Near East University

Faculty of Engineering

Department of Electrical and Electronic Engineering

Fiber Optic Communication Electronics (Operational Principles, Testing and service)

Graduation Project
EE- 400

Student: Kazi Muniruddin Ahmed (981314)

Supervisor: Prof. Dr Sc. Parviz Ali-Zada

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I would also like to thank my parents and all my family members.

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ABSTRACT

In fiber optic communication system connectors are used to connect two fibers or a fiber to active devices. Splices are used to permanently connect two fibers. For both connectors and splices, loss is the primary performance parameter. With durability and repeatability next in importance. Optical return loss (back reflection) is only of importance in single mode fiber networks. Connectors and cable assemblies are tested for insertion loss with meters and sources. Mode power distribution has a large effect on the connector or splice loss measured in multimode fibers. Couplers and switches are tested for output consistency and total excess loss. Mode power distribution is critical for proper measurements in both switches and couplers.

Fiber comes in two major types: singlemode and multimode. Multimode may be either step index or graded index (CI), with CI more common. Fiber is generally tested for attenuation coefficient (dB/km), but manufacturers will also test for diameter and concentricity, numerical aperture (NA) and perhaps even bandwidth. Mode power distribution can greatly affect the measurement of attenuation and bandwidth in multimode fiber. OTDRs can be used to get indirect measurements of attenuation, but with higher measurement uncertainty than with insertion loss measurements. Bandwidth consists of both modal and chromatic dispersion and is very difficult to test.

Standards are necessary for insuring compatibility and interoperability, but should not stifle the development of technology. Standards come from organized standards groups and market acceptance. Primary standards are needed to allow measurements to be made with agreement among groups of users. Networks standards insure product interoperability.

INTRODUCTION

In this project fiber optic communication system is studied with intensive care. Fiber optic communication system is a new technology, which will have a large impact on telecommunications as well as fast data transmission and computer interconnections. The project consists of four chapters.

Chapter 1 gives a short introduction to fiber optic communication system by considering the historical development, the general system and the major advantages & disadvantages provided by this technology.

Chapter 2 gives the basic idea of a communication system and a communication network. Important elements in the communication process are introduced, which consist of Connectors and Splices, Connectorized Cable Testing, Couplers and Switches.

Chapter 3 will cover important and advanced topics in fiber optic communication system. On the fiber optic side, attenuation, optical fiber test, sources for loss measurement and modal effects on attenuation are discussed in detail. Finally, gives the detail idea of fiber optic standards, optical power and more other applications of fiber optic system.

Chapter 4 covers the important networking aspects and installing FO cable plant. Specifically, testing networks and topologies in fiber optic communication are explained, and various innovative networking are described.

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1. Fiber Optic Communication Electronics

1.1 Introduction

In the recent years it has become apparent that fiber-optics are steadily replacing copper wire as an appropriate means of communication signal transmission. Fiber-optic systems are currently used most extensively as the transmission link between terrestrial hardwired systems. They span the long distance between local phone systems as well as providing the backbone architecture of city phone systems. Other systems users include cable television services, universities, offices, industry and electric utility companies. This briefing will give an overview of the beginning of fiber optic, fiber basics, fiber optic structure, fiber-optic advantages, disadvantages, fiber optic devices and it's testing.

1.2 History

The fiber-optic is defined as branch of optics that deals with the transmission of it through ultra pure glass, plastic or some other form of transparent media. One of first noted experiment that demonstrated the transmission of light through a dielectric medium has been created to John Tyndall. In 1854 John Tyndall demonstrated that light could be guided through stream of water based on the principle of total internal reflection. In 1880 Alexander Graham Bell invented the photo phone, a device that transmits voice signals over a beam of light. Charles H.Townes created great interest in communication at optical frequencies in 1958 with die invention of the laser. In 1966 Charles K. Kao and George Hockham of Standard Telecommunications Laboratories of England performed several experiments to prove that, if glass could be made more transparent by reducing its impurities, light loss could be minimized. Their research led to a publication in which they predicted that optical fiber could be made pure enough to transmit light several kilometers. In the next two decades researchers worked intensively to reduce the attenuation to 0.16 dB/km.1n1988 the American National Standards Institute (ANSI) published the Synchronous Optical Network (SONET). 1995 Multimedia applications for business have become the major impetus for increased use of optical fiber within the LAN, MAN, and

WAN environment.

1.3 Theory of Light

In the seventeenth and eighteenth centuries, there were two schools of thought regarding the nature of light. Sir Isaac Newton and his followers believed that light consisted of rapidly moving particles (or corpuscles), whereas Dutch physicist Christian Huygens regarded light as being a series of waves.

The wave theory was strongly supported by an English doctor named Thomas Young. By 1905, quantum theory, introduced by Clark Maxwell, showed that when light is emitted or absorbed it is not only as a wave, but also as an electromagnetic particle called a photon. Photon is said to possess energy that is proportional to its frequency. This is known as Planck's law, which states:

$E = H * V$

   Where E= Photon's energy (J);

     H= Planck's constants (J-s)

     V= Frequency of photon (Hz)

Using the particle theory Einstein and Planck were able to explain photoelectric effect ten visible lights or electromagnetic radiation of a hire frequency shines on a metallic surface; electrons are emitted, which is turning an electric current.

1.3.1 Electromagnetic Spectrum

Fundamentally, light has been accepted as a form of electromagnetic radiation that can be categorized into a portion of the entire electromagnetic spectrum, as shown in Table 1.1. In addition, each frequency can be specified in terms of its equivalent wavelength. Frequency or wavelengths are directly related to the speed of light.

$C = f * \lambda$

Where   C = speed of light in a vacuum or free space,

f = frequency (Hz);

λ = Wavelength (m).

Table 1.1 Electromagnetic spectrum

Range of wavelength, nm	Name of wavelength	
10∧6-770	Inferred	
770-662	Red	
662-597	Orange	
597-577	Yellow	
577-492	Green	Visible
492-455	Blue	
455-390	Violet	
390-10	Ultraviolet	

The portion of the electromagnetic spectrum regarded as light has been expanded in Table 1.1 To illustrate three basic categories of light:

1.   Infrared: that portion of the electromagnetic spectrum having a wavelength ranging from 770 to 10∧6 nm. Fiber optic systems operate in this range.

2.   Visible: that portion of the electromagnetic spectrum having a wavelength ranging from 390 to 770 nm. The human eye responding to these wavelengths allows us to see the colors ranging from violet to red, respectively.

3.   Ultraviolet: that portion of the electromagnetic spectrum ranging from 10 to 390 nm.

The light that we use for most fiber optic systems occupies a wavelength range from 800 to

1600 nm. This is slightly larger than visible red light and falls within the infrared portion of the spectrum.

1.3.2 Snell's Law: Total Interval Reflection

For light to propagate in any medium, the medium must be transparent to some degree. The degree of transparency determines how far light will propagate. Transparent materials can be in the form of a liqni4, gas, or a solid. Some examples are glass, plastic, air, and water. One of the most fundamental principles of light is that when it strikes the interface between two transparent mediums, such as air and water, a portion of the light energy is reflected back into the first medium and a portion is transmitted into the second medium. The path in which light travels from one point to another is commonly referred to as the ray. Figure 1.1 illustrates the classic example of a ray of light incident upon the surface of water. Notice that part of the light is reflected off the surface of water and part of it penetrates the water. The ray penetrating to water refracted or bent toward the normal. The amount of refracted light is determined by the medium's index of refraction, generally denoted by the letter n. Index of refraction is the ratio of the speed of light in a vacuum - C, to the speed of light in the given medium - v. This relationship is given by the equation: $n = C/v$. Since the speed of light is lower in mediums other than a vacuum, the index of refraction in such mediums is always greater than 1.

In 1621, the Dutch mathematician Willebrard Snell established that rays of light could be traced as they propagate from one medium to another based on their indices of refraction. Snell's low is stated by the equation:

$$n_1/n_2 = \sin\theta2/\sin\theta1$$

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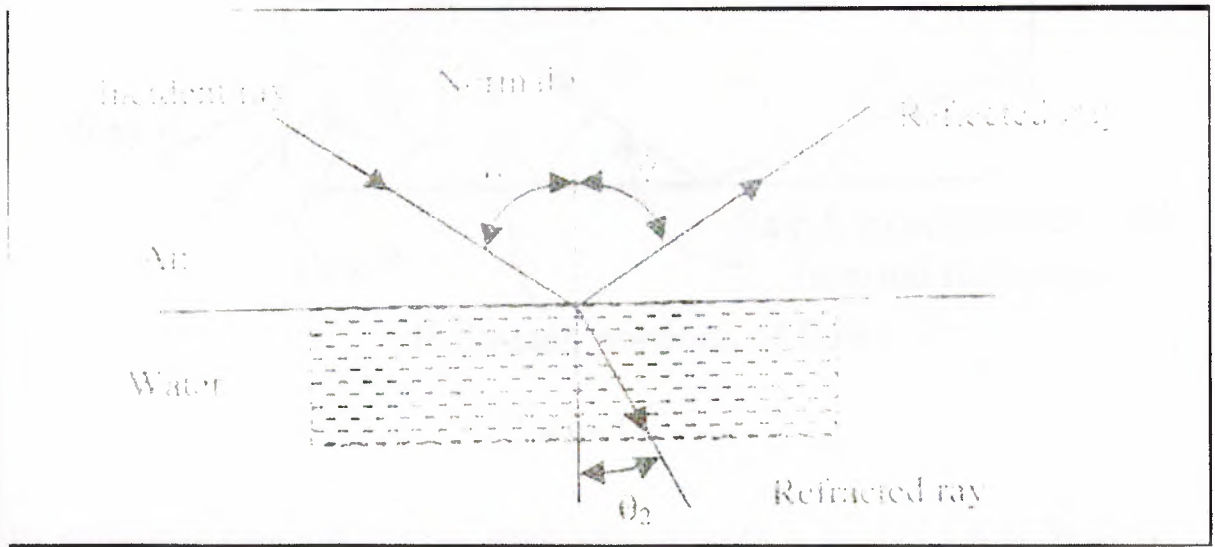
Figure-1.1

Where n_1 - refractive index of material 1; $\theta1$ - angle of incidence; $\theta2$ - angle of refraction; n_2 -refractive index of material 2. When the angle of incidence, $\theta1$, becomes large enough to cause the sine of the refraction angle, $\theta2$, to exceed the value of 1, total internal reflection occurs. This angle is called the critical angle, θc. The critical angle, θc, can be derived from Snell' S law as follows

$$n_1 \sin\theta1 = n_2 \sin\theta2$$
$$\sin\theta1 = n_2 \sin\theta2 / n_1$$

When $\sin\theta1 = \sin\theta2$, then $\sin\theta1 = n2/ n1$. Therefore, critical angle: $\sin\theta c = (n^2 / n1)$

Refracted portions of B ray
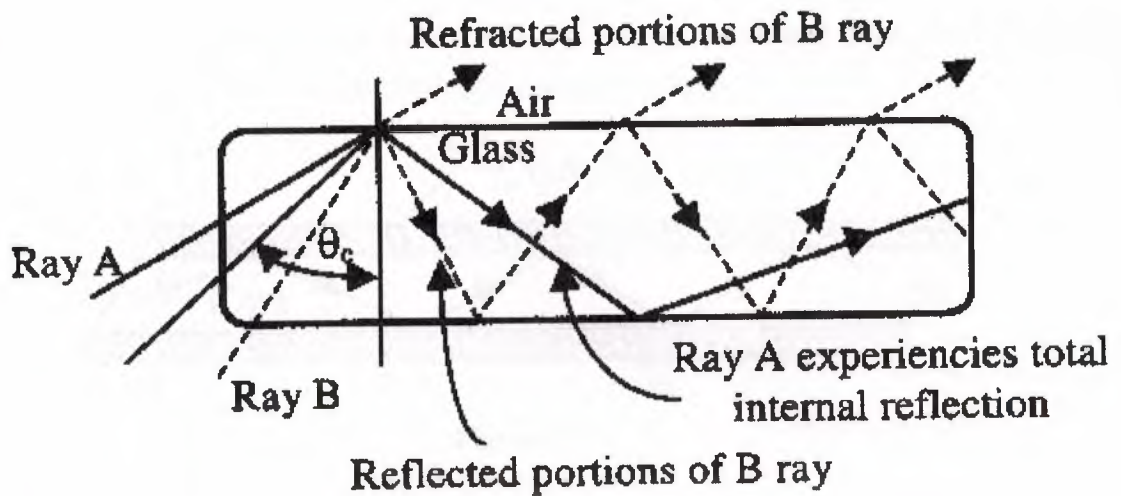
Figure-1.2

By surrounding glass with material whose refraction index is less than that of the glass, total internal reflection can be achieved. This is illustrated in Figure 1.2. Ray A penetrates the glass-air interface at an angle exceeding the critical angle, θc, and therefore experiences total internal reflection. On the other hand, Ray B penetrates the glass air interface at an angle less than the critical angle. Total internal reflection does not occur. Instead, a portion of ray B escapes the glass and is refracted away from the normal as it enters the less dense medium of air. A portion is also reflected back into the glass. Ray B diminished in magnitude as it bounces back and forth between the glass-air interfaces. The foregoing principle is the basis for guiding light through optical fibers. Two key elements that permit light guiding through optical fibers are its core and its cladding. The fiber's core is manufactured of ultra pure glass (silicon dioxide) or plastic. Surrounding the core is a material called cladding. A fiber cladding is also made of glass or plastic. Its index of refraction, however, it is typically 1% less than that of its core. This permits total internal reflection of rays entering the fiber and striking the core-cladding interface above the critical angle of approximately 82-degree. The core of the fiber therefore guides the light and the cladding contains the light. The cladding material is much less transparent than the glass making up the core of the fiber. This causes light rays to be absorbed if they strike the core-cladding interface at an angle less than the critical angle.

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In Figure 1.3, a light ray is transmitted into the core of an optical fiber. Total internal reflection occurs as it strikes the lower index cladding material.
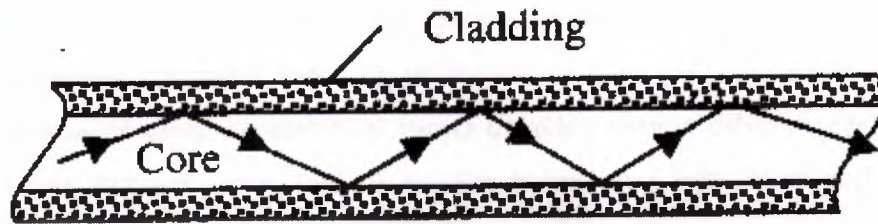
Figure-1.3

1.4 Block Diagram of the FOS

One of the main limitations of communication systems is their restricted information carrying capabilities. In more specific terms what this means is that the communications medium can only carry so many massages. And, as you have seen, this information-handling ability is directly proportional to the bandwidth of the communications channel. In telephone systems, the bandwidth is limited by the characteristics of the cable used to carry the signals. As the demand for telephones has increased better cables and wiring systems have been developed. Further, multiplexing techniques have been used to transmit multiple telephone conversations over a single cable.

In radio communication systems, the information modulates a high frequency carrier. The modulation produces sidebands, and therefore, the signal occupies a narrow portion of the 'if spectrum. However, the RE spectrum is finite. There is only so much space for radio signals. To increase the information capacity of a channel, the bandwidth of the channel must be increased. This reduces available spectrum space. Multiplexing techniques are used to send more signals in a given channel bandwidth, and methods have been developed to transmit more information in less bandwidth.

The information-carrying capacity of the radio signal can be increased tremendously if higher carrier frequencies are used. As the demand for increased communications capacity has gone up over the years, higher and higher RFs are being used. Today, microwaves arc the preferred radio channels for this reason, but it is more complex and expensive to use

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these higher frequencies because of the special equipment required.

One way to expand communications capability further is to use light as the transmission medium. Instead of using an electrical signal traveling over a cable or electromagnetic waves traveling through space, the information is put on a light beam and transmitted through space or through a special cable. In the late nineteenth century. Alexander Graham Bell, the inventor of the telephone, demonstrated that information could be transmitted by light.

Light beam communication was made more practical with the invention of the laser. The laser is a special high-intensity, single frequency light source. It produces a very narrow beam of brilliant light of a specific wavelength (color). Because of its great intensity, he laser beam can penetrate atmospheric obstacles better than other types of light. There by making light-beam communication more reliable over longer distances. The primary problem with such free-space light beam communication is that the transmitter and receiver must be perfectly aligned with one another.

Instead of using free space, some type of light carrying cable can also be used. For centuries it has been known that light is easily transmitted through various types of transparent media such as glass and water, but it wasn't until the early in 1900s that scientist were able to develop practical light carrying media. The mid-1950s glass developed fibers that permitted long light carrying cables to be constructed. Over the years, these glass fibers have been perfected. Further, low cost plastic fiber cable also developed. Developments in these cables permitted them to be made longer with less attenuation of the light.

Today the fiber optic cables have been highly refined. Cables many miles long can be constructed and interconnected for the purpose of transmitting information on a light beam over very long distances. Its great advantage is that light beams have an incredible information carrying capacity. Whereas hundreds of telephone conversations may be transmitted simultaneously at microwave frequencies, many thousands of signals can be carried on a light beam through a fiber optic cable. Using multiplexing techniques similar to those used in telephone and radio systems, fiber optic communications systems have an almost limitless capacity for information transfer.

The components of a typical fiber optic communications system are illustrated in Figure 1.4.

The information signal to be transmitted may be voice, video, or computer data. The first step is to convert the information into a form compatible with the communications medium. This is usually done by converting continuous analog signals such as voice and video (TV) signals into a series of digital pulses. An Analog-to-Digital Converter (ADC) is used for this purpose. Computer data is already in digital form. These digital pulses are then used to flash a powerful light source off and on very rapidly. In simple low cost systems that transmit over short distances, the light source is usually a light-emitting diode (LED). This is a semiconductor device that puts out a low intensity red light beam. Other colors are also used. Infrared beams like those used in TV remote controls are also used in transmission. Another commonly used light source is the laser emitting diode. This is also a semiconductor device that generates an extremely intense single frequency light beam.

