases. It was shown in Section 5-1-1, that the coupling efficiency increases as the size of the source decreases to, or less than, the size of the fiber used. Similarly, for an efficient fiber-to-fiber connector, accurate alignment must be achieved between two equally small fibers.

On the other hand, high coupling efficiency between fiber and detector can be achieved even if the active area of the detector is many times larger than the cross-sectional area of the fiber. The only loss encountered in this case is caused by reflections from the various surfaces encountered by the emitted light and by the angular response of the detector. Very small detectors have active areas that are 0.25 mm square. Meanwhile, typical multimode fibers have cores that have diameters of 0.060 to 0.125 mm. Therefore, to couple a fiber to a detector, it is only necessary to build a fixture that allows the fiber to butt against the detector's active area. A lens may be used to focus the optical power on the active area of the detector if a very high coupling efficiency is required.

CHAPTER 6

DIGITAL TRANSMISSION SYSTEM

In the preceding chapters, fundamental characteristics of individual building blocks of an optical fiber communication links were presented. These blocks included the optical fiber (the transmission medium), the optical source, the photodetector and the fiber connectors and splices. Within this chapter, I will examine how the individual blocks studied so far can be brought together to form a complete point-to-point digital fiber optic link. The selected digital link is a short-haul link with data rate of 20 Mbps, and it has no regenerative repeaters. The link uses a multimode step index fiber with an LED as a source. As mentioned in Chapter 1, a simple digital link such as the one considered in this chapter will help greatly in explaining and demonstrating the basic application of light propagation in a fiber optics cable. This chapter will also present two important topics, which are line coding and time division multiplexing. These two topics help in error minimization, correction, and in utilizing the wide bandwidth available in a fiber optics link.

6-1 LINE CODING

Line coding is important in designing a digital communication link. The first block to be sent in any digital link carries all the information needed to completely define and initialize the digital clock in the receiving terminal. This block will define the type of coding used (NRZ, RZ, or Manchester code). Also, the first block carries specific timing to enable the receiver circuitry to maintain the proper pulse spacing and to completely determine the start and the ending pulses. Coding helps the receiver in error detection and correction. Error detection is accomplished by the introduction of extra bits in a logical and regular order. The information about these extra bits is communicated to the receiver in the first block. If an error was made in the received bit the receiver will acknowledge the existence of an error and the error will be corrected according to the error correction codes. An exact and complete discussion for error detection and correction techniques can be found in References 9, 10, 11 and a good digital communication book.

The three basic types of two-level binary line codes that can be used for optical fiber transmission links are; the non-return-to-zero (NRZ), the return-to-zero (RZ), and the Manchester code.

6-1-1 NRZ CODES

A NRZ code for a binary data represents the binary 1 by a pulse (current or light) that fills the whole bit period. It represents the binary 0 by the absence of a pulse (i.e.

no current or light) in the whole bit period as shown in Fig. 6-1(a). These codes are simple to generate and detect. Detection of digital pulses in general employs the use of the eye pattern. A discussion of the eye pattern can be found in Reference 10.

