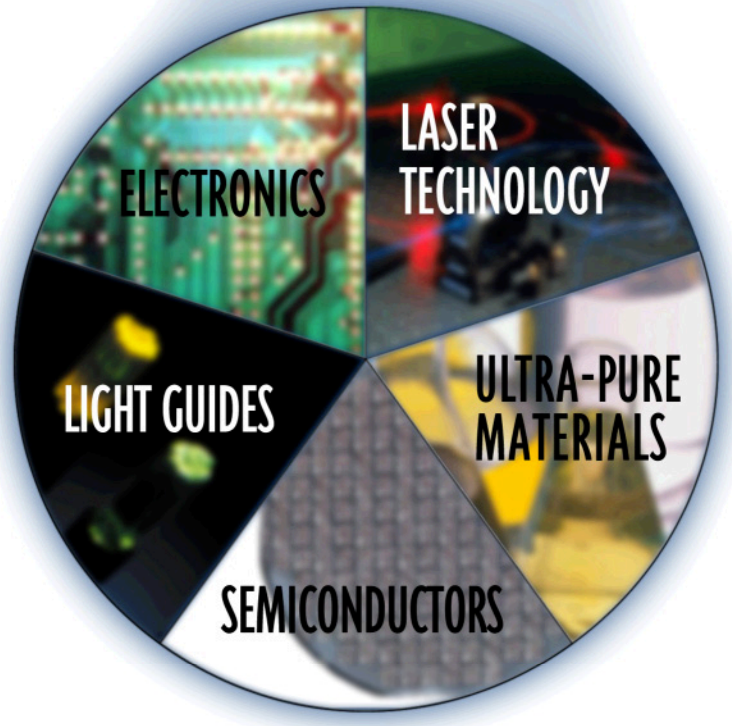

Chipsmall
深圳市津利帝科技有限公司
Geelead Technology Limited
Chipsmall
采购部

Fiber Optic



Mini-Course

*

Revision B

Printed in the United States of America

* * *

* * * * *

INDUSTRIAL FIBER OPTICS
1725 West 1st Street
Tempe, AZ 85281-7622
USA

Table of Contents

This publication serves as an introduction to fiber optics for instructors and their students. It addresses the subject with basic mathematical formulas and includes principles of fiber optics, its components (such as the fiber itself, receivers and transmitters), system design, completed systems, test equipment and industrial applications. The main section of the handbook is followed by two lab sessions, list of references (books, magazines and professional organizations), and a glossary of fiber optic terms used in the handbook and in the field of fiber optics. No prior knowledge of this subject is needed to understand and use this handbook. It will serve as a useful reference for the professional and student as fiber optics becomes a part of their everyday lives.

Warranty Information

This kit was carefully inspected before leaving the factory. *Industrial Fiber Optics* products are warranted against missing parts and defects in materials for 90 days. Since soldering and incorrect assembly can damage electrical components, no warranty can be made after assembly has begun. If any parts become damaged, replacements may be obtained from most radio/electronics supply shops. Refer to the parts list on page 32 of this manual for identification.

Industrial Fiber Optics recognizes that responsible service to our customers is the basis of our continued operation. We welcome and solicit your feedback about our products and how they might be modified to best suit your needs.

HISTORY & INTRODUCTION TO FIBER OPTICS

Fiber optics is essentially a method of carrying information from one point to another. An optical fiber is a thin strand of glass or plastic over which information passes. It serves the same basic function as copper wire, but the fiber carries light instead of electricity. In doing so, it offers many distinct advantages which make fiber optics the best transmission medium in applications ranging from telecommunications to computers to automated factories.

A basic fiber optic system is a link connecting two electronic circuits. Figure 1 shows the main parts of such a link:

Transmitter, which converts an electrical signal into a light signal. A "source" (either a light emitting diode or laser diode) does the actual conversion. A drive circuit changes the electrical signal fed to the transmitter into a form required by the source.

Fiber optic cable, the medium for carrying the light. The cable includes the fiber and its protective covering.

Receiver, which accepts the light and converts it back to an electrical signal. The two basic parts of a receiver are the detector, which converts the light signal to an electrical signal, and the output circuit, which amplifies and, if necessary, reshapes the electrical signal before passing it on.

Connectors, which connect the fibers to the source, detector and other fibers.