The light beam pulses are then fed into a fiber optic cable where they are transmitted over long distances. At the receiving end, a light sensitive device known as a photocell or light detector is used to detect the light pulses. This photocell or photo detector converts the light pulses into an electrical signal. The electrical pulses are amplified and reshaped back into digital form. They are fed to a decoder, such as a Digital-to-Analog Convener (DAC), where the original voice or video is recovered for user.
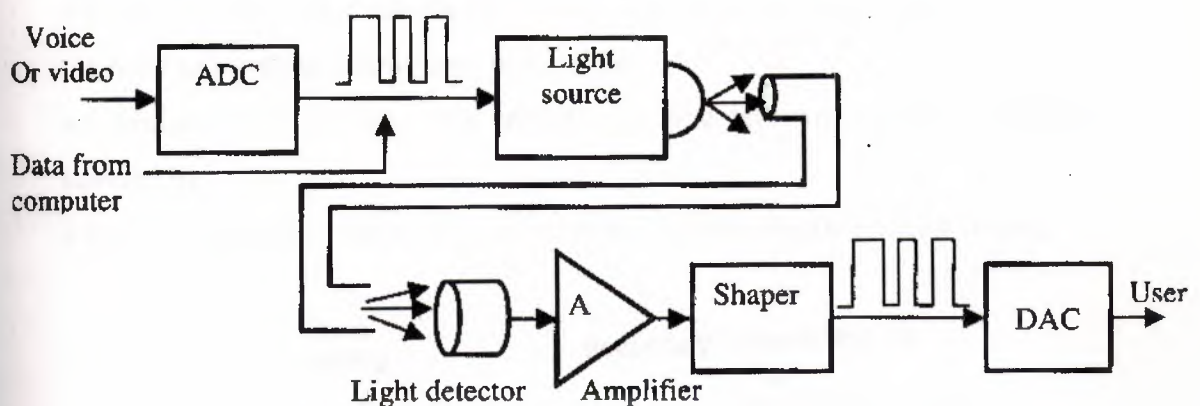
Figure-1.4

1.5 Fiber Optic Cables

Just as standard electric cables come in a variety of sizes, shapes, and types. Fiber optic cables are available in different configurations. The simplest cable is just a single strand of fiber. Complex cables are made-up of multiple fibers with different layers and other elements.

The portion of a fiber optic cable (core) that carries the light is made from either glass or plastic. Another name for glass is silica. Special techniques have been developed to create nearly perfect optical glass or plastic, which is transparent to light. Such materials can carry light over a long distance. Glass has superior optical characteristics over plastic. However, glass is far more expensive and more fragile than plastic. Although the plastic is less expensive and more flexible, its attenuation of light is greater. For a given intensity, light will travel a greater distance in glass than in plastic. For very long distance transmission, glass is certainly preferred. For shorter distances, plastic is much more practical.

All fibers consist of a number of substructures including (Figure 1.5).

• A core, which carries most of the light, surrounded by

• A cladding, which bends the light and confines it to the core, surrounded by

• A substrate layer (in some fibers) of glass which does not carry light, but adds to the diameter and strength of the fiber, covered by

• A primary buffer coating, this provides the first layer of mechanical protection, covered by.

• A secondary buffer coating, this protects the relatively fragile primary coating.

Figure-1.5

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The cladding is also made of glass or plastic but has a lower index of refraction. This ensures that the proper interface is achieved so that the light waves remain within the core. In addition to protecting the fiber core from nicks and scratches, the cladding adds strength. Some fiber optic cables have a glass core with a glass cladding. Others have a plastic core with a plastic cladding. Another common arrangement is a glass core with a plastic cladding. It is called plastic-clad silica (PCS) cable.

1.6 Basic Construction of the Fiber-Optic Cables
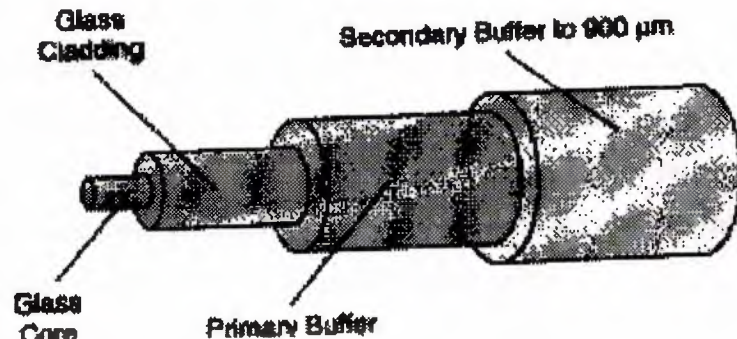
There are two basic ways of classifying fiber optic cables. The first way is an indication of how the index of refraction varies across the cross section of the cable. The second way of classification is by mode. Mode refers to the various paths that the light rays can take in passing through the fiber. Usually these two methods of classification are combined to define the types of cable. There are two basic ways of defining the index of refraction variation across a cable. These are step index and graded index. Step index refers to the fact that there is a sharply defined step in the index of refraction where the fiber core and the cladding interface. It means that the core has one constant index of refraction N1, while the cladding has another constant index of refraction N2.

The other type of cable has a graded index. In this type of cable, the index of refraction of the core is not constant. Instead, the index of refraction varies smoothly and continuously over the diameter of the core. As you get closer to the center of the core, the index of refraction gradually increases, reaching a peak at the center and then declining as the other outer edge of the core is reached. The index of refraction of the cladding is constant.

Mode refers to the number of paths for the light rays in the cable. There are two classifications: single mode and multimode. In single mode, light follows a single path through the core. In multimode, the light takes many paths through the core.

Each type of fiber optic cable is classified by one of these methods of rating the index or mode. In practice, there are three commonly used types of fiber optic cable: multimode step index, single mode step index and multimode graded index cables.

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1.6.1 The multimode step-index fiber

This cable (Figure 1.6(a)) is the most common and widely used type. It is also the easiest to make and, therefore, the least expensive. It is widely used for short to medium distances at relatively low pulse frequencies.

The main advantage of a multimode step index fiber is the large size. Typical core diameters are in the 50-to-1000 micrometers (μm) range. Such large diameter cores are excellent at gathering light and transmitting it efficiently. This means that an inexpensive light source such as LED can he used to produce the light pulses. The light takes many hundreds of even thousands of paths through the core before exiting. Because of the different lengths of these paths, some of the light rays take longer to reach the end of the cable than others. The problem with this is that it stretches the light pulses (Figure 1.6(b)). In Figure 1.6 ray A reaches the end first, then B, and C. The result is a pulse at the other end of the cable that is lower in amplitude due to the attenuation of the light in the cable and increased in duration due to the different arrival times of the various light rays. The stretching of the pulse is referred to as modal dispersion. Because the pulse has been stretched, input pulses cannot occur at a rate faster than the output pulse duration permits. Otherwise the pulses will essentially merge together as shown in Figure 1.6(c). At the output, one long pulse will occur and will be indistinguishable from the three separate pulses originally transmitted. This means that incorrect information will be received. The only core for this problem is to reduce the pulse repetition rate. When this is done, proper operation occurs. But with pulses at a lower frequency, less information can be handled.

| Cross section | Index profile | Beam path | dispersion |

N_1
N_2

cladding
core

Light source

Input

a)

Output

b)

Input

Output
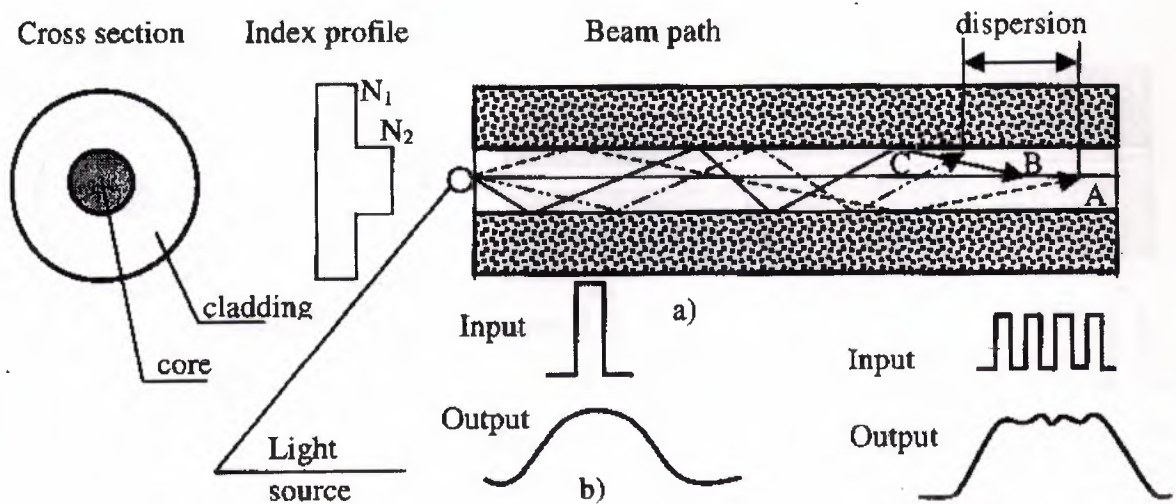
Figure-1.6

1.6.2 Single mode cable

In a single mode, or mono-mode, step-index fiber cable the core is so small that the total number modes or paths high the core are minimized and modal dispersion is essentially eliminated. The typical core sizes are 5 to 15 μm. The output pulse has essentially the same duration as the input pulse (see Figure 1.7).

The single mode step index fibers are by far the best since the pulse repetition rate can be high and the maximum amount of information can be carried. For very long distance transmission and maximum information content, single-mode step index fiber cables should be used.

The main problem with this type of cable is that because of its extremely small size, it is difficult to make and is, therefore, very expensive. Handling, splicing, and making interconnections are also more difficult. Finally, for proper operation an expensive, super intense light source such as a laser must be used. For long distances, however, this is the type of cable preferred.

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Cross section   Index profile   Beam path

N_1
N_2

cladding   Input   Output

core
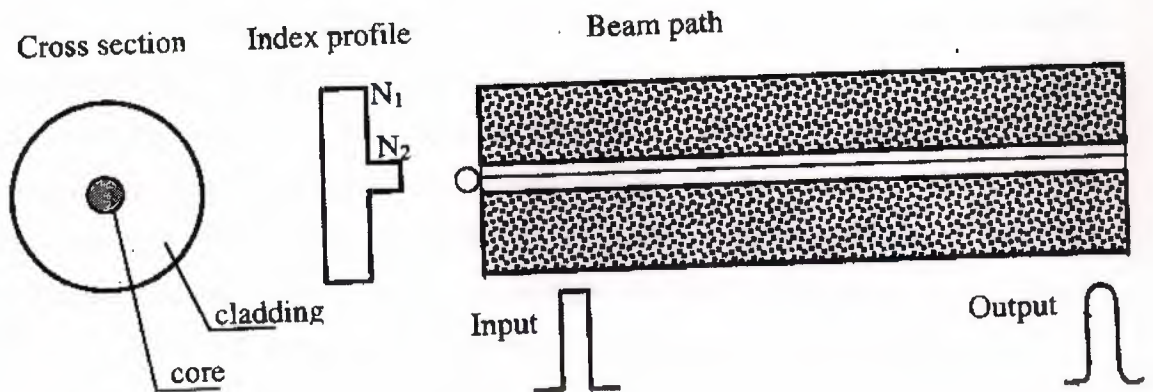
Figure-1.7

1.6.3 Multimode graded-Index fiber cables

These cables have a several modes or paths of transmission through the cable, but they are much more orderly and predictable. Figure 1.8 shows the typical paths of the light beams. Because of the continuously varying index of refraction across the core, the light rays are bent smoothly and converge repeatedly at points along the cable. The light rays near the edge of the core take a longer path butt travel faster since the index of refraction is lower. All the modes or light paths tend to arrive at one point simultaneously. The result is that there is less modal dispersion. It is not eliminated entirely, but the output pulse is not nearly as stretched as in multimode step index cable. The output pulse is only slightly elongated. As a result, this cable can be used at very high pulse rates and, therefore, a considerable amount of information can be carried on it.

Cross section   Index profile   Beam path

N_1
N_2

cladding   Input   Output

core

Figure-1.8

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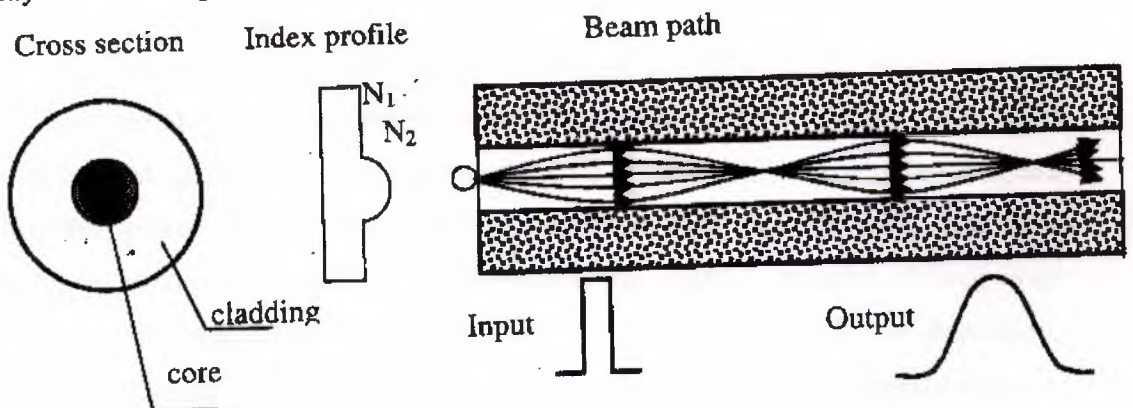
This type of cable is also much wider in diameter with core sizes in the 50 to 100 (μm) ranges. Therefore, it is easier to splice and interconnect, and cheaper, less-intense light sources may be used. The most popular fiber-optic cables that are used in LAN: Multimode-step index cable -65.5/125; multimode-graded index cable - 50/125. The multimode-graded index cable - 100/140 or 200/300 are recommended for industrial control applications because it's large size. In high data rate Systems is used single mode fiber 9/125. Typical core and cladding diameters of these cables are shown in Figure 1.9.
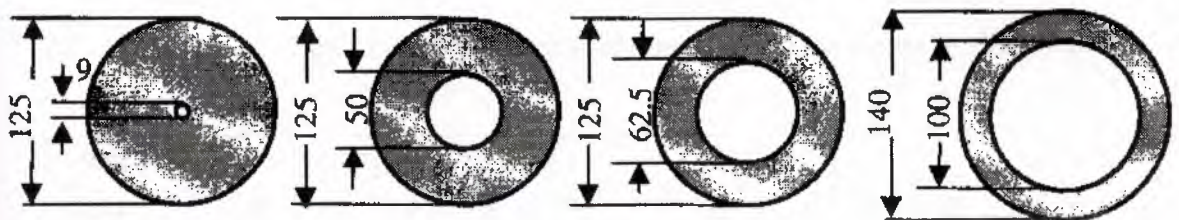
Figure-1.9

1.7 Specifications of the cables

The fiber as a transmission medium is characterized by Attenuation, A, db/km; Numeric aperture, NA and Dispersion, ns/km

1.7.1 Attenuation

The main specification of a fiber optic cable is its attenuation. Light power which does not reach the other end of the fiber has either left the fiber or been absorbed (convened to heat) in it. The amount of attenuation varies with the type of cable and its size. Glass has less attenuation than plastic. Wider cores have less attenuation than narrower cores. But more importantly, the attenuation is directly proportional to the length of the cable. It is obvious that the longer the distance the light has to travel the greater the loss due to absorption, scattering, and dispersion. Doubling the length of a cable doubles the attenuation, and soon. The attenuation of a fiber optic cable is expressed in decibels per unit of length. The

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standard specification for fiber-optic cable is the attenuation expressed in terms of decibels per kilometers. The standard decibel formula used is

$$Loss, dB = 10 \log (Po/Pi)$$

Where Po is the output power and Pi is the input power.

The table 1.2 shows the percentage of output power for various decibel losses. The attenuation ratings of fiber-optic cables vary over a considerable range.

The table 1.2 shows the percentage of output power for various decibel losses.

Table 1.2 the percentage of output power expressed by dB

Loss, (dB)	1	2	3	4	5	6	7	8	9	10	20	30
P	79	63	50	40	31	25	20	14	12	10	1	0.1

The finest single mode step index cables have an attenuation of only 1 dB/km. However, a very large core plastic fiber cables can have an attenuation of several thousands decibels per kilometer. Temperature dependence of the attenuation of fiber optic cable is shown in Figure 1.10.

The following contribute to the attenuation.

Figure-1.10

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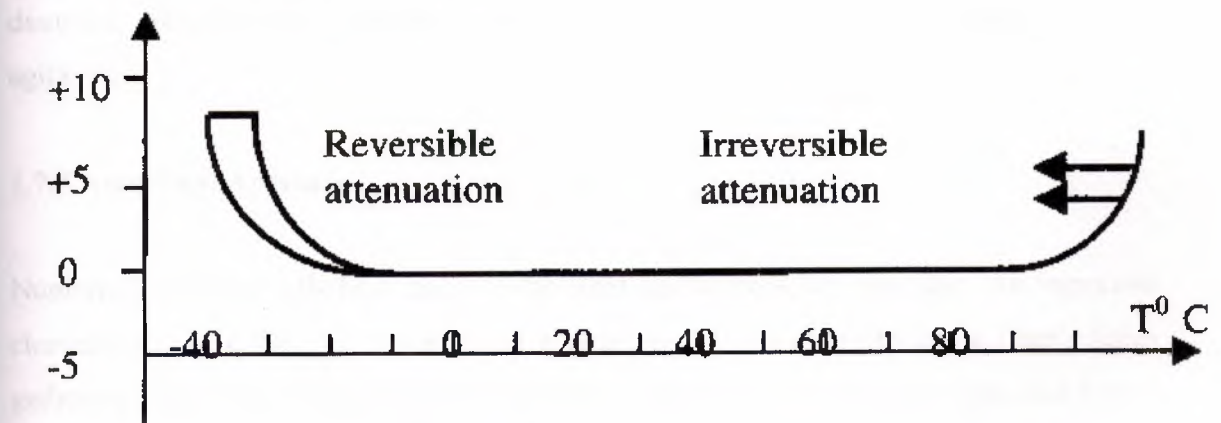
1.7.2 Rayleigh-scattering:

A mechanism called Rayleigh scattering prevents any further improvement in attenuation loss. Rayleigh scattering is caused by micro irregularities in the random molecular structure of glass. These irregularities are formed as the fiber cools from a molten state. Normally, electrons in glass molecules interact with transmitted light by absorbing and reradiating light at the same wavelength. A portion of the light, however, strikes these micro irregularities and becomes scattered in all directions of the fiber, some of which is lost in the cladding. Consequently the intensity of the beam is diminished,

1.7.3 Radiation losses:

A phenomenon called micro bending can cause radiation losses in optical fibers in excess of its intrinsic losses. Micro bends are miniature bends and geometric imperfections along the axis of the fiber that occur during the manufacturing or installation of the fiber. Mechanical stress such as pressure, tension, and twist can cause micro bending. This geometric imperfection causes light to get coupled to various unguided electromagnetic modes that radiate and escape the fiber.