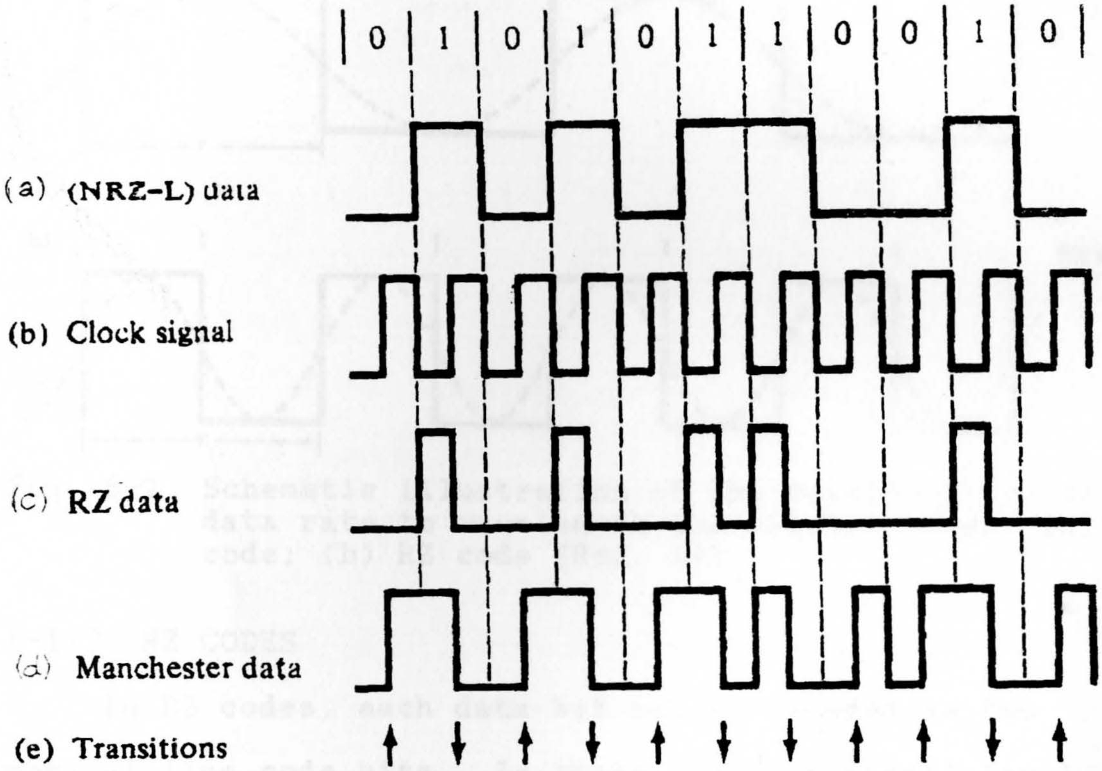

Fig. 6-1 Different coding format: (a) NRZ-L data; (b) clock signal; (c) RZ data; (d) Manchester data; (e) transitions for Macnhester data [Ref. 10].

A long string of 1 or 0 bits in the NRZ code may cause the loss of syncronization[14]. In a NRZ code there are two bits in one wavelength of the information signal (i.e. two bits per second per hertz) as shown in Fig. 6-2(a). Therefore the maximum bandwidth of the information signal B is one-half the maximum data rate or:

$$B_T(\max) = 2B \qquad (6\text{-}1\text{-}1)$$

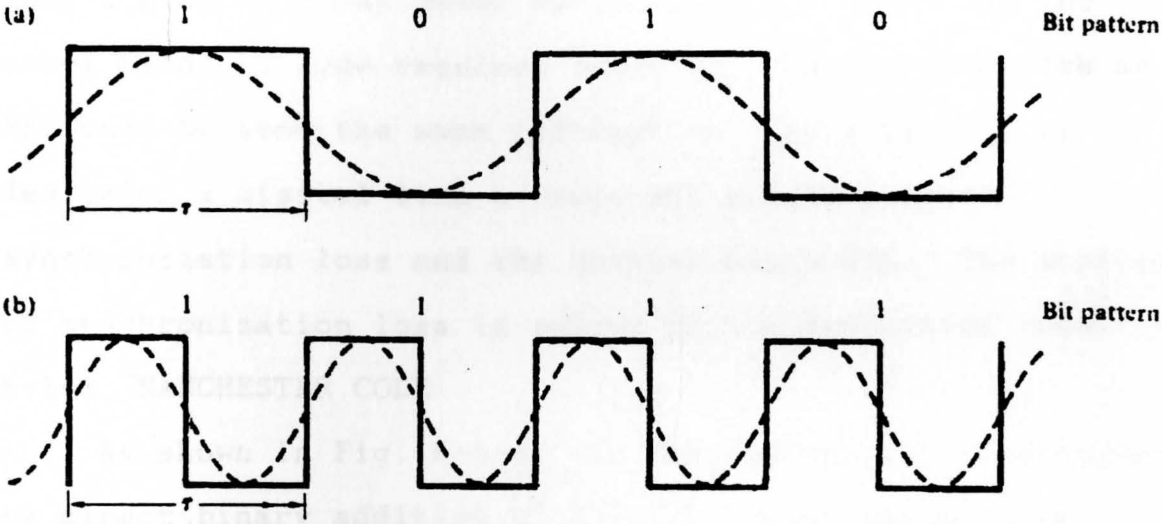

Fig. 6-2 Schematic illustration of the relationships of the data rate to wavelength for digital codes: (a) NRZ code; (b) RZ code [Ref. 14].