As with most electronic systems, the transmitter and receiver circuits can be very simple or very complex.

History of Fiber Optics

Using light for communications is not new. In the United States, lanterns hung in a church signaled Paul Revere to begin his famous ride. Ships have used light to communicate through code, and lighthouses have warned of danger and greeted sailors home for centuries.

Claude Chappe built an optical telegraph in France during the 1790s. Signalmen in a series of towers stretching from Paris to Lille, a distance of 230 km, relayed signals to one another through movable mechanical arms. Messages could travel from end to end in about 15 minutes. In the early years of the United States, an optical telegraph linked Boston and a nearby island. These systems were later replaced by electric telegraphs.

The English natural philosopher John Tyndall, in 1870, demonstrated the principle of guiding light through internal reflections. In an exhibition before the Royal Society, he presented light bending around a corner as it traveled in a jet of pouring water. Water flowed through a horizontal spout near the bottom of a container, along a parabolic path through the air, and down into another container. When Tyndall aimed a beam of light out through the spout along with the water, his audience saw the light following a path inside the curved path of the water.

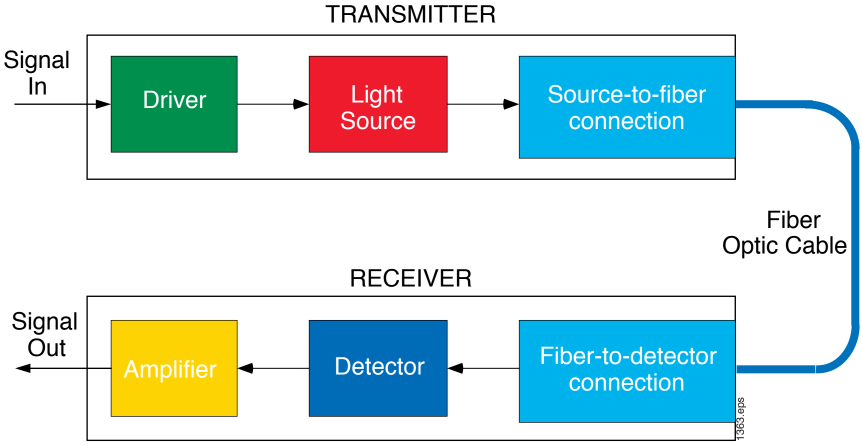


Figure 1. Components found in a basic fiber optic data link.

In 1880, an engineer named William Wheeler patented a scheme for piping light throughout a building. Not believing the incandescent bulb practical, Wheeler planned on using light from a bright electrical arc to illuminate distant rooms. He devised a series of pipes with reflective lining to be used inside the building.

Studies of how to control and use light continued through the twentieth century. Interest in glass waveguides increased in the 1950s, when research turned to glass rods for transmission of images. These are known as "fiberscopes" today, and are widely used in medicine. The term "fiber optics" was coined in 1956 with the invention of glass-coated rods.

In 1966, scientists at ITT proposed glass fiber as a transmission medium. Then, fiber had losses greater than 1000 dB/km. They determined if losses could be reduced to 20 dB/km, a level considered obtainable and quite suited for communication, fiber optic data communication would be practical. Today, losses in the best fibers are around 0.2 dB/km.

During the 1960s, many companies laid the groundwork to make them leaders in fiber optic technology. Corning Glass Works produced the first 20 dB/km fiber in 1970, and by 1972 losses were down to 4 dB/km. AMP produced the first low-cost fiber optic connector in 1974. In 1979 the fiber-optic pigtail was introduced by a joint effort of Motorola and AMP.

The Navy installed a fiber optic link aboard the USS *Little Rock* in 1973. The Air Force replaced the wiring harness of an A-7 aircraft in 1976. The original wiring harness had 302 cables and weighed 40 kg. The optical replacement had 12 fibers and a weight of 17 kg. The military was also responsible for one of the first operational fiber optic data links in 1977 — a 2 km, 20 Mbps (million bits per second) system for a satellite earth station.

The Bell System installed the first trial fiber optic telephone link at the Atlanta Works in 1976. The first field commercial trial occurred in 1977 near Chicago. It was a 44.7 Mbps, 2.5 km system with an outage rate of 0.0001% at the end of one year. (The Bell requirement was 0.02%.) In 1980, Bell announced a 1000 km project from Cambridge, MA, to Washington, DC.