1.7.4 Absorption:

The following contribute to the absorption: Intrinsic impurities irregularities in core diameter, IR-absorption (infrared), OH- absorption (hydroxy, humidity) and molecular agitation.

1.7.5 Numerical Aperture

Numerical Aperture tells how much of the light can be pass into the fiber. An important characteristic of a fiber is its numerical aperture (NA). NA characterizes a fiber's light-gathering capability. Mathematically, it is defined as the sine of half the angle of a fiber's light acceptance cone. For multimode step index fiber typical values for NA are 0.25 to 0.4 for multimode step-index fiber and 0.2 to 0.3 for multimode graded-index fiber.

1.7.6 Dispersion:

Dispersions classified: material dispersion ψmat (ns/km) and modal dispersion, ψmod (ns/km)

1.7.7 Material dispersion:

A light pulse is composed of light of different wavelengths depending on the spectral width of the light source. The refractive index depends weakly on the wavelength. This causes the material dispersion.

1.7.8 Modal dispersion.

As shown above the modal dispersion due to the different arrival times of the various light rays.

The Table 1.3 shows the characteristics of the dispersions

Fiber type	Dispersion (ns/ km)	
	Modal	Material
Step index	$\psi Mod = t*(\Delta/2)$	
Graded index	$\psi Mod = t*(\Delta^2/2)$	$\psi Mat = 0.1\Delta\lambda$
Single mode	$\psi Mod = 0$	

1.8 Optical Transmitters

In an optical communications system the transmitter consist of a modulator and the circuitry that generates the carrier. In this case, the carrier is a light beam that is modulated by digital pulses that turn it on and off. The basic transmitter is nothing more than a light source.

Several devices are emitters of light, both natural and artificial. Few of these devices, however, are suitable for fiber-optic transmitters. What we are interested in a light source

that meets the following requirements:

- The light source must be able to turn on and off several tens of millions and even billions of time per second.
- The light source must be able to emit a wavelength that is transparent to the fiber.
- The light source must be efficient in terms of coupling light energy into the fiber.
- The power emitted must be sufficient enough to transmit through the optical fibers.
- Temperature variations should not affect the performance of the light source.
- The cost of manufacturing the light source must be relatively inexpensive.

Two commonly used devices that satisfy the above requirements are: monochromatic incoherent source-the light emitting diode (LBD) and monochromatic coherent source-the injection laser diode (ILD).

1.8.1 Light Emitting Diode

The major difference between the LBD and the ILD is the manner in which light is emitted from each source. The LED is an incoherent light source that emits light in a disorderly way. A laser is a light source that emits coherent monochromatic light. Monochromatic light has a pure single frequency. Coherent refers to the fact that all the light waves emitted are in phase with one another. Coherent light waves are focused into a narrow beam, which, as a result, is extremely intense. The effect is somewhat similar to that of using highly directional antenna to focus radio waves into a narrow beam, which also increases the intensity of the signal. Figure 1.11 illustrates the differences in radiation patterns. Both devices are extremely rugged, reliable, and small in size, In terms of spectral purity, the LED's half power spectral width is approximately 50 nm, whereas the ILD's spectral width is only a few nanometers. This is shown in Figure 1.11.

Ideally, a single spectral line is desirable. As the spectral width of the emitter increases, attenuation and pulse dispersion increase. The spectral purity for the ILD and its ability to

couple much more power into a fiber make it better suited for long-distances telecommunications links.
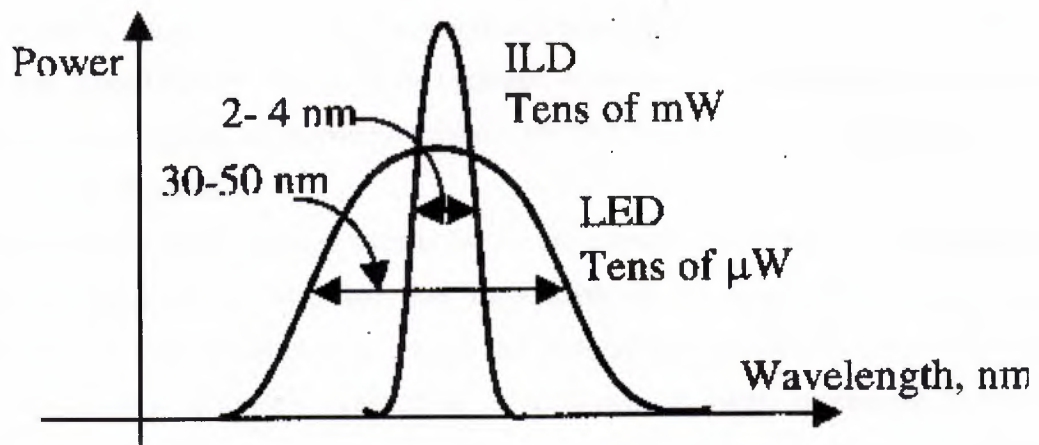
Figure-1.11

In addition, injection laser can be turned on and off at much higher rates than an LBD. The drawback however is its cost, which pay approach several hundreds of dollars as compared to a few dollars for LED's in large quantities. Table 1.4 lists the differences in operating characteristics between the LED and the ILD.

Table 1.4 Typical source characteristics for LED and ILD

	Output Power, μW	Peak Wavelength, nm	Spectral width, nm	Rise time, ns
LED	250	820	35	12
	700	820	35	6
	1500	820	35	6
Laser	4000	820	4	1
	6000	1300	2	1

Various semiconductor materials arc used to achieve this. Pure gallium arsenide (GaAs) emits light at a wavelength of about 900 nm. By adding a mixture of 10% aluminums (Al) to 90%

GaAs, gallium-aluminum-arsenide (GaAlAs) is formed, which emits light at a wavelength of 820 nm. Recall that this is one of the optimum wavelengths for fiber optic transmission. Fly tailoring the amount of aluminum mixed with GaAs, wavelengths ranging from 800 to 900 nm can be obtained.

To take advantage of the reduced attenuation losses at longer wavelengths, it is necessary to include even more exotic materials. For wavelengths in the range 1000 to 1550 nm, a combination of four elements is typically used: indium, gallium, arsenic and phosphorus. These devices arc commonly referred to as quaternary devices, combining these four elements produces the compound indium-gallium-arsenide-phosphate (InGaAsP). Transfer characteristic of LED and ILD are shown Figure 1.12(a) and (b).
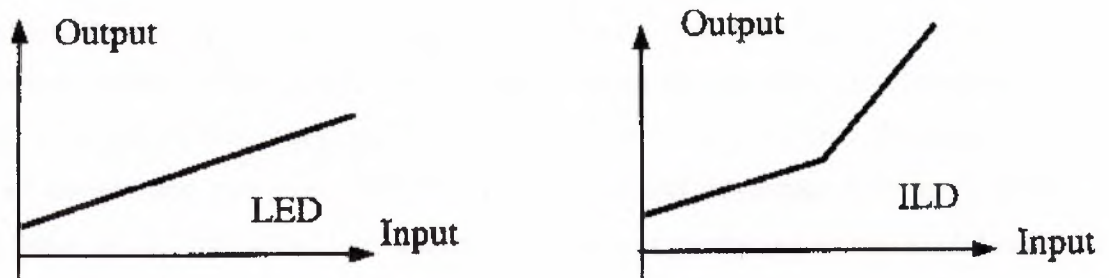
Figure-1.12

1.8.2 Injection Laser Diode

The term laser is an acronym for light amplification by stimulated emissions of radiation. There are many types of lasers on the market. They are constructed of gases, liquids, and solids. Laser diodes are also called injection laser diodes (ILD), because when current is injected across the PN junction, light is emitted relatively large and sophisticated

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device that outputs a highly intense beam of visible light. Although this is in part true, the laser industry is currently devoting a great deal of effort toward the manufacture of miniature semiconductor laser diodes. Figure 1.11 illustrates the spectrum NA). ILDs are ideally suited for use within the fiber-optic industry due to their small size, reliability, and ruggedness. Step response of ILD is shown Figure 1.13.
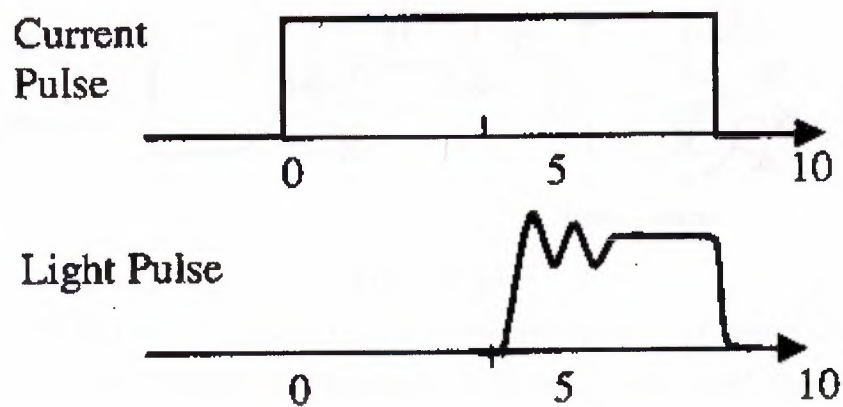
Figure-1.13

The most widely used light source in fiber optic Systems is ILD. Like tile LED, it is a PN junction diode usually made of GaAs. Injection laser diodes are capable of developing light power up to several wafts. They are far more powerful than LEDs and, therefore, are capable of transmitting over much longer distances. Another advantage ILDs have over LEDs is theirs speed. High-speed laser diodes are capable of gigabit per second digital data rates.

1.8.3 Optical Transmitter circuits

The light transmitter consists of the LED and its associated driving circuitry. An optical transmitter circuit using the LED is shown in Figure 1.15. The binary pulses are applied to a logic gate, which, in turn, operates a transistor switch T that turns the LBD off and on. A positive pulse at the NAND gate input causes the NAND output to go to zero. This turns

off T, so the LED is forward-biased through R_1 and turns on. With zero input, the NAND output is 1, so T turns on and shunts current away from the LED.
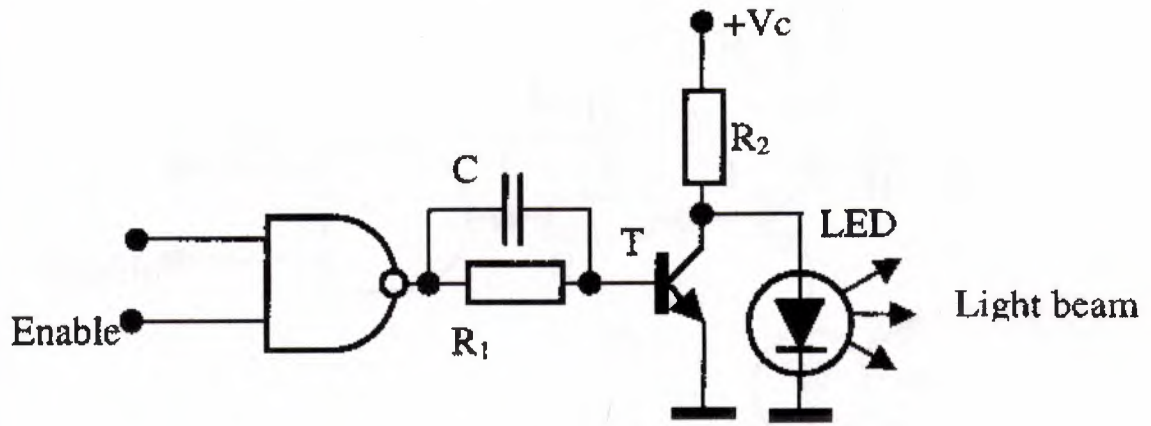
Figure-1.14

Very high current pulses are used to ensure a brilliant high-transmission rates are limited. Most LED like transmitters are used for short-distance, low speed digital fiber optic systems. With zero input, the NAND output is 1, so T turns on and shunts current away from the LED. Most LEDs are capable of generating power levels up to approximately several hundred μW. With such low intensity, LED transmitters are good for only short distances. Further the speed of the LED is limited. Turn-of and turn-on times are no faster than several nanoseconds. A typical injection laser transmitter circuit is shown in Figure 1.15 When the input is zero, the AND gate output is zero, so T is off and so is the laser. Capacitor C_2 charges through R_3 to the high voltage. When a binary I input occurs, T conducts connecting C_2 to the ILD. Then C_2 discharges a very high current pulse into the laser, turning it on briefly and creating the light pulse.
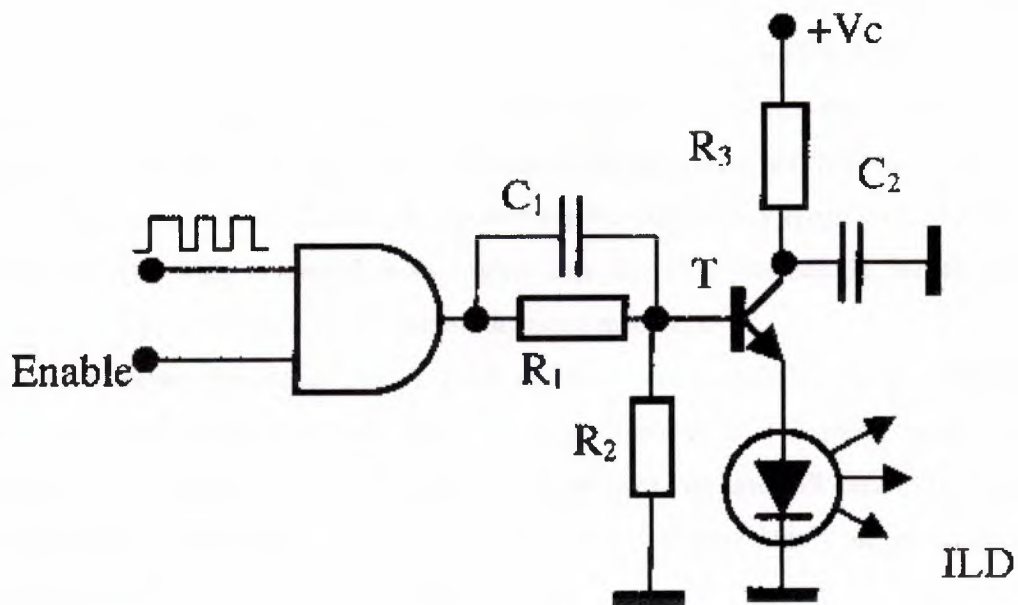
Figure-1.15

1.9 Optical Receiver Circuit

Two kinds of semiconductor receivers are used:

- PIN (P-intrinsic-N) diode;
- APD (Avalanche- Photo-Diode).

Instead of "receiver" some times is used light detector, photo detector or optical-to-electric converter. The receiver pan of the optical communications system is relatively simple. It consists of a detector that will sense the light pulses and convert them into an electrical signal. This signal is then amplified and shaped into the original digital serial data. The most critical component, of course, is the light sensor.

The most widely used light detector is a photo diode. This is silicon PN junction diode that is sensitive to light. This diode is normally reverse-biased. Whenever light strikes the diode, this leakage current will increase significantly. It will flow through a resistor and develop a voltage drop across it. The result is an output voltage pulse.

The resulting voltage pulse is very small, so it must be amplified. This can be done by using a phototransistor. Thus the transistor amplifies the small leakage current into a larger.

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The sensitivity and response time of a photo diode can be increased by adding an undraped or intrinsic (I) layer between the P and N semiconductors to form a PIN diode.

Although the PIN photodiode is extremely well suited for most fiber optic applications, it's sensitively to light (responsively) is not as great as the avalanche photodiode (APD). Due to their inherent gain, typical values of responsively for APDs may range from 5 A/W to as high as 100MW. This is considerably higher than the PIN photodiode, which makes it extremely attractive for fiber-optic communications receivers.

Figure 1.16 shows the basic circuit used in most receivers. The current through the photodiode (PD) generated when light is sensed produced a current, which is then amplified in an amplifier (A). The pulses to ensure fast rise and fall times. The output is passed through a logic gate so that the correct binary voltage levels are produced. Most systems have a data rate of 10 to 500 Mbits/s.

The product of the bit rate and the distance usually indicates a system performance. This fling tells the fastest bit rate that can be produced over a 1-km cable. Assume a system with a 100 Mbits-km/s rating. If the distance increases, the bit rate decreases in proportion.

Another important consideration is the maximum distance between repeaters. Obviously the fewer the repeaters are better. The average distance between repeaters is now up to 100km range.

Figure-1.16

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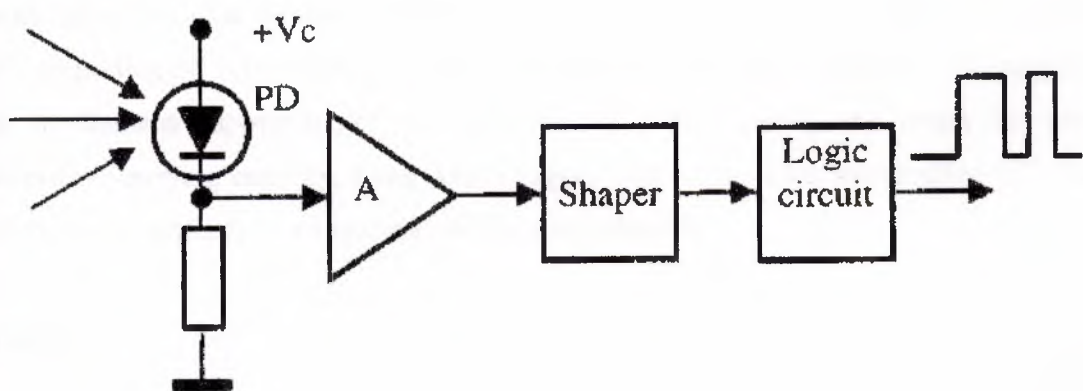
1.10 Advantages and Disadvantages of the FOB

1.10.1 Advantages

The major advantages are

Bandwidth:

One of the most significant advantages that fiber has over copper or other transmission media is a bandwidth. Bandwidth is directly related to the amount of information that can be transmitted per unit time. Today's advanced fiber optic systems are capable of transmitting several gigabits per second over hundreds of kilometers. Ten thousands of voice channels can now be multiplexed together and sent over a single fiber strand.

Less Lose:

Currently, fiber is being manufactured to exhibit less than a few tenths of a decibel of loss per kilometer.

Less Weight and Volume:

Fiber optic cables are substantially lighter in weight and occupy much less volume than copper cables with the same information capacity. For example, a 3-in. diameter telephone cable consisting of 900 twisted-pair wires can be replaced with a single flirt strand 0.005 inch in diameter (approximately the diameter of a hair strand) and retain the same information-carrying capacity. Even with a rugged protective jacket surrounding the fiber, it occupies enormously less space and weights considerably less.