6-1-2 RZ CODES

In RZ codes, each data bit can be encoded as two optical line code bits. In these codes, a signal level transition occurs during a 1 binary bit period (i.e., a 1 level will drop to the 0 level during the bit period). As shown in Fig. 6-1(c), a 1 binary bit has a transition from the 1 level to the 0 level in the middle of the bit period. For a RZ code the data rate is equal to the bandwidth in hertz (i.e. one bit per second per hertz) as shown in Fig. 6-2(b), i.e.,

$$B_T(\max) = B \qquad (6\text{-}1\text{-}2)$$

The problem of losing synchronization is not as pronounced in RZ code as it is in a NRZ code because in a RZ only a long string of 0 may cause synchronization loss. On the other hand, RZ code requires twice the channel bandwidth as NRZ code to send the same information. As a result, in designing a digital link a trade-off exists between synchronization loss and the channel bandwidth. The problem of synchronization loss is solved by the Manchester code.

6-1-3 MANCHESTER CODE

As shown in Fig. 6-1(d) the Manchester code is obtained by direct binary addition of the NRZ signal and a clock signal. In this code there is a transition at the center of each bit interval. A negative-going transition indicates a 1 bit, whereas a positive-going transition indicates a 0. Manchester code has the advantage of not losing synchronization as may happen with the NRZ and RZ. This is because there is a transition of the binary level in each bit. A trade-off exists between the high synchronization in the Manchester code and the high bandwidth needed to send a signal using it. This bandwidth is twice that of the NRZ code.

6-2 TIME-DIVISION MULTIPLEXING (TDM)