Today these projects are history and fiber optics is a proven technology. Nevertheless, many new and exciting applications are currently being developed and the future is bright for many more.

Advantages

In its simplest terms, fiber optics is a communication means to link two electronic circuits. The fiber optic link may be between a computer and its peripherals, between two telephone switching offices, or between a machine and its controller in an automated manufacturing facility. Obvious questions concerning fiber optics are: *Why go to all the trouble of converting the signal to light and back? Why not just use wire?*

The answer lies in the following advantages of fiber optics.

- Wide bandwidth
- Low loss
- Electromagnetic immunity
- Security
- Light weight
- Small size
- Safety and electrical isolation

The importance of each advantage is application-dependent. In some cases, the wide bandwidth and low loss of fiber optics is the overriding factor. In others, security or safety are the determining factors. More details about the benefits of fiber optics will be covered in the next chapter.

Applications

A wide variety of fiber optic systems have been developed through many years of work. Examples of current fiber optic systems include:

- Long-haul telecommunications systems on land or at sea to carry many simultaneous calls over long distances
- Interoffice trunks carrying many simultaneous telephone conversations between local and regional telephone switching facilities
- Telephone lines with much higher speed than common single telephone lines
- Connections between microwave receivers and control facilities
- Links among computers and high-resolution video terminals used for such purposes as computer-aided design
- Cable television
- High-speed local-area networks
- Portable battlefield communication equipment
- Fiber optic gyroscopes for navigation
- Temperature, pressure, magnetic and acoustic sensors
- Illumination and imaging systems

Much of the early use of fiber optics involved data communications. Today, a significant amount of research is being conducted on developing fiber optic sensors. For example, concepts are being tested using optical fibers in aircraft wings and bridges to monitor stress. Optical fiber sensors have the unique advantage of being able to be used in very hostile environments such as high temperatures or in explosive gases.

FIBER OPTIC COMMUNICATIONS

This chapter introduces the important aspects of signals and their transmission. An understanding of the underlying principles of modern electronic communication is fundamental to understanding and appreciating fiber optics. The ideas presented here are fundamental not only to fiber optics, but also to all electronic communications.

Communications

Communication is the process of establishing a link between two points and passing information between them. Information is transmitted in the form of a signal. In electronics, a signal can be anything from the pulses running through a digital computer to the modulated radio waves of an FM radio broadcast. Such passing of information involves three activities: encoding, transmission and decoding.

Encoding is the process of placing information on a carrier. The vibration of your vocal cords places the code of your voice on air. Air is the carrier, changed to carry information by your vocal cords. Until it is changed in some way, a carrier contains no information. A steady oscillating wave electronic frequency can be transmitted from one point to another, but it contains no information unless data is encoded on it in some way. Conveying information, then, is the act of modifying the carrier. This modification is called ***modulation.***

The creation of a signal by impressing information on a carrier is shown in Figure 2. The high-frequency carrier, which in itself contains no information, has impressed on it a lower-frequency signal. The shape of the carrier is now modulated by the information. Although the simple example in the figure conveys very little information, the concept can be extended to convey a great deal. A Morse Code system can be based on the example shown. On the carrier, a low-frequency modulation can be impressed, with one or two periods in length corresponding to dots and dashes, respectively.

Once information has been encoded by modulating the carrier, it is ***transmitted.*** Transmission can occur over air, copper cables, through an optical fiber, or any other medium.

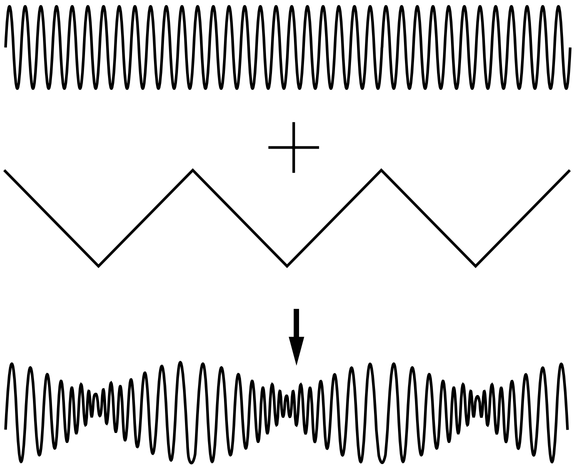


Figure 2. Basic modulation of signals.