Security:

Since light does not radiate from a fiber optic cable, it is nearly impossible to secretly tap into it without detection. For this reason, several applications requiring communications security employ fiber-optic systems. Military information, for example, can be transmitted

over fiber to prevent eavesdropping. In addition, metal detectors cannot detect fiber optic cables unless they are manufactured with steel reinforcement for strength.

Flexibility

The surface of glass fiber is much more refined than ordinary glass. This coupled with its small diameter, allows it to be flexible enough to wrap around a pencil. In terms of strength a 0.005-in. strand of fiber is strong enough to cut one's finger before it breaks, if enough pressure is applied against it.

Economic

Presently, the cost of fiber is comparable to copper at approximately $0.29 to $0.50 per yard and is expected to drop as it becomes more widely used. Since transmission losses are considerably less than for coaxial cable, expensive repeaters can be spaced farther apart. Fewer repeaters mean a reduction in overall system cost and enhanced reliability.

Reliability

Once installed, a longer life span is expected with fiber over its metallic counterparts since it is more resistant to corrosion caused by environmental extremes such as temperature, corrosive gases, and liquids.

1.10.2 Disadvantages

In spite of the numerous advantages that fiber optic systems have over conventional methods of transmission, there are some disadvantages, particularly because of its newness. Many of these disadvantages are being overcome with new and competitive technology.

Interfacing costs

Electronic facilities must be converted to optics in order to interface to fiber; often these costs are initially overlooked. Fiber-optic transmitter, receiver, couplers, and connectors, for example, must be employed as part of the communication system. Test and repair equipment is costly. If the fiber optic cable breaks, splicing can be a costly and tedious task

Strength

Fiber, by itself, has a tensile strength of approximately 1 lb, as compared the to an al cable at 180 lb (RG59U) surrounding the fiber with stranded Kevlar and a protective PCV jacket can increase the pulling strength up to 500 lb. Installations requiring greater tensile strengths can he achieved with steel reinforcement.

Remote Powering of Devices

Occasionally it is necessary to provide electrical power to a remote device. Since this cannot be achieved through the fiber, metallic conductors are often included in the cable assembly. Several manufacturers now offer a complete line of cable types, including cables manufactured with both copper wire and fiber.

2.   FIBER OPTIC DEVICES

2.1   Connectors and Splices

Connectors are used to couple two fibers together or to connect fibers to transmitters or receivers, and connectors are designed to be demountable Splices, however, are used to connect two fibers in a permanent joint. While they share some common requirements, like low loss, high optical return loss and repeatability, connectors have the additional requirements of durability under repeated mating white splices are expected to last for many years through sometimes difficult environmental conditions.

2.1.1   Connectors

Today, there are approximately 70 different connectors in Use. The figure in the next page shows the most widely used connector types. A flaw series of "small form factor" connectors appeared in 1998-2000. Most work by simply aligning the two fiber ends as accurately as possible and securing them in a fashion that is east affected by environmental factors. Many techniques like expanded beam, using lenses, have been tried and abandoned for all but some very specialized applications.

Connectors have used metal, glass plastic and ceramic ferrules to align the fibers accurately, but ceramics seem to be the best choice currently. It is The most environmentally stable material, closely matching the expansion coefficient of glass fibers It is easy to bond to glass fiber with epoxy glues, and its hardness is perfect for a quick posh of the fiber As volume has increased, ceramic costs have been reduced to be competitive to metal connectors.

A new type of plastic, liquid crystal polymers (LCP), offers promise for molded ferrules at lower costs, if performance and durability can be proven.

Splice bushings have been made from metal, plastic and ceramic also. The plastic types work well over environmental conditions, but may suffer problems with repeated mating,

especially under conditions encountered in testing numerous connectors or cable assemblies. The plastic bushings 'shave' small amounts of plastic at each insertion. Some of this material may accumulate on the end of the connector and causes loss. Some may also built up and form a ridge in the bushing to cause an end gap in the mating of two connectors. Check splices bushings for these problems by viewing the end of the connector in a microscope baking for dust.
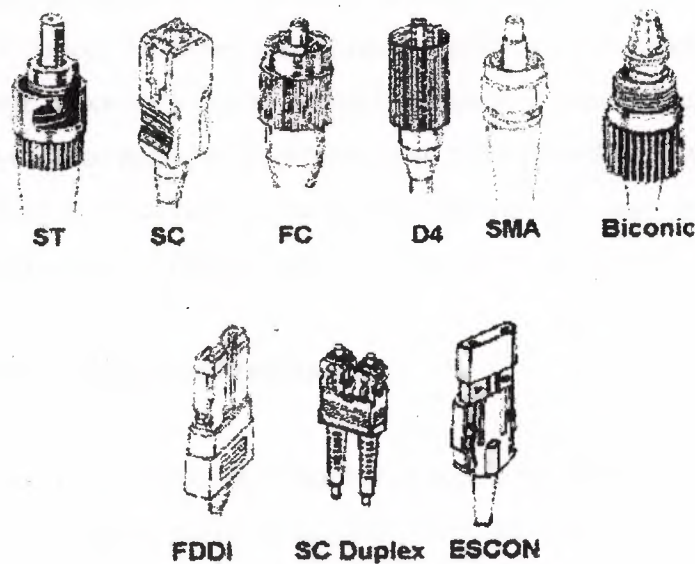
Figure-2.1 Connectors

2.1.2 Splices

There are two types of splices, fusion and mechanical. Fusion splicing (top) is done by welding the two fibers together, usually with an electrical arc. It has the advantages of low loss, high strength, low back reflection (optical return loss) and long term reliability Mechanical splices (bottom) use an alignment fixture to mate the fibers and either a matching gel or epoxy to minimize back reflection Some mechanical splices use bare fibers in an alignment bushing, while others closely resemble connector ferrules without all the mounting hardware. While fusion splicing normally uses active alignment to minimize

splice loss, mechanical splicing relies on tight dimensional tolerances in the fibers to minimize loss.

Low splice loss and high return loss is very dependent on the quality of the leave on both fibers being spliced. Cleaving is done by using a sharp blade to put a surface defect on the fiber hen pulling carefully to allow a crack to propagate across the fiber. In order to get good fusion splices, both fiber ends need to be close to perpendicular to the fiber axis. Then, when the fibers are fused, they will weld together properly.

With a mechanical splice, the fibers are pushed together with an index matching gel or epoxy between them. Since the index matching is not perfect some reflection may occur. If the fibers are cleaved at an angle, about 8 being best, the reflected light will be absorbed in the cladding, reducing the back reflections. Special cleavers have been designed to provide angle cleaves and should be available commercially in the near future.

2.1.3 Connector and Splice Loss Mechanisms

Connector and splice loss is caused by a number of actors, shown above Loss is minimized when the two fiber cores are perfectly aligned. Only the light that is coupled into the receiving fiber's core will propagate, so all the rest of the light becomes me connector or splice loss.

Although it is common to compare the typical connectors quoted by manufacturers, it may not be a fair comparison. The manufacturer has a design that they have qualified by expertly assembling and testing many samples of their connectors. But the actual loss obtained by any end user will be primarily determined by their skill at the termination process. The manufacturer only has control over the basic design of the connector, the mechanical precision in manufacturing, and the clearness of the termination instructions

End gaps cause two problems, insertion loss and return loss. The emerging cone of tight from the connector will spill over the core of the receiving fiber and be lost. In addition, the air gap between the fibers causes a reflection when the light encounters the change n refractive index from the glass fiber to the air in the gap. This reflection (called fresnel

reflection) amounts to about 5%. in typical flat polished connectors, and means that no connector with an air gap can have less than 0.3 dB loss. This reflection is also referred to as back reflection or optical return loss, which can be a problem in laser based systems. Connectors use a number of polishing techniques to insure physical contact of the fiber ends to minimize back reflection. On mechanical splices, it is possible to reduce back reflection by using non-perpendicular cleaves, which cause back reflections to be absorbed in the cladding of the fiber.

The end finish of the fiber must be properly polished to minimize toss. A rough surface will scatter light and dirt can scatter and absorb light. Since the optical fiber is so small, typical airborne dirt can be a major source of loss. Whenever connectors are not terminated, they should be covered to protect the arid of the ferrule from dirt. One should never touch the end of the ferrule, since the oils on one's skin causes the fiber to attract dirt. Before connection and testing, Iris advisable to clean connectors with link-free wipes moistened with isopropyl alcohol.

Two sources of loss are directional; numerical aperture (NA) and core diameter. Differences in these two will create connections that have different losses depending an the direction of light propagation. Light from a fiber with a larger NA will be more sensitive to angularity and end gap, so transmission from a fiber of larger NA to one of smaller NA will be higher toss than the reverse. Likewise, light from a larger fiber will have high loss coupled to a fiber of smaller diameter, while one can couple a small diameter fiber to a large diameter her wit minima loss, since it is much less sensitive to end gap or lateral offset

These fiber mismatches occur for two reasons. The occasional need to interconnect two dissimilar fibers and production variances in fibers of the same nominal dimensions. With two multimode fibers in usage today and two others which have been used occasionally in the past, it is possible to sometimes have to connect dissimilar fibers or use Systems designed for one fiber on another. Some system manufacturers provide guidelines on using various fibers, some don't. If you connect a smaller fiber to a larger one the coupling losses

will be minimum, often only the Fresnel loss (about 0.3 dB). But connecting larger fibers to smaller ones results in substantial losses not only due to the smaller cores size. but also the smaller NA of most small core fibers.

In the chart below, we show the loss incurred in connecting mismatched fibers. The range of values results from the variability of modal conditions. If the transmitting fiber is overfilled or nearer the source, the loss will be higher. If the fiber is near steady state conditions, the loss will be nearer the lower value.

If we are connecting fiber directly to a source, the variation in power will be approximately the same as for fiber mismatch except, replacing the smaller fiber with a larger fiber will result in a gain in power roughly equal to the loss in power in coupling from the larger fiber to the smaller ones.

Whenever using a different (and often unspecified) fiber with a system, be aware of differences in fiber bandwidths also. A system may work On paper, with enough power available, but the fiber could have insufficient bandwidth.

Table 2.1 Mismatched Fiber Connection Losses (excess loss in dB)

Transmitting Fiber			
Receiver fiber	62.5/125	85/125	100/140
50/125	1.6-1.9	3.0-4.6	4.7-9
62.5/125	-	0.9	2.1-4.1
85/125	-	-	0.9-1.4

2.1.4 Connector and Splice Loss Testing

In order to establish a typical loss for connectors, it is necessary to test all connectors in a standardized fashion, to allow for comparisons among various connectors Measurements of connector or splice losses are performed by measuring the transmitted power of a short

length of cable and then inserting a connector pair or splice into the fiber This test (designated FOTP-34 by the EIA) can be used for both multimode and single mode fiber, but the results for multimode fiber are very dependent on mode power distribution.

FOTP-34 has three options in modal distribution: 1) EMD (equilibrium modal distribution or steady state) 2) fully filled, and 3) any other conditions as long as they are specified Besides mode power distribution factors, the uncertainty of the measured loss is a combination of inherent fiber geometry variations, installed connector characteristics, and the effects of the splice bushing used to align the two connectors
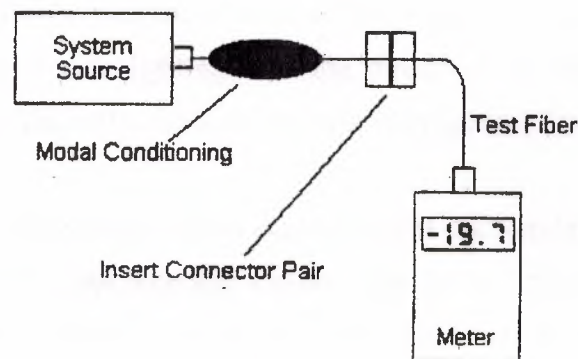
Figure-2.2 Connector and Splice Loss Testing

This test is repeated hundreds or thousands of times by each connector manufacturer, to produce data that shows the repeatability of their connector design, a critical factor in figuring margins for installations using many connectors Thus loss is not the only criteria for a good connector, it must be repeatable, so its average loss can be used for these margin calculations with some degree of confidence

2.1.5 Inspecting Connectors with a Microscope

Visual inspection of the end surface of a connector is one of the best ways to determine the quality of the termination procedure and diagnose problems. A well made connector will have a smooth, polished, scratch free finish, and the fiber will not show any signs of cracks or pistoning (where the fiber is either protruding from the end of the ferrule or pulling back into it)

The proper magnification for viewing connectors is generally accepted to be 30-100 power. Lower magnification, typical with a jeweler's loupe or pocket magnifier, will not provide adequate resolution for judging the finish on the connector. Too high a magnification tend to make small, ignorable faults look worse than they really are. A better solution is to use medium magnification. But inspect the connector three ways: viewing directly at the end of the polished surface with side lighting, viewing directly with side lighting and light transmitted through the core, and viewing at an angle with lighting from the opposite angle.

Viewing directly with side lighting allows determining if the ferrule hole is of the proper size, the fiber is centered in the hole and a proper amount of adhesive has been applied. Only the largest scratches will be visible this way, however. Adding light transmitted through the core will make cracks in the end of the fiber caused by pressure or heat during the polish process, visible.

Viewing, the end of the connector at an angle, while lighting it from the opposite side at approximately the same angle will allow the best inspection for the quality of polish and possible scratches. The shadowing effect of angular viewing enhances the contrast of scratches against the mirror smooth polished surface of the glass.

One needs to be careful in inspecting connectors, however. The tendency is to be overly critical, especially at high magnification Only defects over the fiber core are a problem. Chipping of me glass around the outside of the cladding is not unusual and will have no effect on the ability of the connector to couple light in the core. Likewise, scratches only on

the cladding will not cause any loss problems.

2.1.6 Connector and Splice Durability

Another factor important to a connector is the durability of the design shown by its ability to withstand many mating without degradation in loss. Testing connector durability is simply a mailer of repeated mating and demating of a connector pair while measuring loss. Since the loss is a function of both connectors and alignment sleeve, it is helpful to determine which the contributors to degradation are. Plastic alignment sleeves, when used with ceramic connectors, for example, will usually wear out much faster, shaving plastic off onto the connector ferrules and causing increased toss and return loss. When testing durability periodic inspection of the connector end faces and ferrules with a microscope to determine wear or contamination is very important.

Splice durability is one of withstanding many cycles of environmental stress, since splices are often used in splice enclosures in pedestals or mounted on poles where they are exposed to the extremes of climatic changes. Manufacturers usually test a number of. splices through many environmental cycles and accelerated aging to determine their durability. Such tests may take years.

2.1.7 Optical Return Loss In Connectors

If you have ever looked at a fiber optic connector on an OTDR, you are familiar with the characteristic spike that shows where the connector is. That spike is a measure of the back reflection or optical return loss of the connector, or the amount of light that is reflected back up the fiber by light reflecting oft the interface of the polished end surface of the connector and air. It is called fresnel reflection and is caused by the light going through the change in index of refraction at me interface between the fiber (n=1.5) and air (n=1).

For most systems, that return spike is just one component of the connectors loss, representing about 0.3 dB loss (two air/glass interfaces at 4% reflection each), the

minimum loss for non-contacting connectors without index-matching fluid. But in high-bit rate single mode systems, that reflection can be a major source of bit-error rate problems. The reflected light interferes with me laser diode chip, causes mode-hopping and can be a source of noise. Minimizing the light reflected back into the laser is necessary to get maximum performance out of high bit rate laser systems, especially the AM modulated CATV Systems.

Since this is only a problem with single mode Systems, manufacturers have concentrated on solving the problem for their single mode components. Severn schemes have been used to reduce back-reflections, including reducing the gap between connectors to a few wavelengths of light, which stops the fresnel reflection. The usual technique involves polishing the end surface of the fiber to a convex surface or at a slight angle to prevent direct back reflections.

Measuring this back reflection per standard test procedure SIA FOTP-107 is straightforward, but requires a special test setup. This test setup can be used with a bare fiber output into which a connector pair is installed (analogous to a FOTP-34 connector insertion loss test) or with a connector zed output for testing preconnectorized jumpers (like FOTP-171).

For the ELA FOTP-107 test procedure, one needs a calibrated coupler which can be used to inject a source into me test cable or pigtail and measure the light reflected back up the fiber, along with a standard power meter and laser source. The coupler split ratio must be calibrated to know how much of the return signal goes to the power meter and how much is diverted to the source side of the coupler to calculate the total amount of back reflection. Due to the dynamic range required to measure return losses in the range of -25 to-60dB, a high power laser source is necessary. And the source must be stable enough to allow making accurate measurements over relatively long times required for the experiment.

To measure return loss, measure the amount of power transmitted to the end of the cable (Pout) and the power reflected back up through the coupler test port (Pback) with a fiber

optic power meter. To calibrate out any crosstalk in the coupler or the back reflections of any intermediate connectors or splices, dip the connector end being tested in an index matching fluid (alcohol works well and isn't messy to clean up) and record the power at the coupler test port (Pzero). If the coupler split ratio is Rsplit (the fraction of the light that goes to the measurement port when transmitting in the back direction), the return loss is:

Optical return loss (dB) = (P Back – P zero)/(R split* P out)

State-of-the-art connectors will have a return toss of about 40-60 dB, or about one-ten thousandth to one millionth of the light is reflected back towards me source. Measurements setups need to be carefully controlled to get valid data. The test connector being used to test other connectors or jumper cables must be kept dean and periodically re-polished to insure as perfect a surface finish as possible Purists will note that measurements of Pout ignore the fresnel reflection from the end of the test cable fiber and perhaps even me window of the detector, which can add a few percent to. the errors.

The measurement of optical return loss is not a precise measurement. The coupling ratios are hard to calculate, reflections in the coupler and connectors are hard to zero out, any dirt or wear on the test connector will affect measurements and the dynamic range of the measurements are so large that uncertainties of up to +/-1 dB are common.

Like all fiber optic power measurements, instrument makers have been guilty of providing too much instrument resolution than that warranted by the uncertainty of the measurement Manufacturers also offer dedicated instruments to measure ORL, but the measurement can be made easily with a standard meter and laser source.

While the techniques mentioned above refer to testing connector or splice return loss using sources and power meters, the techniques also refer to testing connectors on jumper cables. However, they do not refer to tests on connectors or splices which are installed in a link. Once they are installed, testing should be done with an.

The spike seen when viewing a connector on an OTDR can be measured with respect to the backscatter signal on the OTDR. Most OTDRs are calibrated to make this measurement directly the coupler/laser source/meter technique (sometimes referred to as "optical continuous wave reflectometry" or OCWR) cannot be used once the components are part of a cable plant, since the continuous backscatter from the fiber masks the effects of any one component. Besides, if you have a problem, you need to know where it is, and only the OTOR can give that information.