TDM is a technique by which the time domain for a

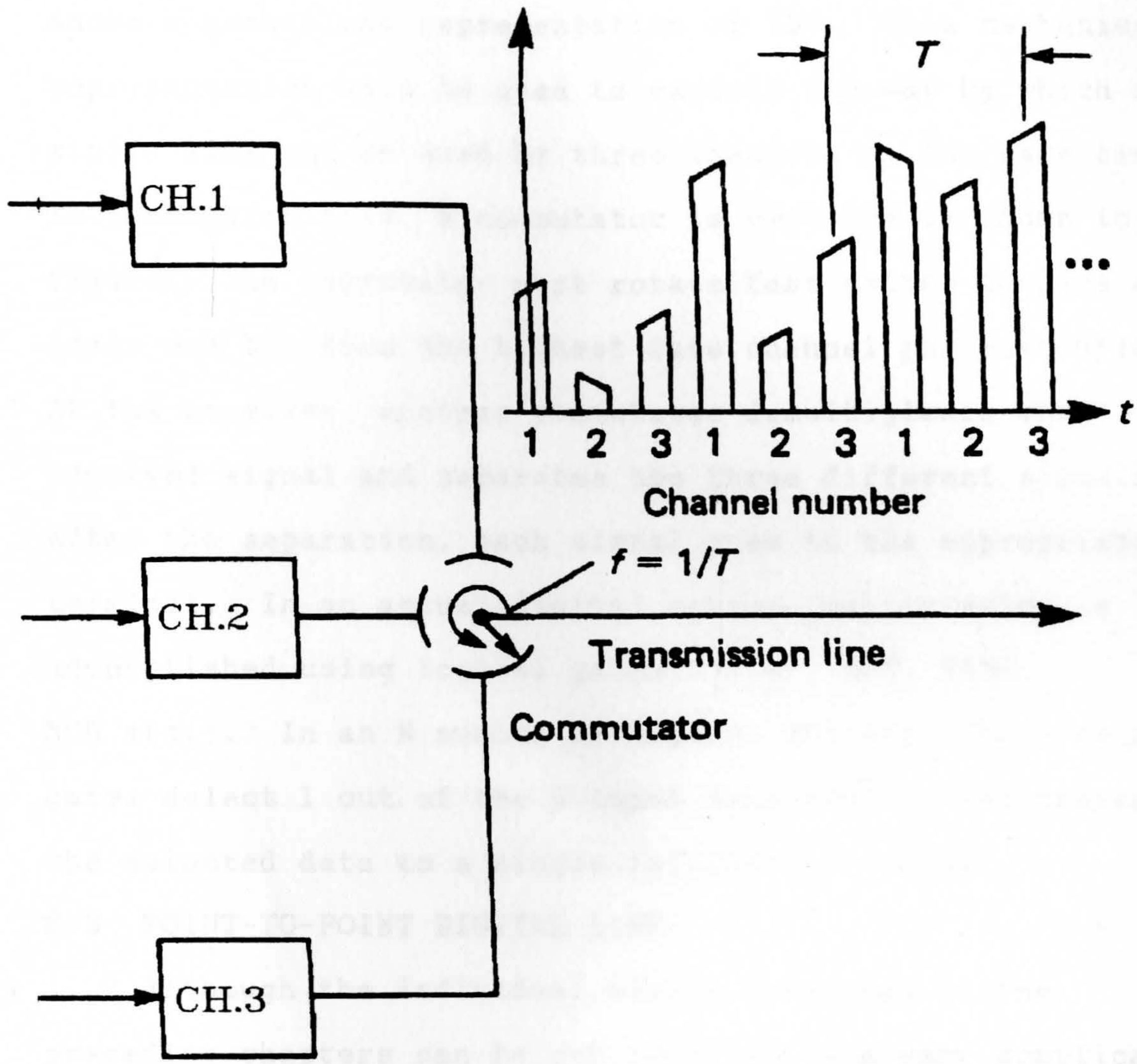

Fig. 6-3 Mechanical representation of TDM for three channels [Ref. 14].

communication system is divided. As a result of this division, many sources can share the same line simultaneously. At the receiving side of the TDM system, the individual signals can be recovered by a circuit that demultiplexes the received signal. To explain the way by which TDM in a link is achieved consider Fig. 6-3. Fig. 6-3 shows a mechanical representation of TDM. This mechanical representation will be used to explain the way by which a single link can be used by three channels at the same time. To accomplish this, a commutator is employed as shown in the figure. The commutator must rotate fast enough to have at least one bit from the highest rate channel per revolution. At the receiver, another commutator demultiplexes the received signal and separates the three different signals. After the separation, each signal goes to the appropriate terminal. In an actual digital system, multiplexing is accomplished using logical gates[15] (i.e., AND, NAND, NOR,etc.). In an N number of digital sources, the digital gates select 1 out of the N input data sources and transmit the selected data to a single information channel.

6-3 POINT-TO-POINT DIGITAL LINK

Although the individual blocks presented in the preceding chapters can be put together in a very complicated way in order to produce very sophisticated links with high information carrying capacity, a simple link (point-to-point) meets the goal of this thesis. A point-to-point link has only one transmitter, one terminal (receiver), and only two connectors, one at the beginning of the link and the other at its end. A complex link will use a single mode fiber, IL as a source, more than one terminal, and many connectors and/or splices. Also, a complex link may use couplers and splitters.

In designing an optical link, many interrelated variables have to be studied. Among these variables are the fiber, source, and photodetector. The design involves many trade-offs between the above variables to achieve the desired link performance. Before any system design procedures can be initiated, it is essential that certain basic system requirements be specified. These specifications include:

1. transmission type; digital or analog,
2. acceptable system fidelity; system fidelity generally specified in terms of the maximum tolerable BER for digital systems or the received SNR for analog systems,
3. required transmission bandwidth,
4. the maximum distance between the transmitter and the receiver without a repeater to achieve the required fidelity,
5. cost,
6. reliability.

While specifications 1 and 2 are fully determined, trade-offs exist among the other specifications. Specifications 5 and 6 are beyond the scope of this thesis. Complete consideration of these two specifications is found in References 16, 17.