At end of transmission, the receiver separates the information from the carrier in the ***decoding*** or demodulation process. A person's ear separates the vibrations of the air and turns then into nerve signals. Radio receivers strip away the high frequency carrier, while keeping the audio frequencies for further processing. In fiber optics, light is the carrier on which information is impressed.

There are three basic ways to modulate the carrier. See Figure 3 for examples.

Amplitude Modulation (AM) - A signal that varies continually (e.g., sound waves).

Frequency Modulation (FM) - Frequency modulation changes the frequency of the carrier to correspond to the differences in signal.

Digital Modulation - Signals that have been encoded in discrete levels, typically binary *ones* and *zeros*.

Amplitude Modulation (AM)

The world around us is analog. "Analog" implies continuous variation, like the moment of hands on a clock. Sound is analog. Ocean waves are analog. Analog is the variation of the amplitude in the medium. Before the invention of digital logic, everything was analog. In fact, the very first computers were analog.

Frequency Modulation (FM)

This type of modulation is used least in fiber optics due to difficulty of implementation. The transmitter must emit a single frequency and be stable. To demodulate an FM transmission a local optical oscillator must be used, and the oscillator must have a wavelength identical to that of the transmitter. FM radio does not suffer from these adverse characteristics, since radio frequencies are five decades lower and frequency control of electrical signals has been mastered.

Frequency modulation, however does offer the largest information bandwidth capabilities, and researchers are actively developing FM fiber optic links. Theoretical studies and demonstration systems have been constructed. Today, there are no commercial FM optical links in use, but students of today will see them in years to come.

Digital Modulation

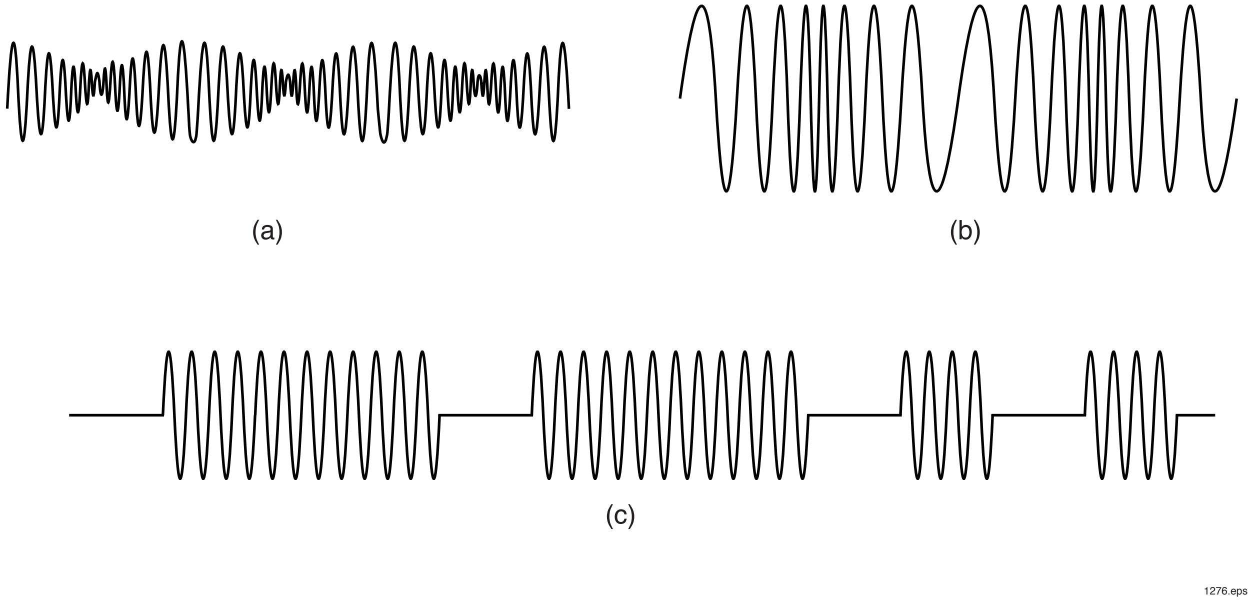
The word "digital" implies numbers — distinct units, like the display of a digital watch. In a digital system, all information exists in numerical form.