2.2 Connectorized Cable Testing

After connectors are added to a cable, testing must include the loss of the fiber in the cable plus the loss of the connectors. On very short cable assemblies (up to 10 meters long), the loss of the connectors will be the only relevant loss, while fiber will contribute to the overall losses in longer cable assemblies, In an installed cable plant, one must test the entire cable from end to end, including every component in it, such as splices, couplers, and connectors intermediate patch panels.
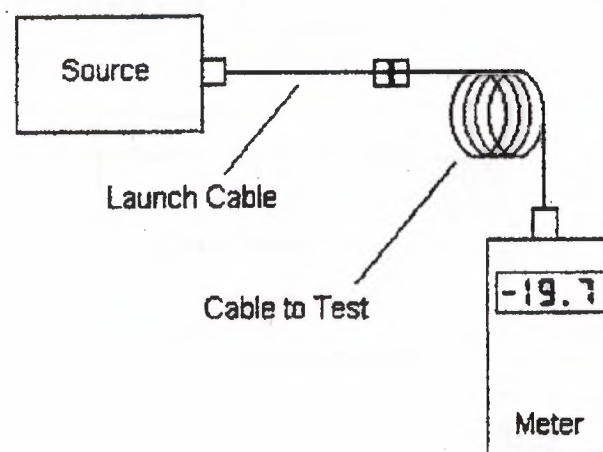
Figure 2.3 Connectorized cable testing

Obviously one cannot test cable assemblies in the same manner as fiber connectors alone,

since those tests are destructive. Instead of using a cutback test' one uses a source with a launch cable attached to calibrate the power being Launched into the cable under test.

This method was not used at first; a cable substitution test was used. In this method, one attaches a reference cable of short length (about 1 m) and high quality to the source and records the power. Mar removing this cable from the source; the cable to be tested is then attached to the source and the power measured. The loss of the cable is them referenced to the first cable. This method was abandoned, since it often lead to contusion when the cable under test was better than the reference cable and had a "gain" not a toss, the coupling to the source was highly unrepeatable, and the test did not adequately test the centering geometry of the fiber in the ferrule of the connector.

A better test, FOTP-171 was developed along the lines of FOTP-34 for connectors. One begins by attaching a launch cable to the source made from the same size fiber and connector type as the cables to be tested. The power from the end of this 'launch cable" is measured by a power meter to calibrate the launch power for the test. Then the cable to test is attached and power measured at me end again, One can calculate the loss incurred in the connectors mating to the launch cable and in the fiber in the cable itself.
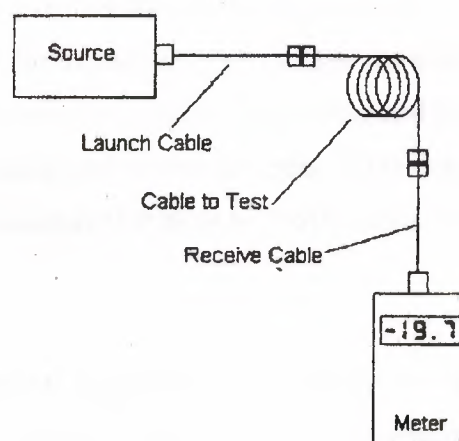
Figure -2.4 Double-ended loss tests

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Since this only measures the loss in the connector mated to the launch cable, one can add a second cable at the power meter end, called a receive cable so the cable to test is between the launch and receive cables Then one measures me Joss at both connectors and in everything in between. This is commonly called a "double-ended' loss test.

There have been two interpretations of the calibration of the output of the source in this test. One interpretation is that one attaches the launch cable to the source and the receive cable to the meter the two are then mated and this becomes the "0 dB" reference. The second method only attaches the launch cable to me source and measures the power from the launch cable with the power meter.

With the first method, one has two new measurement uncertainties. First, this method underestimates the loss of the cable plant by the loss of one connection, since that is zeroed out in the calibration process Secondly, if one has a bad connector on one or both of the test cables, it becomes masked by the calibration, since even if The two connectors have a loss of 10 dB, it is not seen by the calibration method used.

In the second method, the launch power is measured directly by the meter. This also allows one to measure both connectors on the test cable, since power is referenced to the output power or the launch connector In addition, one can test me mating quality of the test cables' connectors by attaching the receive jumper to the meter and then measuring me loss of the connection between the launch and receive jumpers. If this loss is high, one knows there is a problem with the test connectors that must be fixed before actual cable loss measurements should be made.

Obviously, the second method is preferred. Both methods are detailed in OFSTP-14, the extension of FOTP-171 to include installed cable plants which also discusses the problems associated with mode power distribution.

2.2.1 Finding Bad connectors

If a test shows a jumper cable to have high loss, there are several ways to find the problem. If you have a microscope, inspect the connectors for obvious defects like scratches, cracks or surface contamination. If They look OK, dean them before retesting. Retest the launch cable to make certain it is good. Then retest the jumper cable with the single-ended method, using only a launch cable. Test the cable n both directions. The cable should have higher loss when tested with the bad connector attached to the launch cable, since the large area detector of the power meter will not be affected as much by the typical loss factors of connectors.

2.2.2 Mode Power Distribution Effects on Loss in Multimode Fiber Cables

The biggest factor En the uncertainty of multimode cable loss tests is the mode power distribution caused by the test source. When testing a simple 1 m cable assembly, variations in sources can cause 0.3 to I dB variations in measured loss. The effect is similar to the effect on fiber loss discussed earlier, Since the concentration of light in the tower order modes as a result of EMD or mode filtering will minimize the effects of gap, offset and angularity on mating loss by effectively reducing the fiber core size and numerical aperture.

While one can make mode scramblers and filters to control mode power distribution when testing in the laboratory, it is more difficult to use these in be field, An alternative technique is to use a special mode conditioning cable between the source and launch cable that induces the proper mode power distribution. This can be done with a step index fiber with a restricted numerical aperture. Experiments with such a cable used between the source have been shown to greatly reduce the variations in mode power distributions between sources. This technique works wet with both lab tests of connector toss and field tests of loss in the installed cable plant.

2.2.3 Choosing a Launch Cable for Testing

Obviously, the quality of the launch cable will affect measurements of loss in cables assemblies tested against it. Good connectors with proper post are obviously needed, but can one improve measurements by specifying tight specifications on the fiber and connectors? If the fiber is closer to nominal specifications and the connector ferrule is tightly tolerance, one should expect more repeatable measurements.

It seemed obvious to the committee specifying the cable plant for FDDI in the mid 1980s that one could get more precise data on cable plant loss and power coupled in to the cable by a transmitter by specifying a precision cable assembly.

In a series of tests performed on a large sample of cables, it was shown that the tightness of fiber and connector tolerances had little effect on the variability of the cables when intermitted. In fact, the least variability came from a set of cables manufactured using off the shelf components, but with a cable design which had a much stiffer jacket than the other cables, which reduced the bending loss changes at the back shell of the connector.

It seems that the large number of factors involved in mating losses makes controlling these tolerances impossible. Therefore, it is recommended that launch cables he chosen for low loss, but not specified with tighter tolerances n the fiber or connector characteristics. It is probably much more important to carefully handle the test cables and inspect the end surfaces of the ferrules for dirt and scratches regularly.

2.2.4 Optical Return Loss Testing of Cable Assemblies

Testing the optical return loss of cables and cable assembles is very important for single mode laser systems, since light reflected back into the laser may cause instability, noise or nonlinearity. While testing the ORL Of a cable assembly is similar to that of a connector, using either FOTP-107 or the OTDR method, several factors should be noted to minimize errors.

First, be certain that the launch connector is of the finest quality obtainable and inspect it

often for dirt, contamination and scratching. Re-polishing is possible for most keyed ceramic ferrule connectors and will often improve measurements. Also insure the splice bushing used is kept clean and does not show wear.

Remember to terminate the connector on the far end of the cable assembly, otherwise it will reflect light and give false reading. Dipping the connector into
index matching fluid or gel will usually db, but putting several tight turns in the fiber to create attenuation will also minimize the reflection effects.

OTDRs are limited in their usefulness in testing jumper cables, since the jumpers are often too short for the resolution of the OTDR. This can be helped by using a long launch cable and carefully terminating the open connector to prevent it reflecting light which would be included in the single spike seen by the OTOR. On the installed cable plant, make certain that the OTOR back reflection spike does not exceed the dynamic range of the OTDR, or me measurement will underestimate the reflection.

2.3   Couplers and Switches

2.3.1   Fiber Optic Couplers

Couplers split or combine light in fibers. They may be simple splitters or 2 x 2 couplers or up to 64 X 64 ports star couplers. Most are made by fusing fibers under high temperatures while monitoring light transmission through the fibers to get the proper coupling ratios. The fusing of the fibers causes light to split or combine in appropriate ratios. Others have been fabricated by diffusing light paths into a glass substrate and attaching fibers to it.

Relevant specifications for couplers are the coupling ratios of each port or the consistency across all the ports, crosstalk and the excess loss caused by the fusing. Excess loss is the difference between the sum of all the outputs and the sum of all the inputs. When used in laser based Systems, couplers may need testing for optical return loss and wavelength dependence also. Thus, testing couplers involves coupling a test source to each input port in

turn and measuring all the outputs for consistency, then summing all the output powers and subtracting that number from the input power to calculate excess loss. Connectorized couplers are tested like Connectorized cables, using a launch cable, while couplers with bare fibers must use a cutback method or a pigtail and temporary splice to couple the launch source. Single mode couplers have another characteristic that must be considered: they are very wavelength sensitive. Most couplers are optimized at one wavelength unless they are specially designed for both 1300 and 1550 nm operation. Some are even built to be wavelength division multiplexers, coupling light from 1300 and 1550 nm lasers into separate output ports Therefore, sources for testing couplers must be accurately characterized for wavelength to minimize measurement uncertainty.

2.3.2 Fiber Optic Switches

Switches may use one of several techniques to transfer light from one fiber to another. Some merely use fibers on the arm of a relay with v-block alignments to change from one fiber output to another. Others use lenses and prisms to collimate me light from the incoming fiber and switch it to the outgoing fiber. Like couplers, switch testing involves measuring the light lost in the switch by measuring the input from a source and the appropriate output for each switch position. Again, these components are very sensitive to mode power distribution. For single mode couplers or switches, coupling ratios will be sensitive to whether the incoming Fight is really single mode. In multimode components, mode power distribution can cause wide variation in switch losses or coupling ratios. Mode filters are necessary in single mode tests and mode scrambler and filter combinations are needed in multimode tests to insure minimal effect from unknown mode power distribution.

3. APPLICATION OF FOC

3.1 Fiber Optic

Optical fiber is composed of a light carrying core and a cladding that traps the light in the core, causing total internal reflection. Fiber has two basic types, multimode and single node. Multimode fiber means that tight can travel many different paths (called modes) through the core of the fiber, which enter and leave the fiber at various angles. The highest angle that light is accepted into the core of the fiber defines the numerical aperture (NA).Two types of multimode fiber exist, distinguished by the index profile of their cores and how light travels in them.

Step index multimode fiber has a core composed of one type of glass. Light traveling in the fiber travels in straight lines, reflecting off the core/cladding interface. The numerical aperture is determined by the differences in the indices of refraction of the core and cladding and can be calculated by Snell's law. Since each mode or angle of light travels a different path link, a pulse of light is dispersed while traveling through the fiber, limiting the bandwidth of step index fiber.

In graded index multimode fiber, the core is composed of many different Layers of glass, chosen with indices of refraction to produce an index profile approximating a parabola. Since the tight travels faster in lower index of refraction glass, the light will travel faster as it approaches the outside of the core. Likewise, the light traveling closest to the core center will travel the slowest. A property constructed index profile will compensate for the different path lengths of each mode, increasing the bandwidth capacity of the fiber by as much as 100 times that Of step index fiber.

Single mode fiber just shrinks the core size to a dimension about 6 times the wavelength of the fiber causing all the light to travel in only one mode. Thus modal dispersion disappears and the bandwidth of the fiber increases by at least another factor of 100 over graded index fiber.

Each type of fiber has its specific application. Graded index fiber is used where large core size and efficient coupling of source power is more important than low loss and high bandwidth. It is commonly used in short, low speed data links. It may also be used in applications where radiation is a concern, since it can be made with a pure silica core that is not readily affected by radiation.

Table 3.1 Fiber Types and Typical Specifications

Fiber Type	Core/cladding Diameter	Attenuation coefficient (dBkm)		Bandwidth @1300 nm	
-	(Microns)	850nm	1300nm	1550nm	(MHz-km)
Step Index	200/240	6	NA	NA	50@850
Multimode	50/125	3	1	NA	600
Graded Index	62.5/125	3	1	NA	500
-	85/125*	3	1	NA	500
-	100/140*	3	1	NA	300
Single mode	8-9/125	NA	0.5	0.3	High
Plastic	1mm	(1 dB/m @ 665nm)			Low

While mere have been four graded index multimode fibers used over the history of fiber optic communications, one fiber now is by far the most widely used, 62.5/125. Virtually all multimode datacom networks use this fiber. The first multimode fiber widely used was 50/125, first by the telephone companies who needed its greater bandwidth for long distance phone lines. Its small core and low NA made it difficult to couple to LED sources, so many data links used 100/140 fiber. It worked well with these data links, but its large core made it costly to manufacturer and its unique cladding diameter required connector manufacturers to make connectors specifically for it. These factors led to its declining use. The final multimode fiber, 85/125 was designed by Coming to provide efficient coupling to

LED sources but use the same connectors as other fibers. However, once IBM standardized on 62.5/125 fiber for its fiber optic products, the usage of all other fibers declined sharply.

The telcos switched to single mode fiber for its better performance at higher bit rates and its lower loss, allowing faster and longer unrepeatered links for tong distance telecommunications. Virtually all telecom applications use single mode fiber. it is also used in $CATV_1$ since analog CATY networks use laser sources designed for single mode fiber other high speed networks are using single mode fiber either to support gigabit data rates or long distance links.

3.1.1 Optical Fiber Testing

For optical $fiber_1$ testing includes fiber geometry attenuation and bandwidth. The most fundamental parameter for optical fiber is geometry, since the dimensions of the fiber determine its ability to be spliced and terminated. The core diameter, cladding diameter and concentricity are the most important factors on how well one can connect or splice two fibers. Thus manufacturers work very hard to control these parameters, including continuous testing throughout the manufacturing process.

While testing diameter and concentricity may sound simple, measurements must be made to submicron precision. The process is complicated by the fad that the material is transparent and the dimensions are small enough to reach the limits of optical measurements.

3.1.2 Attenuation

The attenuation of the optical fiber is a result of two factors absorption and scattering. The absorption is caused by the absorption of the light and conversion to heat by molecules in the glass. Primary absorbers are residual OH+ and dopants used to modify the refractive index of the glass. This absorption occurs at discrete wavelengths, determined by the elements absorbing the light. The OH+ absorption is predominant, and occurs most

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strongly around 1000 nm, 1400 nm and above 1600nm.

The largest cause of attenuation is scattering. Scattering occurs when light collides with individual atoms in the glass and is anisotropic. Light that is scattered at angles outside the numerical aperture of the fiber wilt be absorbed into the cladding or transmitted back toward the source Scattering is also a function of wavelength, proportional to the inverse fourth power of the wavelength of the light. Thus if you double the wavelength of the light. you reduce the scattering losses by 2 to the 4th power or 16 times. Therefore, for long distance transmission it is advantageous to use the longest practical wavelength for minimal attenuation and maximum distance between repeaters. Together, absorption and scattering produce the attenuation curve for a typical glass optical fiber shown above.

Fiber optic systems transmit in the "windows" created between the absorption bands at 850 nm, 1300 nm and 1550 nm, where physics also allows one to fabricate lasers and detectors easily. Plastic fiber has a more limited wavelength band that limits practical use to 660 nm LED sources.

3.1.3 Sources for Loss Measurements

On the test source, two factors must be controlled to minimize measurement uncertainty, the spectral output and modal characteristics. The spectral output characteristics obviously include wavelength, as seen in the spectral attenuation curve, but may also include the spectral width. A wide spectral width source suffers absorption over a larger range of wavelengths making it more difficult to obtain.
precise data on spectral attenuation at any specific wavelength. Monochromators are used as sources for spectral loss testing, since the spectral width of the source can be controlled exactly.

For single wavelength measurements the source can be a fixed wavelength LED or laser. Generally, attenuation measurements will be made with a source appropriate to the fiber. Most multimode fiber systems use LED sources while single mode fiber systems use laser

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sources. Thus testing each of these fibers should be done with the appropriate source. Lasers should not be used with multimode fiber, since coherent sources like lasers have high measurement uncertainties in multimode fiber caused by modal noise. The wide spectral width of LEDs sometimes overlap the single mode fiber cutoff wavelength (the lowest wavelength where the fiber supports only one mode) at lower wavelengths and the 1400 nm OH: absorption band at the upper wavelengths.

The additional absorption at either end of the LEDs spectral output may bias me measurements of attenuation on single mode fiber substantially. Tests from Bellcore showed the effects of sources on measurements of single mode fiber loss. The LED spectrum covers from the single mode cutoff wavelength around 1200 nm well into the OH absorption *band*, while the laser concentrates all its, power in an extremely narrow spectral band where the fiber is actually used. Over the range covered by the LED output, the fiber loss varies by 0.2 dB/km, ignoring the Oh absorption band.Bellcore tests showed an error of loss caused by the use of the LED of 0.034dB/km.

Even with laser sources, the loss varies substantially according to the wavelength of the source. Again Bellcore tests showed a variation of loss of 0.05 dB/km with source variations of 29 nm (1276 and 1305 nm), within me range of typical sources used in the network. So testing should be done with sources as dose to the system wavelength as possible, especially with longer links. (Peters, Bellcore reference).

3.1.4 Modal Effects on Attenuation

In order to test multimode fiber optic cables accurately and reproducibly, it is necessary to understand modal distribution, mode control and attenuation correction factors. Modal distribution in multimode fiber is very important to measurement reproducibility and accuracy.

3.2 Fiber Modal Distribution

In multimode fibers, some light rays travel straight down the axis of the fiber while all me others wiggle or bounce back and forth inside the core. In step index fiber, the off is rays, called "higher order modes" bounce back and forth from core/cladding boundaries as they are transmitted down the fiber. Since these high order modes travel a longer distance than the axial my, they are responsible for the dispersion that limits the fibers bandwidth.