After completing the choice of components, a power budget analysis should be carried to determine whether the fiber link meets the attenuation requirements. Otherwise, a repeater is needed to boost the power level. Finally, the system rise time analysis should be carried to verify that the over-all system performance requirements are met.

6-4 SYSTEM SPECIFICATIONS

Before initiating any design procedure, the specifications for the required system should be known. The system to be designed in this chapter has the following specifications:

1. data rate equal 10 Mbps,
2. BER equal 10^{-9},
3. short-haul, point-to-point. Only two connectors will be used, one at the beginning, and the other at the end.

6-5 SYSTEM DESIGN

After knowing the system specifications, general system considerations should be observed. With the system specifications in Section 6-4, trade-offs between the characteristics, the cost and the complexity of the three main building blocks (light source, detector, and fiber cable) can be established. For example, using laser diodes for a system will give better BER, more repeaterless transmission distance, and higher data rates (up to 400 Gbps with single mode fiber) than an LED. Meanwhile, laser diodes are more expensive, have more complex driving circuitry and are less stable to changes in temperature than LEDs. The latter disadvantages of lasers overrule the use of a laser diode as a light source for the specifications in Section 6-4. The same trade-offs exist between the use of an avalanche photodiode and PIN photodiode receiver. Avalanche photodiodes are more sensitive to light. As a result, if the detection of a low optical power level and a low BER are required, then an avalanche photodiode should be used. On the other hand, avalanche photodiodes are more expensive, and have higher driving voltages (several hundred volts) than PIN photodiodes (around 50 volts). Since the link considered in this chapter is a short-haul link with relatively low data rate, a PIN photodiode will be used.

The third main building block is the optical fiber. The choice of an LED as a light source overrules the use of single mode fiber. At the same time, the relatively low data rate for the system considered here makes the use of a single mode fiber unjustifiable because it has information carrying capacity up to 400 Gbps if used with a laser diode.

6-6 COMPONENT SELECTION

In Section 6-5, the system specifications were studied to make a general choice of the system building blocks. In this section the exact component will be chosen. The first step in deciding the exact model and kind of a component is determined by the wavelength used for transmission. After that the receiver and then the transmitter will be chosen. During the process of wavelength selection, the fiber type will be decided upon.

In choosing an operating wavelength, the maximum tolerable attenuation and dispersion are the main factors that dictate the choice. For a link with the specifications in Section 6-4, low attenuation at wavelength in the range 800 to 900 nm will be taken advantage of as shown in Fig. 3-1. In this wavelength range, the LEDs are available and inexpensive. The lower attenuation (shown in Fig. 3-1), for wavelengths in the range 1300 to 1500 nm, will be considered only if a long-haul link is to be used with higher data rate. Light sources at the latter range are not as available as the those in the first range.

6-6-1 PHOTODETECTOR

PIN MFOD2404 Motorla photodiode (high performance family) with specifications given below:

1. input wavelength 850 nm,
2. sensitivity at 10 Mbps, NRZ, and with BER of 10^{-9} equal to 0.1 μw (i.e., 0.1 μw has to fall in the active area of the photodetecter to achieve the given BER with the above specifications),
3. typical rise time is equal to 35 ns.

6-6-2 SOURCE

MLED 77 Motorla LED with specifications given below:

1. wavelength equal to 850 nm,
2. output power 2.5 mw,
3. rise time 25 ns,
4. spectral width equal to 40 nm,
5. operation voltage is around 6 volts,
6. the best temperature range is -40 to 100 °c.

6-6-3 FIBER

AMP 502082-1 multimode step-index silicon fiber with specifications given below:

1. radius between 50-125 μm,
2. NA = 0.2,
3. attenuation coefficient (α) = 4 dB/Km.

For such a fiber, the coupled power from an LED (with specifications in Section 6-6-2) is found using (5-1-5) to be 100 μw.