The bit, the fundamental unit of digital information, has two states; a *one* or *zero.* In electronics, the presence or absence of a voltage is the most common digital representation. Unfortunately, the single bit 1 or 0 can represent only a single state, such as on or off. A single bit has limited usefulness. Extending the number of bits increases the amount of information. For example, a three-way household lamp can have four states:

Off = 00
On = 01
Brighter = 10
Brightest = 11

The more bits in a unit, the more potential information can be expressed. A digital computer typically works with units of eight bits (or multiples of eight). Eight bits permits 256 different meanings in a given pattern of 1s and 0s. This can communicate all the characters of the number system and upper and lower case letters of the alphabet.

Information in digital systems is transferred by pulse trains as shown in Figure 3 (c).


(a)

(b)

(c)

Figure 3. Types of modulation (a) AM, (b) FM, (c) digital modulation.

Advantages

The introductory section of this handbook listed and introduced the advantages of fiber optics. Following is a more detailed description of optical fiber's advantages.

Bandwidth

The information-carrying capacity of a carrier wave increases with the carrier frequency. The carrier wave for a fiber optic signal is light, and is several orders of magnitude higher in frequency than the highest radio wave. Fibers have higher bandwidths, which allows for very high-speed transfer of data. With multiplexing, several channels can be sent over a single fiber. In computers, for instance, the capability of multiplexing paralleled bus lines into serial form for transmission over a fiber can reduce hardware and cabling costs. In telephony, a fiber optic system can carry 672 voice channels one way in a single line. Planned optical multiplexing techniques, such as wavelength division multiplexing, will increase this capacity to thousands of voice channels.

Optical fibers have potential frequency ranges up to about 1 Terahertz, although this range is far from being exploited today. The practical bandwidth of an optical fiber greatly exceeds that of copper cable. Furthermore, the bandwidth of fiber optics has only begun to be utilized, whereas the potential of copper cable is nearing its limits.

Low Loss

Loss determines the distance that information can be sent. As signals travel along a transmission path (copper or fiber), they lose strength. This loss is called attenuation. In a copper cable, attenuation increases with frequency: the higher the frequency of the carrier signal, the greater the loss. In an optical fiber, the attenuation is flat; loss is the same up to very high modulation frequencies.

Electromagnetic Immunity (EMI)

Because fiber is a dielectric, it is not affected by ordinary electromagnetic fields. This offers several advantages over copper cables. Any copper conductor acts as an antenna, either transmitting or receiving. This can cause the quality of data being transmitted or received to be degraded, or in the extreme, lost. EMI control for copper wires commonly involves adding shielded or coaxial cables. The increased shielding raises costs, making fiber system more competitive, and still does not totally alleviate the EMI problem.

Security

It is virtually impossible to "tap" a fiber optic cable surreptitiously, because attempts to reach the light-carrying central portions of the fiber generally affect transmission enough to be detectable. Since fiber does not radiate energy, other eavesdropping techniques fail. Such security reduces data encryption costs.

Weight

A glass fiber optic cable with the same information-carrying capacity as copper cable weighs less than copper cable because the copper requires more lines than the fiber. For example, a typical single-conductor fiber cable weighs 1.2 kg/km. A comparable coaxial cable weighs nine times as much - about 10 kg/km In applications such as ships and aircraft, weight savings allow for more cargo, higher altitude, greater range, or more speed.

Small Size

A fiber optic cable is smaller than its copper equivalent, and a single fiber can often replace several copper conductors. A fiber optic cable containing 144 fibers in a 12 mm diameter has the capacity to carry 24,192 conversations on a single fiber, or nearly two million calls on all the fibers. A comparable coaxial cable would be about nine times larger.

REVIEW OF LIGHT & GEOMETRIC OPTICS

Light travel through an optical fiber depends on the basic principles of optics and light’s interaction with matter. The first step in understanding fiber optics is to review light and optics. From a physical standpoint, light can be represented either as electromagnetic waves or as photons. This is the famous “wave-particle duality theory” of modern physics.