In graded index fiber, the reduction of the index of refraction of the core as one approaches the cladding causes the higher order modes to follow a curved path that is longer than the axial ray (the "zero order mode"), but by virtue of the lower index of refraction away from the axis, light speeds up as it approaches the cladding and it takes approximately the same time to travel through the fiber. Thus the "dispersion" or variations in transit time for various modes$_1$ is minimized and bandwidth of the fiber is maximized.

However, the fact that the higher order modes travel farther in the glass core means that they have a greater likelihood of being scattered or absorbed, the two primary causes of attenuation in optical fibers. Therefore, the higher order modes will have greater attenuation than lower order modes and a long length of fiber that was fully filled (all modes had the same power level launched into them) will have a lower amount of power in the higher order modes than will a short length of the same fiber.

This change in "modal distribution" between long and short fibers can be described as a "transient loss", and can make big differences in the measurements one makes with the fiber. It not only changes the modal distribution, it changes the effective core diameter and numerical aperture also.

The term "equilibrium modal distribution" CEMO) is used to describe the modal distribution in a long fiber which has lost the higher order modes. A long" fiber is one in EMD, while a "short' fiber has all its initially launched higher order modes.

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3.2.1 What Does System Modal Distribution Look Like?

System modal distribution depends on your source, fiber, and the intermediate "components" such as connectors, couplers and switches, all of which affect the modal distribution of fibers they connect. Typical modal distributions for various fiber optic components are shown here.

In the laboratory, a critical optical system is used to fully fill the fiber modes and a "mode filter?', usually a mandrel wrap which stresses the fiber and increases loss for the higher order modes, is used to simulate EMO conditions. A "mode scrambler', made by fusion splicing a step index fiber in the graded index fiber near the source can also be used to fill all modes equally.

In a system, such controlled conditions obviously do not exist In act some work presented by Corning at a recent EIA Standards meeting shows how far the real world is from what we expected it to belt has been accepted as "common knowledge" that microlens LEDs (as used with most multimode datacom systems) overfill fibers, and when we use them as test sources, we are testing with an overfilled launch. Not so- Tests on microlens LEDs indicate. That they underfill compared to EMD. And edge-emitter LEDs, typical of the high speed emitters at 1300 nm, concentrate their power even more into the Tower order modes.

Other facts that come out of the Corning project shows that connectors mix some power back into the higher order modes due to angular misalignment and switches strip out higher modes. In a simulated FDDI system using 8 fiber optic switches and 20 pairs of connectors, with fiber lengths of 10 to 50 meters between them, the majority of system power was concentrated in the lower order modes.

what conclusions can we draw? The most significant conclusions am that it may not be prudent to design datacom and IAN systems on the worst-case loss specifications for connectors and switches. In actual operation₁ the simulated system exhibited almost 15 dB less loss than predicted from worst case component specifications (obtained with fully

filled launch conditions).

And, when testing systems, using a LED source similar to the one used in the system and short launch cables may provide as accurate a measurement as is possible under more controlled circumstances, since the LED approximates the system source. Alternately, one may use a mode modifier or a Fotec universal launch cable (ULC) to establish consistent modal distributions appropriate for testing the cables.

Relative Model Distribution of Multimode Fibers: Sources and Mode Modifiers

A fully filled fiber means that ail modes carry aqua power, as shown by the me across the top of the graph. A long length of fiber losses the higher order modes faster leading to the gently sloping 'EMD" curve. Mode filtering strips off the higher order modes, but provides any a crude approximation of EMD. The microlensed LED, often thought to overfill' the modes actually couples most of its power !:fl lower order modes Tie ELED (edge-emitting LED) couples even more strongly in the Owen order modes. Connectors are mode mixers since misalignment asses cause some power in rower order modes to be up to higher order modes

3.2.2 .The Effect on Measurements

If you measure the attenuation of a long fiber in EMD (or any fiber with EMD simulated launch conditions) and compare it to a normal fiber with "oven; launch conditions' (that is the source fills all the modes equally) you will find the difference is about 1 dB/km, and this figure is the "transient loss". Thus, the EMO fiber measurement gives an attenuation that is 1 dB per Km less than the overt conditions.

Fiber manufacturers use the EMD type of measurement for fiber because it is more reproducible and is representative of the losses to be expected in long lengths of fiber.

However, with connectors the EMD measurement: can give overly optimistic results since

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it effectively represents a situation where one launches from a smaller diameter fiber of lower NA than the receive fiber, an ideal situation for low Connector loss. The difference & in connector loss caused by modal launch conditions can be dramatic. Using the same pair of biconic or SMA connections. It is possible to measure 0.6 to 0.9 dB with a fully filled launch and 0.3 to 0.4 dB with an EMO simulated launch. Which is a valid number to use for this connector pairs loss?

That depends on the application if you are connecting two fibers near a LED source; the higher value may be more representative, since the launch cable is so short. However, if you are connecting to a cable one km away, the tower value may be more valid

3.3 Mode Conditioners

There are. three basic "gadgets" to condition the mode! distribution in multimode fibers:

- Mode strippers which remove unwanted cladding mode light,
- Mode scramblers which mix modes to equalize power in all the modes,
- Mode filters which remove me higher order modes to simulate EMD or steady state conditions.

3.31 Cladding Mode Strippers

Cladding mode strippers are used to remove any light being propagated in the cladding to insure that measurements include only the effects of the core. Most American fibers am "self-stripping'; the buffer is chosen to have an index of refraction mat will promote the leakage of light from the cladding to the buffer. If you are using at least 1 meter of fiber, cladding modes will probably not be a factor in measurements. One can easily tell if cladding modes are a factor. Start with 10 meters of fiber coupled to a source and measure the power transmitted through it. Cut back to 5 meters and then 4, 3, 2, and 1 meter, measuring the power at every cutback. The loss in the fiber core is very small in 10 meters, about 0.03-0.06dB. But if the power measured increases rapidly, the additional light

measured is cladding light, which has a very high attenuation, and a cladding mode stripper is recommended or accurate measurements if short lengths of fiber must be used.

To make a cladding mode stripper, striper off the fibers buffer for 2 to 3 inches (50 to 75 mm) and immerse the fiber in a substance of equal or higher index of refraction than the cladding. This can be done by immersing the *fiber* in alcohol or mineral oil in a beaker, or by threading the fiber through a common soda straw and filling the straw with index matching epoxy or an optical gel (Note: stripping the buffer away from the end of a fiber is easily done, using a chemical stripper. If the fiber cannot be chemically stripped, like those with Teflon buffers, check with the fiber manufacturer for instructions.) A caution. Do not stress the fiber after the mode stripper as this wilt reintroduce cladding modes, negating the effects of the mode stripper. Mode stripping should be done last if mode scrambling and filtering are also done on a fiber under test

3.3.2 Mode Scramblers

Mode scrambling is an attempt to equalize the power in all modes, simulating a fully filled launch. This should not be confused with a mode filter which simulates the modal distribution of a fiber in equilibrium modal distribution (EMO). Both may be used together sometimes however, to properly simulate test conditions. Mode scramblers are easily made by fusion (or mechanical) splicing a short piece of step index fiber in between two pieces of graded index fiber being tested. One can also use methods that produce small perturbations on the fiber, such as running the fiber through a tube of lead shot. But these scramblers are difficult to fabricate and calibrate accurately. In the laboratory, they are usually unnecessary since accurate launch optics are used to produce fully filled launch conditions.

3.3.3 Mode Filters

Mode filters are used to selectively remove higher order modes to attempt to simulate EMD conditions, assuming that one starts with fully filled modes. Higher order modes are easily removed by stressing the fiber in a controlled manner since the higher order modes are more susceptible to bending losses.

The moat popular mode filter is the "mandrel wrap", where the fiber is snugly wrapped around a mandrel several times. The size of the mandrel and the number of turns will determine the effect on the higher order modes. Other mode filters can be made where the fiber is subjected to a series of gentle S bends, either in a form or by wrapping around pins in a plate or by actually using a long length of fiber attached to an overfilling source.

3.4   Bending Losses

Fiber and cable are subject to additional losses as a result of stress. in fact, fiber makes a very good stress sensor. However, this is an additional source of uncertainty when making attenuation measurements. It is mandatory to minimize stress and/or stress changes on the fiber when making measurements. If the fiber
or cable is spooled it will have higher loss when spooled tightly. It may be advisable to unspoiled it and respool with less tension. Unspooled fiber should be carefully placed 6n a bench and taped down to prevent movement. Above all, be careful about how connectorized fiber is placed. Dangling fibers that stress the back of me connector will have significant losses.

3.4.1 Transmission vs. OTDR tests

So far, we have only discussed testing attenuation by transmission of light from a source, but one can also imply fiber losses by backscattered light from a source using an optical time domain reflect meter (OTOR).
OTDRs are widely used for testing fiber optic cables. Among the common uses *are* measuring the length of fibers, finding faults in fibers, breaks in cables, attenuation of fibers, and losses in splices and connectors. They are also used to optimize splices by monitoring splice loss. One of their biggest advantages is they produce a picture (called a trace) of the cable being tested. Although OTORs are unquestionably useful for all these tasks₁ they have error mechanisms that are potentially large, troublesome and not widely understood.

The OTDR uses the lost light scattered in the fiber that is directed back to the source for its operation. It couples a pulse from a high powered laser source into the fiber through a directional coupler. As the pulse of light passes through the fiber, a small fraction of the light is scattered towards the source. As it returns to the $OTUR_l$ it is directed by the coupler to a very sensitive receiver. The OTDR
display shows the intensity of the returned signal in dB as a function of time, converted into distance using the average velocity of light in the glass fiber.

To understand how the OTDR allows measurement, consider what happens to the light pulse it transmits. As it goes down the fiber, the pulse actually 'Tilts" the core of the fiber with light for a distance equal to the pulse width transmitted by the OTDR. in a typical fiber, each nanosecond of pulse width equals about 8 inches C200 mm). Throughout that pulse, tight is being scattered, so the longer the pulse width in time, the greater the pulse length in the fiber and the greater will be the amount of backscattered light, in direct proportion to the pulse width. The intensity of the pulse is diminished by the attenuation of the fiber as it proceeds down the fiber, a portion of the pulse's power is scattered back to the OTDR and it is again diminished by the attenuation of the fiber as it returns up the fiber to the OTDR. Thus the intensity of the signal seen by the OTDR at any point in time is a function of the position other light pulse in the fiber.

By looking at the reduction in returned signal over time, one can calculate the attenuation coefficient of the fiber being tested. Since the pulse travels out and back, the attenuation of the fiber diminishes the signal in both directions, and the transit time from pulse out to return is twice the one way travel time. So both the intensity and distance scales must be divided by two to allow for the round-trip path office Tight.
If the fiber has a splice or connector, the signal will be diminished as the pulse panes it, so the OTDR sees a reduction in power, indicating the light loss of the joined fibers. if the splice or connector reflects light (see optical return loss) the OTOR will show the reflection as a spike above the backscattered signal The OTDR can be calibrated to use this spike to measure optical return loss.

The end of the fiber will show as deterioration or the backscatter signal into noise, if it is within the dynamic range of the OTDR. If the end of me fiber is cleaved or polished, one will also see a spike above the backscatter trace. This allows one to measure the total length of the fiber being tested.

In order to enhance the signal to noise ratio of the received signal, the OTOR sends out many pulses and averages the returned signals. And to get to longer distances, the power in the transmitted pulse is increased by widening the pulse width. The longer pulse width fills a longer distance in the fiber as we noted above. This tonger pulse width masks all details within the length of the pulse, increasing the minimum distance between features resolvable with the OTOR.

3.4.2 Bandwidth

Fibers information transmission capacity is limited by two separate components of dispersion: modal and chromatic. Modal dispersion occurs in step index multimode fiber where the paths of different modes are of varying lengths. Modal dispersion also comes from the fact that the index profile of graded index (01) multimode fiber isn't perfect. The graded index profile was chosen to theoretically allow all modes to have the same group velocity or transit speed along the length of the fiber. By making the outer parts of the core a lower index of refraction than the inner parts of the core, the higher order modes speed up as They go away from the center of the core, compensating for their longer path lengths.

In an idealized graded index fiber, all modes have the same group velocity and no modal dispersion occurs. But in real fibers, the index profile is a piecewise approximation and all modes are not perfectly transmitted, allowing some modal dispersion. Since the higher order modes have greater deviations, me modal dispersion of a fiber (and therefore its laser bandwidth) tends to be very sensitive to moda conditions in the fiber. Thus the bandwidth of longer fibers degrades nonlinearly as the higher order modes are attenuated more strongly.

The second factor in fiber bandwidth is chromatic dispersion. Remember a prism spreads out *me* spectrum of incident light since the light travels at different speeds according to its color and is therefore refracted at different angles. The usual way of stating this is the index of refraction of the glass is wavelength dependent. Thus a carefully manufactured graded index multimode fiber can only be optimized for a single wavelength, usually near 1300 nm, and light of other colors will suffer from chromatic dispersion. Even light in the same mode will be dispersed if it is of different wavelengths.

Chromatic dispersion is a bigger problem with LEDs, which have broad spectral outputs unlike lasers which concentrate most of their light *in a* narrow spectral range. Chromatic dispersion occurs with LEDs because much of the power is away from the zero dispersion wavelength of the fiber High speed systems like FDDI, based on broad output source emitter LEDS suffer such intense chromatic dispersion that transmission over only two km of d2.5/125 fiber can be risky.

3.5 Fiber Optic Standards

Accurate test and measurement always requires standard test methods and good calibration standards. In fiber optics this means this standardized test procedures for optical loss of fibers, cables connectors and splices under many varying environmental conditions. Primary and transfer standards for optical power, attenuation, bandwidth and the physical characteristics of fiber are also required.

These standards are developed by a variety of groups working together. Testing standards primarily come from the EA in the US (Electronics Industries Association), internationally from the IEC (International Electrotechnical Commission), and other groups worldwide. Primary and transfer standards are developed by national standards laboratories such as NIST (National Institutes of Standards and Technology, formerly the US National Bureau of Standards) which exist in almost all countries to regulate all measurement standards International cooperation is available to insure worldwide conformance to all absolute standards

We can also discuss "de facto" standards, those generally accepted standards for components and systems that developed because there weren't any de jur standards yet and everyone accepted the work of a supplier. In fact, we want to discuss at of those and their status in today's fiber optic Systems.

3.5.1 De Facto Standards Come First

In any fast developing technology like fiber optics, them is always resistance for developing standards. Critics say standards stifle technology development Some critics object because its not their standard that is proposed, and in some cases, nobody really knows what standards are best. Under these circumstances, users choose the best solutions for their problems and forge ahead.

In fiber optics, those who have gone ahead and committed heavily to the technology or who have marketing strength have established many of the standards for today. Thus most fiber optic tetecom systems in the US are based on singe mode fiber and 1300 nm lasers These components offer the best solution for the application, and had the largest suppliers and users behind them, so they became dominant. Overseas the government- co telecom authorities generally dictate the system configurations, but only the connectors seem to differ each country choosing its own national suppliers. The IEC has voted to recommend the SC style connector, which has already been adopted by several US telcos but the single mode ST and the FC connector still have their supporters

In telecom systems. there are many types of systems but all are operating on single mode fiber at 1300 or 1550 nm wavelengths. Bit rates of 1.544 Mbitas/S up to 5 Gbits/S are already in operation, with up to higher rates promised. Today there is virtually no compatibility between manufacturers of terminal equipment, but SONET (Synchronous Optical. Network) or SDH (Synchronous Digital Hierarchy) premises to relieve some of the system incompatibility in telecommunications.

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In datacom Systems (the generic category that includes datalinks and LANs), the situation is reaching consensus. Four multimode fibers have been used in datacom systems: 50/125, 62.5/125, 85/125 and 100/140 (core/dad in microns), but 62.51125 fiber has become dominant. It was chosen as the preferred fiber for Fool and ESCON, and the US government is using 82.5/125 in offices exclusively (FED STD 1070). Connectors have often been SMA but AT & Ts ST is now the multimode connector of choice. Most datacom Systems need a duplex connector, but so far none has become widely acceptable. Perhaps the FDDI connector will become the duplex standard. While short wavelength LED (820-850 nm) systems have been most popular to date, the higher bit rates of new systems are requiring 1300 am LED's due to the limiting effects of chromatic dispersion in the fiber. Higher speed standards like Fiber Channel will probably be based on single mode fiber and 1300 nm lasers to accommodate the GB/s speeds of these networks

3.5.2 Industry Standards Activities

In fight of these de facto standards, many groups are Working to develop standards that are acceptable throughout the industry.

3.5.3 Primary Standards

The keeper of primary standards in the US is the Dept of Commerce, National Institute of Standards and Technology (NIST). Although some optical standards work is done at Gaithersburg₁ MD, fiber optic and laser activity is centered at Boulder, CO. Today, NIST is actively working with all standards bodies to determine the primary reference standards needed and provide for them. fiber optics applications, their concern has been with fiber measurements, such as attenuation and bandwidth, mode field diameter for single mode fiber, and optical power measurements.

NIST standards are in place for fiber attenuation and optical power measurements, the most important measurement in fiber optics. Since all other measurements require measuring power, several years ago NIST ran a "round-robin" which showed up to 3 dB differences (50%) in power measurements among participants. A optical power calibration program at

NIST has resulted in reliable transfer standards at 850, 1300 and i550 nm. Using new transfer standards, measurements of better than 5% accuracy should be easily obtained.

3.5.4 Component and Standards

Several bodies are looking at fiber optic testing standards, but the most active by far is the Electronic Industries Association. EIA FO-6 and FO-2 committees meet at least twice a year to discuss technical issues and review progress on the writing of standards test procedures and component specifications. At the current time, there are over 100 EA FOTPs (fiber optic test procedures) in process or published and many component specifications are being prepared. The EIA publication "Component Bulletin 9F" provides a full summary of all EIA FOTP activity with cross references

Besides being a standards writing body, the FO-6 and FO-2 committees are a forum for the discussion of technical issues, relevant to the FOTPs being prepared, and are sometimes scenes of heated debate over these issues. But real progress is being made in defining relevant tests for fiber optic component and system performance.

Another body active in fiber optic standards is the US Dept. of Defense (DOD) Though OESC (the Defense Electronics Supply Center in Dayton, OH), hey are evaluating the EIA work for applicability in the DOD and adopting or changing standards as needed. With the magnitude of the fiber optic projects in the military and government today, me OESC project has become very important. Fiber has such high priority at the NAVY, they are funding a project (NAVSIEA 58ZC) to assess the standards requirements of me NAVY for the foreseeable future and develop those standards.

Within the US, Bell communications Research (Bellcore), the spin-off R&D organization for the divested REOCs (Regional Bell Operating companies), sets standards for its RBOCs by issuing Technical Advisories (TAS) on subjects of mutual interest Bellcore is working on specifications covering cable, connectors and test equipment. as well as a variety of other fiber optic equipment- Work regarding transmission equipment standards is also being considered.