6-7 LINK POWER BUDGET

Link power budget is an analysis which considers the maximum power that can be lost in the link, P_T and still meet the required performance. The power that reaches the photodetector depends on the power coupled from the source, P_s, the loss at connectors and the fiber attenuation. If the total power loss in a link is large enough to reduce the optical power level to a level below the level required by the detector specifications P_t a repeater is needed to boost the power level. In addition to all types of power loss in an optical fiber system, a certain power margin (usually 6 dB) is included in the power budget analysis. The power margin is added to compensate for any loss that may happen due to component aging and any future expansion of the system. The maximum P_T can be expressed as:

$$P_T = P_S - P_r \tag{6-7-1}$$

From Section 6-6-4 the receiver sensitivity, P_r, is 0.1 μw i.e. -40 dBm (the dBm power is the power level with respect to 1 mw). The source optical power P_s, in dBm is equal to -10 dBm. Equation (6-7-1) gives P_T equal 30 dBm. The total power loss is divided between all loss contributors (i.e., connector's loss, fiber attenuation loss, and the system power margin, 6dB) or:

$$30 = 2(1dB) + \alpha_f L + 6 \tag{6-7-2}$$

this gives $\alpha_f L$ = 22 dBm. Having α_f = 4 dB/km gives the maximum transmission distance as 5.5 km.

The system power budget is represented graphically in Fig. 6-4. In Fig. 6-4, the LED power is drawn at -10 dBm power level. A 1 dBm is subtracted from the -10 dBm to represent the source-to-fiber connector loss. Another 1 dBm is subtracted for the fiber-to-detector connector. A 6 dB power margin subtraction at this point leaves the fiber

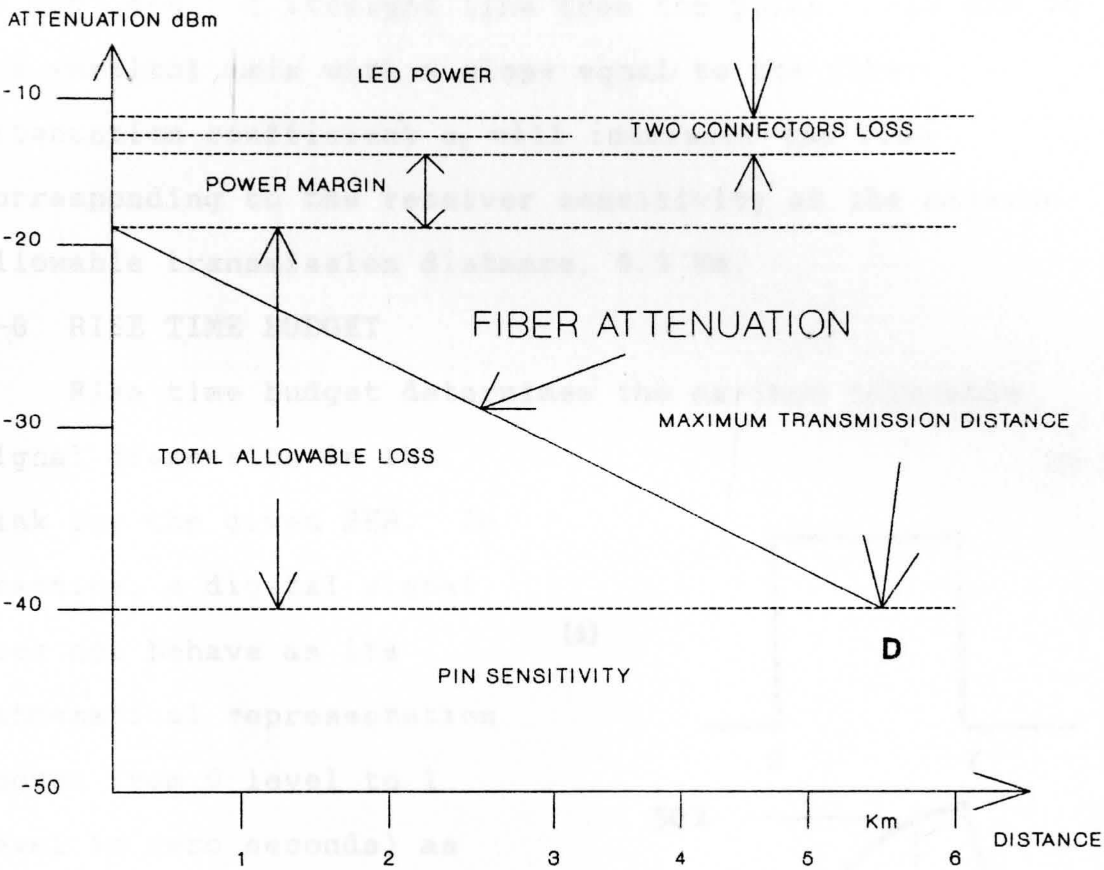

Fig. 6-4 Graphical representation of the link loss power budget.