Light

Many of light's properties can be explained by thinking of light as a wave within the electromagnetic spectrum. This spectrum is shown in Figure 4. Light is higher in frequency and shorter in wavelength than the more common radio waves. Visible light is from 380 nanometers (nm), far deep violet, to 750 nm, far deep red. Infrared radiation has longer waves than visible light. Most fiber optic systems use infrared light between 750 and 1500 nm. Plastic optical fiber operates best in the 660 nm red wavelength region.

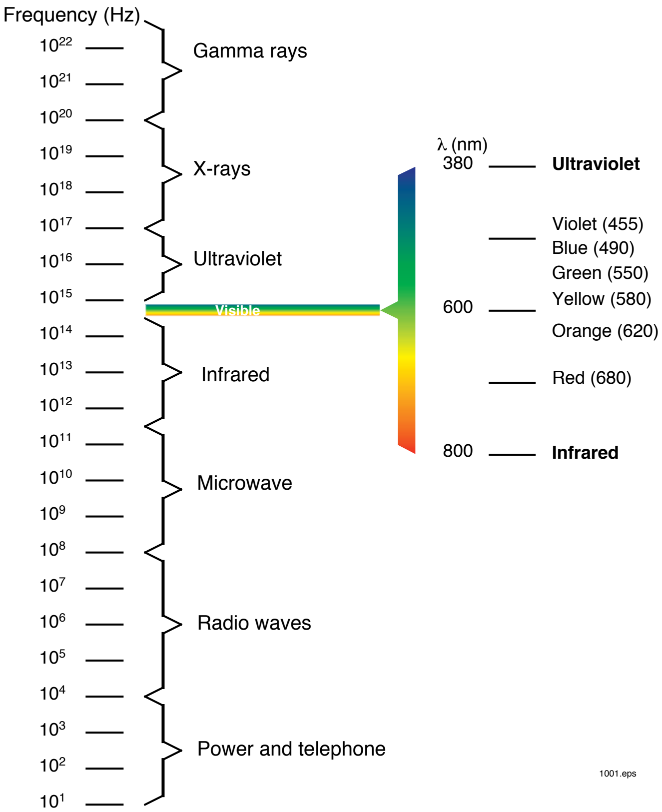


Figure 4. The electromagnetic spectrum.

The relationship between frequency and wavelength of light is defined by Equation 1,

$$! = \frac{c}{f} \qquad \text{Equation 1}$$

where c is the speed of light and f is frequency.

Light also exhibits some particle-like properties. A light particle is called a photon, a discrete unit of energy. The amount of energy contained by a photon depends on its wavelength. Light with short wavelengths has higher energy photons than does light at longer wavelengths. The energy E, in joules, contained in a photon is

$$! = \frac{h \bullet c}{f} \qquad \text{Equation 2}$$

where f is frequency and h is Planck's constant, which is 6.63 X 10^{-34} joule-seconds.

Treating light as both a wave and as a particle aids understanding of fiber optics. It is necessary to switch between the two descriptions to understand the different effects. For example, many properties of optical fiber vary with wavelength, so the wave description is used. In the case of optical detectors, responsivity to light is best explained with the particle theory.

Refractive Index

The most important optical measurement for any transparent material is its refractive index (!). Refractive index is the ratio of the speed of light in a vacuum to the speed of light in the transparent material.

$$! = \frac{C_{vacuum}}{C_{material}} \qquad \text{Equation 3}$$

The speed of light through any material is always slower than in a vacuum, so a material's refractive index is always greater than one. In practice, the refractive index is measured by comparing the speed of light in the material to that in air, rather than in a vacuum. This simplifies the measurements and does not make any practical difference, since the refractive index of air is very close to that of a vacuum. See Table 1.

Table 1. Refractive Indices of Some Common Materials.

Material	Refractive Index
Vacuum	1.0
Air	1.00029
Water	1.33
Fused Quartz	1.46
Glass	1.45 - 1.6
Diamond	2.0
Silicon	3.4
Gallium Arsenide	3.6

Snell's Law

Light travels in straight lines through most optical materials, but something different happens at the point where different materials meet. Light bends as it passes through a surface in which the refractive index changes — for example, passing from air into glass, as shown in Figure 5. The amount of bending depends on the refractive indices of the two materials and the angle of the incident ray striking the transition surface. The angles of incidence and transmission are measured from a line perpendicular to the surface. The mathematical relationship between the incident and transmitted rays is known as Snell's Law.

$$\eta_1 \cdot \sin\theta_1 = \eta_2 \cdot \sin\theta_2 \qquad \text{Equation 4}$$

where η_1 and η_2 are the refractive indices of the initial and secondary mediums, respectively. The angles θ_1 and θ_2 are the angles from normal of the light rays in initial and secondary materials respectively.