Internationally, almost every country has its own standards bodies, but most work through the EC (International Electrotechnical Commission) to produce mutually acceptable standards. The IEC work is at least as large in scope as the EIA.

3.5.5 System Standards

Very few standard fiber optic Systems have been proposed to date. Most systems are compatible to some electrical standards such as T-3, RS-232, etc., but each manufacturer uses their own protocol on the optical part of the network. As a result, there is little current compatibility in fiber optic systems Even in telephone, fiber optic links developed as adapters for standard T-carrier systems so each manufacturer used their own protocol. Bellcore has been working on developing SONET and CCITT works on 5011 to provide a standard protocol for telephony.

Work is being done by ANSI and the IEEE on developing standard systems for computer networks. The ANSI FODI (Fiber Distributed Data Interface, X3T9,5 committee) is a high bit-rate system for computer network that is reaching commercial reality. Another ANSI committee, X3T9.3, is working on the even faster Fiber Channel (not FIBER l) specification for *Gals* datacommunications. The IEEE considerations include a token-ring LAN (802.5), metropolitan area LAN (802.6) and fiber versions of Ethernet (802.3).

3.6 Optical Power

The most basic fiber optic measurement is optical power from the end of a fiber. This measurement is the basis fiber loss measurements as welt as the power from a source or at a receiver. While optical power meters are the primary measurement instrument, optical loss test sets (OLTSs) and optical time domain reflectometers (OTORs) also measure power in testing loss. ELA standard test FOTP-95 covers the measurement of optical power.

Optical power is based on the heating power of the light and some instruments actually

measure the heat when light is absorbed in a detector. While this may work for high power lasers, these detectors are not sensitive enough for the power levels typical fbr fiber optic communication systems. Table 3.2 shows typical power levels in fiber optic systems.

Table 3.2 Optical power levels of optic communication systems

Network Type	Wavelength, nm	Power Range, dBm	Power Range, W
Telecom	1300,1550	+3 to -45 dBm	50 nW to 2 mW
Datacom	665,790,850,1300	-10 to -30 dBm	1 to 100 uW
CATV	1300,1550	+10 to -6 dBm	250 uWto 10 nW

Optical power meters typically use semiconductor detectors since they are extremely sensitive to light in the wavelengths common to fiber optics Most fiber optic power meters are available with a choice of 3 different detectors, silicon (Si), Germanium (Ge), or Indium-Gallium-rsenide (InGaAs).

Silicon photodiodes are sensitive to light in the range of 400 to 1000 nm and germanium and indium-gallium-arsenide photodiodes are sensitive to light in the range of 800 to 1600 nm.

Silicon detectors are very low noise detectors sensitive to tight at approximately 400 to 1100 nm wavelength₁ depending on the exact method of fabrication. Thus, they are useful for standard datacom links using 820 nm LEDs and glass fiber or 665 nm LEDs and plastic fiber. They can also be used with older telecom Systems that used 850 nm lasers. Silicon detectors have inherently low noise, tow Leakage currents and therefore very low noise floors when used with transimpedance amplifiers in power meters. Typical noise floors on fiber optic instruments using Si detectors am -70 to -90 dBm, or about 1 to 100 Pico watts.

Germanium detectors are sensitive to light in the 800 to 1800 nm wavelength, making them useful for all Systems using glass fiber, including 1300 and 1500 nm single mode systems.

Ge detectors are noisier however, creating a higher noise floor for low level measurements. This noise is proportional to detector area, so by using a smaller detector, one obtains a lower noise floor. However, smaller detectors require positioning the fiber end very close to the window of the detector and centered accurately over the detect sensitive area. The noise of a 2 mm Ge detector is typically 10 to 50 times lower than room temperature 5 mm Ge detectors.

Some manufacturers of fiber optic power meters have chosen to cool these large Ge detectors to reduce the noise and get lower measurement limits. This leads to more sensitive measurements but with a penalty of increased circuit.

Complexity instrument weight and short battery life, since one must provide up to 1 amp current to the thermoelectric cooler in the Ge detector package.

Another solution for extremely low level measurements at 1300 and 1550 nm is to utilize InGaAs detector technology, which has been developed for the receivers of high speed long wavelength communication systems. InGaAs detectors have me same sensitivity range as Ge, but are much less noisy. With InGaAs detectors, measurements can be made to -65 dBm (less than 0.5 nW) with ease. However, InGaAs detectors are very expensive, limiting their usage to only the most expensive instruments.

Table 3.3 Characteristics of detectors used in Fiber Optic Power Meters

Detector Type	Wavelength(nm)	Range Power(dBm)	Range Comment
Silicon	400-1100	+10 to -70	Small area detector
Germanium	800-1600	+10 to -60	Small attenuator
InGaAs	800-1600	+10 to -70	Overload at high power

3.6.1 Calibration

Calibration fiber optic power measurement equipment requires setting up a reference standard traceable to the US National Institute of Standards and Technology for comparison purposes while calibration every power meter or other instrument The NIST standard for all power measurements is an ECPR, or electrically calibrated pyroelectric radiometer, which measures optical power by comparing the heating power of the light to the well-known heating power of a resistor. Calibration is done at 850, 1300 and 1550 nm. Sometimes 1310 nm is used, a holdover from the early 1980s when the telcos and AT&T used i310 nm as a standard, but today me standard is 1300 nm To conveniently transfer This measurement to fiber optic power meter manufacturers calibration laboratories, NIST currently uses .a Hewlett-Packard laboratory type optical power meter with a cooled germanium detector.

To transfer from this transfer standard to production instruments, power meter manufacturers use calibrated detectors or power meters which are regularly checked against one another to detect any one detector's variability, and all are periodically recalibrated to NIST's transfer standards.

In order to transfer the calibration, one needs a source of known characteristics. Typically laser sources at 850, 1300 and 1550 nm pigtailed to single mode fibers are used. The laser sources have very narrow spectral width to allow accurate wavelength calibration, and the single mode fiber controls the output beam presented to the detector of the instrument. Each of these sources is checked for wavelength regularly to insure that no drift has occurred. The output power of these lasers is precisely controlled by an optical feedback circuit to insure stability. Even the temperature of the laser is often controlled precisely to insure no drift in output power or wavelength occurs during the calibration process.

Using the sources described above, one measures the output of one of the lasers on a standard meter or detector and record the value. The instrument under test is hen adjusted to read the same value as the standard detector and a single point calibrator is done.

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For all power meters, especially those with auto ranging, one must calibrate on every range, double checking to insure that the meters have a smooth transition between ranges to prevent calibration discontinuities. Calibration is therefore checked at several points near the top and bottom of the range for even meter.

Meters calibrated in this manner have an uncertainty of calibration of about +/- 5 %, compared to the NIST primary standards. Limitations in the uncertainty are the inherent inconsistencies in optical coupling about 1% at every transfer and slight variation in wavelength calibration. NIST is working continuously with instrument manufacturers and private calibration labs to try to reduce the uncertainty of these calibrations.

Recalibration of instruments should be done annually, however experience has shown that the accuracy of meters rarely changes significantly during that period as long as the electronics of the meter do not fail. Unfortunately, the calibration of fiber optic power meters requires considerable investment in capital equipment and continual updating of the transfer standards so very few private calibration jabs exist today. Most meters must be returned to the original manufacturer for calibration.

3.6.2 Understanding FO power meter measurement uncertainty

Much attention has been paid to developing transfer standards of fiber optic power measurements. The US NIST is Boulder, Colorado and standards organizations of most other countries have worked to provide good standards to work from. We can now assure traceability for our calibrations, but even so the errors and their problem causes will insure a realistic viewpoint on fiber optic power measurements.

The first source of error is optic coupling .Light from the fiber is expanding in a core. It is important that the detector to fiber geometry be such that all the light from the fiber hits the detector, otherwise the measurement will be lower than the actual value. But every time light passes through a glass to air interface. Such as the window on the detector, a small

amount of the connector is reflected. Some is lost, but some can be re-reflected by the polished end surface the connector back in to the detector, the amount dependent on the type of connector and the quality of its polished surface And although detectors have an antireflection coating. Some light is affected from the detector surface which can be reflected from the window connector, etc. Finally the cleanliness of the optical surfaces involved can cause absorption and scattering. The sum total of these potential errors will be dependent on the connector type wavelength, fiber size and NA.

Beyond the coupling errors ,one has errors associated with the wavelength calibration Semiconductor detectors used in fiber optics instruments(and systems too) have a sensitivity that is wavelength dependent since the actual source wavelength is rarely known, there is an error associated with the spectral sensitivity of the detector. By industry convention the three cardinal wavelengths (850, 1300 and 1550 nil) are used for all power measurements, not the exact source wavelength. The source has a finite spectra 'width, very, narrow for 'lasers, quite broad for a LED. In order to accurately measure the power of the source, one needs to know the spectral power distribution of the actual source being measured the sensitivity of the detector and perform a complicated integration of the two.

Another source of error exists for high and low level measurements. At high levels, the optical power may overload and saturate the detector, causing me measurement to be in error on the low side. Consistent overload may even permanently damage the detector, especially with smelt area detectors. This is particularly a problem with CAW systems, where the transmitter power is extremely high to get good signal to noise performance at the receiver. CATY power levels are high enough to damage the detector in many power meters₁ especially those with small area InGaAs detectors. Specialized CAJV meters exist where the detector window has been replaced by a calibrated attenuator of approximately 20 dB. Thus they can make measurements at high power levels, up to +20 or +30 dBm, but sacrifice low level power measurements.

At low levels, the inherent detector noise adds to the signet and becomes an error. If the signal is 10dB above the noise floor (10 time the noise), the offset error is 10% or 0.4 dB.

Fotec has always specified the measurement range of its fiber optic power meters as 10 dB above the noise floor, but at least one manufacturer specifies it as only 3 dB, which can cause an error of 50%.

Even when two FOPMs are calibrated within specifications, the uncertainty may be +A 5% (about 0.2 dB) on each meter. A worst case scenario could have two meters deviating from nominal in opposite directions, leading to a potential 10% (0.4 dB) error when measuring the same source and fiber combination. A similar error can occur in a FOPM when amplifiers auto range, unless the manufacturer includes a balance adjustment for calibration of the meter.

When one considers why FO power is measured (determining source output or receiver power to determine if a system in within margin or measuring loss), the impact of errors becomes apparent. But without knowing the system source spectra output system detector spectral sensitivity and the spectral attenuation characteristics of the fiber one cannot accurately predict system performance anyway.

How does one cope with all this uncertainty? On short systems, design the system with adequate margin. On long Systems, specify system and test source wavelength and test the cable at that wavelength (or correct for variations in system sources and test source wavelengths.) And remember that the error in optical power measurement may be small to the unknown variations in system components.

Fiber optic components are sensitive to physical stress which can induce toss. One can see the effects of physical movement of fiber optic cables and connectors on fiber optic assemblies. A simple bend in single mode fiber cable can induce seven dB losses. All connectors are very sensitive to forces acting on the cable as it exits the back shell. Just handling fibers to make measurements can cause readings to vary by several tenths of dB.

3.6.3 Instrument Resolution vs. Measurement Uncertainty

Considering the uncertainty of most fiber optic measurements, instrument manufacturers

have provided power arid loss meters with a measurement resolution that is usually much greater than needed. The uncertainty of optical power measurements is about 0.2 dB (5%), loss measurements are more likely to have uncertainties of 0.5 dB or more and optical return loss measurements have a 1 dB uncertainty. instruments which have readouts with a resolution of 0.01 dB are generally only appropriate for laboratory measurements of very low losses such as connectors or splices under 1 dB or for monitoring small changes in loss or power over environmental changes within the laboratory, a resolution of 0.01 dB can be extremely useful, since one often measures the loss of connectors or splices that are under 0.10 dB or changes in loss under environmental stress that are under 0.1 dB. stability of sources and physical stress on cables limits measurement uncertainty to about 0.02 to 0.05dB per day, but 0.01 dB resolutions can be helpful in determining small changes in component performance.

Field instruments are better when the instrument resolution is limited to 0.1dB since the readings will be less likely to be unstable when being mad and more indicative of me measurement uncertainty and especially important since field personnel are usually not as well trained in the nuances of measurement uncertainty

3.6.4 Non-Intrusive Power Measurements

Since one can induce loss in the fiber or cable by bending it, this lost power can be measured. By using a clip-on detector, such as used in fiber identifiers, the induced loss can be measured. However, the uncertainty of the measurement is very high, due to the uncertain percentage of the power in the fiber that will be coupled out of the core by the induced stress the amount of power that will be transmitted through the buffer of the fiber (especially with colored buffers) and the jacket of the fiber. Thus this type of measurement is only used as a qualitative indicator of systems power presence, not quantitative measure of system power.

4. NETWORKING

4.1 Fiber Optic Data Links

Fiber optic transmission systems all work similar to that shown above. They consist of a transmitter which takes an electrical input and converts it to an optical output from a laser diode or LED. The light from the transmitter is coupled into the fiber with a connector and is transmitted through the fiber optic cable plant The light is ultimately coupled to a receiver where a detector converts the light into an electrical signal which is then conditioned properly for use by the receiving equipment- 'just as with copper wire or radio transmission, the performance of the fiber optic data link can be determined by how well the reconverted electrical signal out of the receiver matches the input to the transmitter.

The ability of any fiber optic system to transmit data ultimately depends on the optical power at the receiver as shown below, which shows the data link bit error rate as a function of optical power at the receiver. Either too little or too much power will cause high bit error rates. Too much power, and the receiver amplifier saturates, too little and noise becomes a problem. This receiver power depends on two basic factors: how much power is launched into the fiber by the transmitter and how much is lost by attenuation in the optical fiber cable that connects the transmitter and receiver.

Data links can be either analog or digital in nature. Both have some common critical parameters and some major differences for both, me optical loss margin is most important. This is determined by connecting the link up with an adjustable attenuator in the cable plant, and varying the toss until one can generate the curve shown below. Analog data links will be tested for signal to noise ratio to determine link margin, while digital links use bit error rate as a measure of performance. Both links require testing over the full bandwidth specified for operation, but most data finks are now specified for a specific network application, like AM CAW or RGB color monitors for analog links and SONET, Ethernet, FDDI or ESCON for digital links.

The optical power margin of the link is determined by two factors, the sensitivity of the receiver, which is determined in the bit error rate curve above and the output power of the transmitter into the fiber. The minimum power level that produces an acceptable bit error rate determines the sensitivity the receiver. The power from the transmitter coupled into the optical fiber determines the transmitted power. The difference between these two power levels determines the loss margin of the link. If the link is designed to operate at differing bit rates, it is necessary to generate the performance curve for each bit-rate. Since the total power in the signal is a function of pulse width and pulse width will vary with bit-rate (higher bit-rates means shorter pulses), the receiver sensitivity will degrade at higher bit-rates.

Every manufacturer of data links components and systems specify them for receiver sensitivity (perhaps a minimum power required) and minimum power coupled into the fiber from the source. Typical values for these parameters are shown in Table 4.1. In order to test them properly, it is necessary to know the test conditions. For data link components, it includes input frequency or bit rate and duty cycle, power supply voltages and the type of fiber coupled to the source. For systems, it will be the diagnostic program needed by the system.

Table 4.1 Typical Fiber Optic link/system performance parameters

Link type	Source/Fiber Type	Wave-length (nm)	Transmit Power (dBm)	Receiver Sensitivity (dBm)	Margin (dB)
Telecom	Laser/SM	1300	+3 to -6	-40 to -45	34 to 48
		1550	0 to -10	-40 to -45	40 to 45
Datacom	LED/MM	850	-10 to -20	-30 to -35	10 to 25
		1300	-10 to -20	-30 to -35	10 to 25
CATV(AM)	Laser/SM	1300	+10 to 0	0 to -10	10 to 20

Within the data communications links and networks, there are many vendor specific fiber optic systems, but there are also a number of industry standard networks. These networks have agreed upon specifications common to all manufacturers' products to insure interoperability. Table 4.2 shows a summary of these systems.

Table 4.2 Fiber Optic Data communications Networks

Network	IEEE802.3 FOIRL	IEEE802.3 10baseF	IEEE802.5 Token Ring	IEEE802.3 100base-FX	ANSI X3T9.5 FDDI	ESCON IBM
Bit rate(Mb/s)	10	10	4/16	100	100	200
Architecture	Link	Star	Ring	Star	Ring	Branch
Fiber Type	MM,62.5	MM,62.5	MM,62.5	MM,62.5	MM/SM	MM/SM
Link Length(km)	2	-	-	2	2/60	3/20
Wavelength(nm)	850	850	850	1300	1300	1300
Margin(dB, MM/SM)	8	-	12	11	11/27	8*(11)/16
Fiber BW(MHz-km)	150	150	150	500	500	500
Connector	SMA	ST	FDDI	SC/ST	FDDI	ESCOn

*IBM specifies a nonstandard method of testing cable plant toss that reduces the loss to 8 dB max. However, the component specifications are similar to FDDI, so testing to FDDI margins is appropriate.

4.2 Installing & Testing the Fiber Optic Cable Plant

Typical fiber optic cable plants are composed of a backbone cable connecting path panels

and several short jumper cables which connect the equipment onto the cable plant Building and campus systems look like the figure above, where the backbone fiber is terminated in wiring closets and short jumpers connect wail outlets or directly to the equipment These installations often have no splices at all, since distances are short. Telco cable plants look more like the figure below, where the cable runs are long, requiring splices every 24 km. in addition, the fibers are not terminated directly, but high quality factory made pigtails am spliced onto the backbone cable. The process of testing any fiber optic cable plant during and after installation includes all the procedures covered so far. To thoroughly test the cable plant, one needs to test it three times, before installation, each installed segment and complete end to end loss.

One should test the cable on the reel for continuity before installing it, to insure no damage was done in shipment from the manufacturer to the job site. Since the cost of installation usually is high, often higher than the cost of materials, it only makes sense to insure that one does not install bad cable. It is generally sufficient to just test continuity, since most fiber is installed without connection and then terminated in place and connectors are the most likely problem to be uncovered by testing for loss. After installation and termination, each segment of the cable plant should be tested individually as it is installed, to insure each connector and cable is good.

4.3 Testing Networks

Although fiber optic networks have some major differences from copper-based networks, testing and troubleshooting them is actually very similar. The techniques can be easily mastered by technicians with some basic training in fiber optics and network testing. The basic procedures outlined below were originally developed by Fotec personnel in conjunction with the customer engineering groups of suppliers of fiber optic networks. These procedures have, therefore, been thoroughly field proven in thousands of installations.