system with maximum total allowable power loss of 22 dBm. After the subtraction of the power margin, the total power will be at the -18 dBm level on the vertical axis as shown in Fig. 6-4. A straight line from the point -18 dBm on the vertical axis with a slope equal to the fiber attenuation coefficient α_f will intersect the line corresponding to the receiver sensitivity at the maximum allowable transmission distance, 5.5 Km.

6-8 RISE TIME BUDGET

Rise time budget determines the maximum tolerable signal dispersion in the link for the given BER. In practice, a digital signal does not behave as its mathematical representation (moves from 0 level to 1 level in zero seconds) as shown in Fig. 6-5(a). A pulse takes a small finite time in order to rise from the zero to the one level as shown in Fig. 6-5(b).

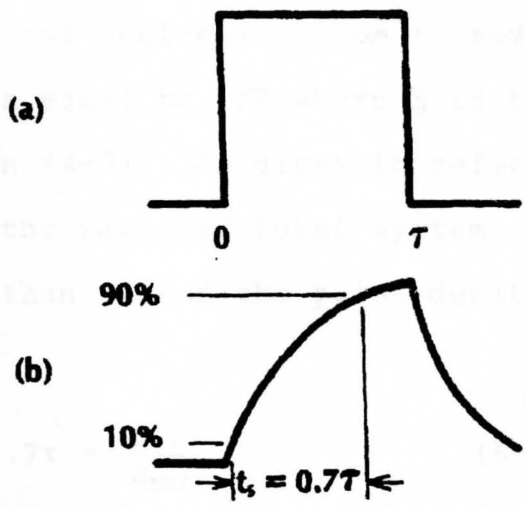

Fig. 6-5 Rise time for a digital pulse; (a) ideal pulse; (b) real pulse [Ref. 1].

The rise time is defined as the time it takes the pulse to rise from 10% to 90% of its final value.

"The total system rise time, t_{sys}, is given by the rootsum-square of the rise times from each contributor, t_i, to the pulse rise time degradation[10]". This can be expressed as:

$$t_{sys} = \left(\sum_{i=1}^{N} t_i^2 \right)^{1/2} \tag{6-8-1}$$

where N is the number of contributors to the pulse rise time. These contributors are:

1. the transmitter t_{tx},
2. material dispersion t_{mat},
3. modal dispersion t_{mod}, and
4. the receiver t_{rx}.

Considering a NRZ code, the pulse duration τ, and the repetition period T, are both equal to 1/B where B is the data rate as shown in Section (4-3). As given in referance 1, a reasonable estimate of the required total system rise time is taken to be no more than 70% of the pulse duration τ, i.e.,

$$t_{sys} = .7\tau = \frac{0.7}{B_{NRZ}} \tag{6-8-2}$$

For the system considered here a NRZ code was used, this gives t_{sys} = 70 ns, which is the total allowable rise time. Using a typical value of t_{mat} = 4 ns/km and t_{mod} = 4 ns for the 5.5 Km gives the system rise time as:

$$t_{sys} = \left[(25ns)^2 + (35ns)^2 + (22ns)^2 + (4ns)^2\right]^{1/2}$$

$$= 48.48ns \qquad (6\text{-}8\text{-}3)$$

It was found that the maximum tolerable rise time would be 70 ns while the actual rise time for the system is 48.48 ns. This means that the choice of the components for the link was adequate enough for the system specifications.