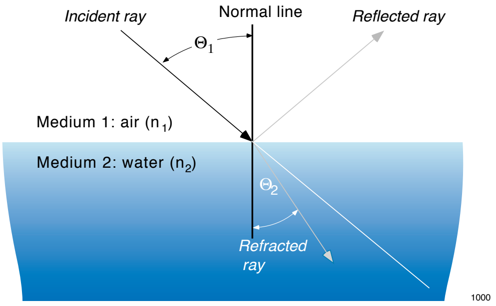


Figure 5. Optical rays at optical interface.

Critical Angle

Snell's law indicates that refraction cannot take place when the angle of incidence becomes too large. (Light traveling from a high index to a low index.) If the angle of incidence exceeds the critical value, where the sine of the angle equals one, light cannot exit the glass. (Recall from trigonometry that the maximum value of the sine of 90 degrees is 1.) All power is reflected when the reflected angle equals or is greater than the angle of incidence. This phenomenon is called total internal reflection. Total internal reflection is what keeps light confined to an optical fiber. The critical angle above which total internal refection occurs can be derived from Snell's Law.

$$\theta_{critical} = arc\ \sin\left(\frac{\eta_2}{\eta_1}\right) \qquad \text{Equation 5}$$

Numerical Aperture

The numerical aperture (NA) of a fiber is related to the critical angle and is the more common way of defining this aspect of a fiber. Critical angles of fibers are not normally specified. Calculation of the numerical aperture of an optical fiber, using the index of refraction of the core and the cladding, can be done with Equation 6.

$$\mathrm{NA} = \left(\eta_{core}^2 - \eta_{cladding}^2\right)^{0.5} \qquad \text{Equation 6}$$

Another term that is sometimes useful is acceptance angle, which can be obtained from the numerical aperture.

$$\theta_{\mathrm{acceptance}} = arc\ \sin\ \mathrm{NA} \qquad \text{Equation 7}$$

Acceptance angle is the half cone angle of the light that can be sent into an optical fiber and be reflected internally. The numerical aperture and acceptance angles of fibers are used for analyzing the collection efficiency of light sources and detectors.

Fresnel Reflections

Even when light passes from one index to another, a small portion is always reflected back into the first material. These reflections are known as Fresnel reflections. The greater the difference in the indices of the two materials, the greater the reflection. The magnitude of the Fresnel reflection at the boundary between any two surfaces is approximately:

$$R = \frac{(\eta_1 - \eta_2)^2}{(\eta_1 + \eta_2)^2} \qquad \text{Equation 8}$$

Light passing from air into an optical fiber and back to air has double this loss.

Construction

The simplest fiber optic cable consists of two concentric layers. The inner portion, the core, carries the light. The outer covering is the cladding. The cladding must have a lower refractive index than the core; therefore, the core and cladding are never exactly the same material.

A cross section of an optical fiber is shown in Figure 6. A light ray, within the acceptance angle, travels down the fiber. Light striking the core-cladding interface at less than the critical angle passes into the cladding. The cladding is usually optically glossy or opaque to dissipate light launched into the cladding. If these rays were allowed to travel down the cladding, the fiber bandwidth would be severely degraded.

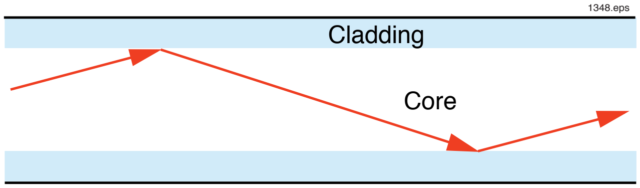


Figure 6. Cross-section of an optical fiber (step-index).

Light travel in an optical fiber depends upon several factors:

- Size of fiber
- Numerical aperture
- Material
- Light source

Modes

The "mode" is an abstract concept originating from mathematicians that lets physicists describe an occurrence in electromagnetic theory. Mode theory can be applied to Maxwell's equations on electromagnetic energy. Maxwell's equations simply state: The boundary conditions of an electromagnetic waveguide determine the characteristics of light’s passage. As it turns out for many of the world’s conditions, including fiber optic cables, many simultaneous solutions to Maxwell's equations exist. Each solution is different, and each solution is called a mode.