4.3.1 Test Equipment Required

For all cables being tested, the equipment used will be a fiber optic test kit, which includes

a fiber optic power meter and a LED or laser source. The source should be of the type and wavelength used as transmitters in the network being tested. Instrument adapters provide the interface needed to the connectors used with the network. Reference test cables are needed as launch and receive jumpers for testing the network cables, and a connector coupling kit is required to interconnect the test jumpers with the cables to be tested.

4.3.2 Handling and Cleaning Procedures

Connectors and cables should be handled with care. Do not bend cables too tightly, especially near the connectors, as sharp bends can break the fibers. Do not drop the connectors; as they can be damaged by a blow to the optical face. Do not pull hard on the connectors themselves, as this may break the fiber in the back shell of the connector or cause pistoning if the bond between the fiber and the connector ferrule is broken.

If there is any question about the condition of the connectors, clean them before testing. A fiber optic inspection microscope with appropriate stages to hold the connectors should be used to verify the condition of the connectors if there is any doubt about their cleanliness or physical condition.

4.3.3 What Goes Wrong on FO Installations?

In assisting users in installing and testing FO networks, the first problem we routinely encounter is incorrect fiber optic connections. A fiber optic link consists of two fibers, transmitting in opposite directions to provide full duplex communications. It is not uncommon for the transmit and receive fibers to be switched, so you transmit to a transmitter and receive from a receiver. This doesn't work too well.

A visual tracer will make it easy to verify the proper connections quickly. A visual tracer is a visible light that you shine down the fiber and use your eyeball to trace the fiber through the cables patch panels etc. to the far end.

The tracer itself can be a flashlight (although it's really hard to hold the fiber in place to couple enough tight to see it), a modified flashlight or even microscope that will hold the fiber in place steadily and couple an adequate amount of power into the fiber, or a special test source using a bright red LED like those used in plastic fiber links. (Do not worry about eye safety. The power level in these sources is not high enough to cause harm.)

The tracers can allow you to trace fibers up to 2-1/2 miles or 4 km. Besides tracing fibers, the tracer can be used to check continuity and find broken fibers in cables. Another highly recommended use is to check continuity of every fiber in multifiber cables before installation to insure all fibers are OK. Installing a cable with bad fibers can be an embarrassing (and expensive) proposition. Fiber tracers are inexpensive and a valuable tool for every member of the installation crew. There is also a more powerful tool availabte₁ a high power visible laser coupled to fiber, called a 'visual fault locator' (or VFL). These use red lasers, either HeNe or diode lasers, with enough power to actually show breaks in the fiber through the jacket of the fiber! They can also be used to optimize splices and splice type connectors for verification of proper termination.

4.3.4 The Installed Cable Plant

Fiber optic networks are always specified to operate over a range of loss, typically called the system margin. Either too much loss or too little loss can be a problem. If the loss is too high, the signal will be low at the receiver, causing a poor signal to noise condition in the receiver. If the loss is too Jow₁ the power level at the receiver will be too high causing receiver saturation. Both these conditions will cause high bit error rates in digital systems or poor analog signal performance.

Test the complete cable plant, including all individual jumper or trunk cables, for loss, using a power meter and source and the double-ended method described above in the chapter on testing the cable plant. Use the double-ended method, since system margin specifications include the loss of connectors on both ends of the fiber. If the end-to-end (transmitter to receiver) loss measurement for a given fiber is within the network margin specification, the data should be recorded for future reference. If the loss is too low₁

notation should be made that that fiber will probably need an inline attenuator to reduce receiver power to acceptable levels. If the loss is too high, it will be necessary to retest each link of the complete cable run to find the bad link.

Possible causes of high end-to-end link loss are bad connectors; bad splice bushings in patch panels, cables bent too tightly around comers, broken fibers in cables or even bad launch or receive cables or instruments. There are only two ways to find me problem: test each segment of the cable individually to find the problem or and OTDR, if the lengths are long enough for viewing with the limited resolution of the OTDR.

Do not use an OTDR for measuring end to end loss. It will not accurately measure actual link loss as seen by the actual transmitters and receivers of the fiber optic link. As normally used, the OTOR will not count the end connectors' loss. The OTDR uses a laser which has very restricted mode power distribution which minimizes the loss of the fiber and the intermediate connectors. Finally, the difference in backscattering coefficients of various fibers leads to imprecise connector toss measurements.

4.3.5 Testing and Troubleshooting Networks

The installed network can be tested quickly and easily with a fiber optic power meter. The network transmitter needs to be set to transmit a clock output or other bit stream of known duty cycle. Set the power meter calibration on the proper wavelength and the tending units on watts. To test the received power, the most critical element in the network₁ merely disconnects the fiber optic cable connector at the receiver, attach the power meter, and measure the power.

If the receiver power is low~ the transmitter power should be measured by disconnecting the source jumper cable at the first available connector and measuring the power with the fiber at that point. Alternatively one can disconnect the cable at the transmitter and use a known good test jumper to measure the coupled power. If the output is measured through a short network jumper cable (less than 10 meters), no compensation or jumper loss is

necessary. For longer jumpers some compensation may be necessary.

If receiver power is low, but transmitter power is high, there is something wrong with the cables. They must be tested at every connection to isolate the bad cable(s) and or connectors. This can be done from either end. Starting from the transmitter or receiver end, follow the network cables to every patch panel. Disconnect the connector and measure the power at each point. By making measurements in dB, one easily calculates the loss of the cable network to each point by subtracting successive reader.

When a suspect cable is found by noting a larger than expected loss in the cable link, the suspect cable needs testing by the appropriate method described above. If a cable has attenuation that is higher than specifications but still transmits light, check connectors on a microscope to determine if they have been damaged and should be replaced. If the connectors look good, the best solution may be to replace the cable or switch to a spare. If a visual fault locator is available, it can be used to visually locate breaks in the fiber and find broken connectors. Under some circumstances such as high loss in long jumper or trunk cables, an OTDR (optical time domain reflect meter) can he used to diagnose cable faults.

4.3.6 Transceiver Loopback Testing

The datacom capabilities of the network can be tested with a loopback test. This test uses a calibrated fiber optic attenuator placed between the transmitter and receiver on a piece of equipment to see if it can transmit data to itself. Many types of network equipment have diagnostics to do loopback testing. This will test the transmitter and receiver of the unit under standard data transmission conditions over the specified link loss budget.

Some equipment can also institute an electrical network loopback test, where the loopback path is inside the equipment and looping back over the entire data link to the equipment on the far end of the link. If both ends of the link pass a unit loopback test but fail a network Loopback test, the problem is in the cables, which then need testing by the methods described above.

4.3.7 Surviving with Fiber Optics

Once the installation is complete, the cable plant tested, the network equipment running smoothly, what is likely to go wrong in a fiber optic network? One of the biggest selling points for fiber optics has been its reliability. But there are potential problems that can be addressed by the end user.

With the cable plant, the biggest problem is what the telcos call "backhoe fade" where someone mistakenly cuts or breaks the cable. While this most often happens when an underground cable is dug up, it can happen when an electrician is working on cables inside a building. Outdoors the best defense is to mark where cables are buried and bury a marker tape above the cable which will hopefully be dug up first. Inside buildings, using orange or yellow jacket cable instead of black or gray will make the fiber cable more visible and distinctive. Outside cable faults are best found by using an OTDR to localize the fault then having personnel scout the area looking for obvious damage. Inside buildings, the short distances make OTDRs unusable, so a visual fault locator is necessary. Another problem is breaking the cable just behind the connectors in patch panels. This is a difficult fault to find, but a visual fault locator is often the best way. Unless the jumper cables are quite long, an OTDR won't help at all.

Within the fiber optic link, the most likely component to fail is the LED or laser transmitter, since it is the most highly stressed component in the link. Lasers are feedback stabilized to maintain a constant output power so they tend to fail all at once. LEDs WI drop in power output as they age, but the time frame is quite long 100K to 1 million hours. If there is no power at the receiver, the next place to check should be the transmitter LED or laser, just to isolate the problem to either the transmitter or the cable plant. Receivers are low stressed devices and highly reliable. But the electronics behind them can fail. If there is receiver power but no communications, a loopback test to see if the receiver is working is the best test of its status.

4.4 Error Testing

Fiber optic receivers translate the arriving light signal back into an electrical signal. The wavelength of the receiver must match the wavelength of the transmitter. A 1.31 0 nm receiver cannot receive a signal sent at 1,550 nm.

The Bit Error Rate is the expected number of errors occurring between transmitter and receiver; a typical rate is 10^{-9}, one error for every one billion bits transmitted. With native capacities in the gigabits per second, hundreds and thousands of errors will occur every day, even with Bit Error Rates of 10^{-9}. Thorough testing of the fiber is critical, born to ensure service quality and to serve as a reference for future troubleshooting and maintenance.

An Optical Time Domain Reflectometer (OTOR) is a kind of optical radar used in installing and testing fiber. It emits light pulses then measures what comes back through the fiber. While it can find faults and measure splice and connector points, its attenuation results can be erratic, so use an optical power meter (similar to a VOM device in electronics) to measure the actual attenuation.

4.4.1   Topologies

Several networking protocols can be used with fiber optic cable.

1. Ethernet-Devised by Intel and Xerox in me 70's, it is an asynchronous data transmitter. Ethernet nodes constantly send and receive information, causing signal congestion which is counteracted by a collision detection scheme. A fiber Ethernet system uses a star topology, and can operate at either 10 Mbs or 100 Mbs.

2. Token Ring-Developed by IBM, Token Ring is also asynchronous, but is configured as a ring topology (data is passed from node to node in a circular fashion). Data is passed between nodes using tokens, which act as engines putting data from one station to the next. Speeds for Token Ring are either 4 Mbs or 16 Mbs.

3. ESCON (Enterprise Systems Connection)-A star topology invented by IBM, ESCON is the intended successor to Token Ring. Tokens are no longer used to transmit data, and there is direct communication between hubs and peripherals. ESCON systems are capable of 150 Mbs.

4. Fool (Fiber Data Distributed information)-The first system developed specifically fiber optic communications, it uses a ring topology operating at 100 Mbs with a backup mechanism ensuring that a break in the main ring wilt not bring down the entire ring. FDOI supports older systems such as Ethernet, Token Ring, and ESCON.

5. ATM (Asynchronous Transfer Mode)-Capable of 155 Mba₁ it can support voice as welt as data services such as FODI or digital video. Companies such as 3Com are developing Gigabit ATM which can push gigabits of data per second through glass.

6. SONET (Synchronous Optical Network)-Designed by the telcos, SONET is a single mode fiber network capable of huge variations in speed, ranging from 51.84 Mbs (OC-1) to 2.48 Gbs (OC-24). Like ATM, it can handle voice and data applications.

7. TOM (Time Division Multiplexing)-Also from the telecommunication industry, this method combines information of varying types into a single signal, and then sends it down the wire. The received signal is then demultiplexed into its original components. Data rates for this system are 1.54 Mbs (T-1), 6.16 Mbs (T-2), and 45 Mbs (T-3)

Fully explaining networking topologies is beyond the scope of this paper, but a few generalizations about topologies for fiber optic networking follow.

• Bus topology, where all nodes share a common line, should be avoided because any break in the cabling completely disables the network.

- Star topology generates the least attenuation and is the easiest to troubleshoot and maintain.

- Ring topology minimizes the amount of cabling necessary, but does so at the cost of troubleshooting ease. Because of its looped configuration diagnosing breaks can be problematic.

Consult an installer when planning a fiber optic system to best meet local needs.

So far, fiber optics has only played a small role in practical Local Area Networks. Many papers have been published in scholarly journals describing experimental fiber optic LANs. A few companies even offer commercial fiber optic LANs, but the few that have been installed are only a small fraction of LANs in use. Local Area Networks themselves are not as widespread one might think. Fiber optics has been used in few practical LANs but has been tested in many laboratory LANs.

This will be changing. Most present terminals and personal computer require only modest transmission rates, which often can be sent over telephone lines Current LANs operate at speeds about 10Mbits/s, at which there is little benefit from using optical fibers (except in some special cases). Future devices will require faster data transmission to allow better quality graphics, faster access to databases and more efficient sharing of information. The need for faster transmission will accelerate the development of LANs and their use of fiber optics. To get a good understanding of fiber optics in networks, we wilt have to see how finer optics can improve the capability of present and the next generation LANs being developed around fiber optics. Interest in higher speed transmission could motivate uses of fiber optics in networks.

Ethernet, developed by Digital Equipment, Intel and Xerox, was the first Local Area Network to gain much acceptance. Ethernet distributes digital data packets of variable length at 10 Mbits/s to terminals dispersed along a coaxial cable bus, as shown on the figure on the right. Separate cables up to 50 meters long, containing four twisted wire pairs₁

run from individual devices (e.g. terminals or printers) to transceivers joined to the coaxial cable. The network has no overall controller; control functions are handled by individual transceivers.

If a terminal is ready to send a signal, its transceiver checks if another signal is going along the coaxial cable. Transmission is delayed if another signal is present. If not, the terminal begins transmitting and continues until it finishes or detects a collision, the transmission of data at the same time by a second terminal. Such collision happens because it takes time, several nanoseconds a meter, for signals to travel along the coaxial cable. The terminal stops transmitting if it detects a collision and waits a random interval before trying again. Data signals contain an address header specifying me terminal to which they are directed. They pass through all transceivers but are sent only to the terminal to which they are directed. The choice of coaxial cable limits the Ethernet performance. Maximum terminal separation is 2.5 km, with no more than 500 m between terminals and no more than 1024 terminals altogether. This is adequate for most, but not all applications. Optical fibers can stretch transmission distances beyond the limit imposed by loss of the coaxial cable to limits imposed by delays in signal propagation.

One all-fiber-optic version of Ethernet is based on a central transmissive star coupler. This system relies on transmission directly between network nodes and the central passive star coupler, which mixes and distributes signals throughout the network. The figure on the left shows a certain star coupler. This network requires separate transmit and receive fibers to each node, which has a separate fiber optic transmitter and receiver. The output fiber goes to the input of the transmissive star coupler; the input is connected to the star coupler's output. The standard design uses a coupler with 32 input and output ports, but the number of connections can be increased by adding signal amplifying repeaters and extra star couplers in place of nodes. With a second level of identical star couplers, the number of terminals can be raised to 1024, the upper limit for Ethernet. The standard version of this system operates with short wavelength light emitting diodes. The receiver sensitivity is -28.2 dBm.
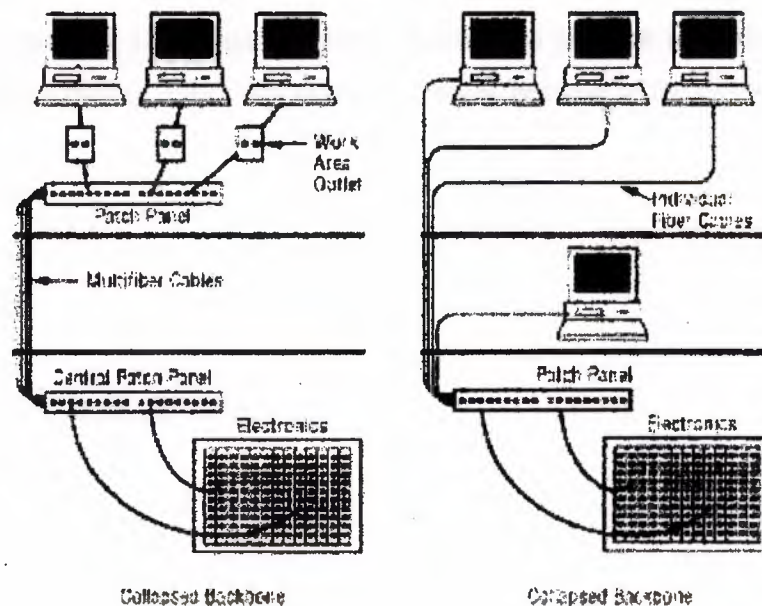
Figure -4.1 Ethernet Configurations

What advantage does the fiber optic approach give? Besides the typical ones for all data transmission that has been described, it also can deliver signals to nodes over an area up to 5 km^2, larger than possible than a coaxial cabled Ethernet. Apart from this, other all-fiber versions include one with a ring topology and one that uses an active star coupler[1] which contains receivers that detect input signals and amplify them for retransmission through the network. Fiber optic components can also be added to coaxial cable Ethernets. One standard product is an Ethernet extender, which uses fiber optic cable to extend transmission distance between an Ethernet transceiver and station to a kilometer from the standard 50 meters.

Fiber optic Local Area Networks based on Ethernet like concepts are used today. Some are small scale networks, used where fibers are essential because of problems such as ground loops and severe electromagnetic interference (EMI), which will be discussed in greater detail in a later chapter in this report. Others are designed to allow future upgrading. One of the largest systems is one Southwestern Bell installed in its 44 story headquarters in St.

Louis. Over 2000 terminals in the 1.5 million & building are connected by 144 km of fiber. Part of the network is an Ethernet like system carrying asynchronous data at 10 Mbits/s. The rest of me network allows synchronous transmission between individual terminals and a central computer facility. Fiber was primarily chosen because of the ease of upgrading.

CONCLUSION

Fiber optic transmission has found a vast array of applications in computer systems. Some design considerations depend largely on the application. For certain terminal to terminal application, crucial factors including maximizing transmission speed and distance and minimizing fiber and splice loss. By contrast, connector loss becomes important in local area networks that operate within buildings. In other Systems it is important to minimize the cost of cable, with the intention of reducing the cost of terminal equipment. These system considerations make design and construction of practical fiber optic systems a difficult task. Guidelines appropriate for one system are usually not suitable for another system.

There are a number of essential points about fiber optics that have been mentioned throughout this report. As we move towards a more sophisticated and modern future, the uses of fiber optics are going to grow in all computer systems as well as telecommunication networks. Modern information systems handle ever-increasing data loads which strain the data throughput ability of information systems. Designers have made significant progress in increasing processor speeds; however progress in the design of high-speed interconnection networks has lagged so much so that the most significant bottleneck in today's information Systems is the low speed of communications between integrated chips. These low speed communications networks consume increasing amounts of power in an effort to keep up with the faster processors. The slow communications speed is brought on by the small bandwidth available to existing communications networks based on the propagation of electrical signals through metallic lines.

Optical interconnections offer several advantages over metallic interconnections, may include: higher bandwidth; higher interconnection densities; lower crosstalk; crosstalk which is independent of data rate; inherent parallelism; immunity from electromagnetic interference and ground loops; the ability to exploit the third dimension; tower clock and signal skew; and a higher fan-in/fan-out capability. These advantages mean that optical interconnections have the potential to exhibit higher data rate communication, higher densities of interconnections with lower crosstalk, and lower power consumption.

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