The fiber optics link presented in this chapter is one of the simple optical links that can be designed for a communication system. Although the link is very simple, it has information carrying capacity comparable to a very sophisticated conventional communication link. In this system a data rate of 10 Mbps is found to transmit a distance of 5.5 Km with an BER of 10^{-9} without the need of a repeater. Considering that in this system only a small fraction of the source power was initially coupled to the fiber (4%), the maximum transmission distance is relatively long (5.5 Km). With an improvement in the coupling techniques at least for the source side, the maximum transmission distance can be increased significantly. In the fiber optics link considered in this chapter an LED, PIN photodiode, and a multimode step index fiber were used. These link components are relatively inexpensive and available. If TDM is used for this link, the communication carrying capacity of the link will increase several times facilitating the use of a large bandwidth undreamed of in metallic communication links.

CHAPTER 7

CONCLUSION

7-1 SUMMARY

My study is focused on how light is used in fiber optics communication (optical communication). A fiber optic link consists of a light source, a fiber as the transmission medium, and a photodetector. A brief description of the theories of light emission, propagation, and detection are presented. Both the light source and the photodetector are basically p-n junctions. To increase the sensitivity of a PN photodetector, the junction is made wider by doping it with an intrinsic material to produce a PIN photodetector.

Since the simplest fiber link that may exist has to have at least two connectors (one at each end), connectors are important components in any fiber optic link. The simplest connector used in a fiber optic link is a butt-joint connector.

The driving circuits for both the light source and the photodetector greatly affect the performance of the optical link. The treatment of these topics are beyond the scope of my study and can be used as separate topics for a thesis.

Line coding and TDM are two important topics used in digital communication links. Line coding is the format of the transmitted digital data. TDM is a method by which more than one message can be sent in a single optical fiber simultaneously. A simple communication link is a short-haul point-to-point link with data rate of 10 Mbps. The bit error rate is 10^{-9}. This simple link is presented in this study to demonstrate the high information carrying capacity of fiber links. High information carrying capacity is one of the most important advantages of optical communication links. A 10 Mbps is considered a very high data rate in conventional links. This rate can easily be achieved in any simple, inexpensive fiber link such as the link considered in this thesis.

7-2 CONCLUSION

This study gives a clear answer of the question "why fiber optic links?" The advantages of fiber optic links makes them compete successfully for all communication needs. The extremely high bandwidth (information carrying capacity) makes a fiber link a leader for the use for digital communication links which started to dominate communication systems in the 80's. The high bandwidth needed for any video and conference communication makes fiber optic links superior in such links. Moreover, the signal security that fiber optics links provide makes them important in miliary communication and in banking links. The small size and light weight optical fibers have made them important in airplane, satellite, and the crowded ducts in big cities. The advances in manufacturing techniques make the production and the installation of complicated fiber links an attractive reality.

7-3 FUTURE WORK

Fiber optics is a new area of science which is far from being near its maturation stage. This makes the field of fiber optics full of chances and research areas. These areas vary from being theoretical studies to experimental research activities. The theoretical studies include:

1. study the effect of numerical aperture in the coupled power to different kinds of fibers,
2. the relation between the number of modes that can propagate in a multimode fiber and different kinds of signal dispersion,
3. different types of studies which may be joined between physics and electrical and chemical engineering dealing with the different structures of both the fiber and the material that makes the fiber,
4. study of the S/N (signal to noise ratio) in different kinds of fibers, and how it affects the maximum attainable bandwidth,
5. study of the effects of skew rays on both the fiber bandwidth and dispersion that exists in a fiber link,
6. many other studies can be done on skew rays, such as finding their effect on the numerical aperture and the equilibrium NA,
7. study of a single mode fiber link with a laser

diode as a source and avalanche photodetector to demonstrate the extremely high data rate that can be carried in fiber links (400 Gbps).

In addition to all the above topics there are hundreds of topics that can deal with each of the building blocks of an optical fiber link. On the other hand, there are many topics that can be used in experimental research such as:

1. the effect of the type of fiber in both of the maximum transmission distance and the lowest BER achievable in an optical link,
2. the effect of using TDM in increasing the information carrying capacity of an optical fiber link,
3. the effects of the source and the photodetector on the maximum attainable data rate of an optical link.

In addition to all the research areas mentioned above there are many different opportunities in the work field. One of these opportunities is to use connector and splices more efficiently and quickly with low loss (especially, with single mode fibers).

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