A mode traveling in a fiber cable has a finite path and a characteristic energy defined by Maxwell's equations. Optical fibers can sustain as few as one mode to greater than 100,000. The low-order modes travel near the center of the core and the higher-order modes are those traveling closest to the critical angle.

Fiber Types

In defining fiber types, we will not use physical materials for classification. Fiber types are classified according to the type of mode structure and light passage paths in the fiber. The three fiber types are step-index, graded-index and single-mode. (See “mode” in the Glossary.)

Step-index Fiber

Step-index fiber was the first fiber developed and the simplest of the three types. It has many modes depending on the size and numerical aperture. A step-index fiber is depicted in Figure 6. The diameter of this type of fiber ranges from 50 µm to 13 cm. It suffers from having the lowest bandwidth and greatest loss. The lowest dispersion is about 15 nanoseconds/km. (Lower dispersion is better; this will be covered later.)

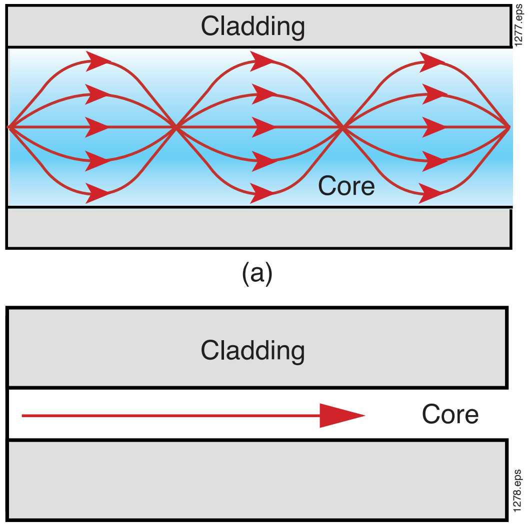
Graded-index Fiber

In a step-index optical fiber, the higher-order modes travel farther distance than lower modes as they bounce down the optical fiber. To overcome this lengthening effect, a graded refractive index core was developed. This construction is similar to having many concentric cylinders or tubes of optical material. Figure 7 (a) shows the refractive index profile and light rays traveling in the fiber. The outer layers have a lower refractive index to "speed up" these light rays, compensating for the greater distance traveled. Modal dispersion in this type of fiber is 1 nanosecond/km.

Single-mode Fiber

This fiber construction only allows a single mode to pass efficiently. The core is very small, only 5 to 10 µm in diameter. A single-mode fiber is shown in Figure 7 (b). Single-mode fibers have a potential bandwidth of up to 100 GHz-km.

For a fiber to behave as a single mode, the diameter of the core must be very close to the same size as the wavelength of the optical carrier. The cladding of an optical fiber must be greater than 10 times thicker than the core to satisfy the boundary conditions of Maxwell's equations. A single-mode fiber at 1300 nm may not be single-mode at 820 nm. Most commonly available single-mode fibers are for 1300 and 1500 nm systems.



(a)

(b)

Figure 7. (a) Graded index and (b) single mode fiber.

Attenuation

Light transmission by optical fiber is not 100 percent efficient. Light lost in transmission is called attenuation. Several mechanisms are involved — absorption by materials within the fiber, scattering of light out of the fiber core, and leakage of light out of the core caused by environmental factors. Attenuation depends on trans-mitter wavelength (covered in more detail later).

Attenuation is measured by comparing output power with input power, Equation 9. Attenuation of a fiber is often described in decibels (dB). The decibel is a logarithmic unit, relating the ratio of output power to input power. A fiber's loss, in decibels, is mathematically defined as:

$$10 \bullet Log_{10}\left(\frac{P_o}{P_i}\right) \qquad \text{Equation 9}$$

Thus, if output power is 0.001 of input power, the signal has experienced a 30 dB loss. The minus sign has been dropped for convenience and is implied on all attenuation measurements.

All optical fibers have a characteristic attenuation in decibels per unit length, normally decibels per kilometer. The total attenuation in the fiber, in decibels, equals the characteristic attenuation times the length.

Dispersion

Dispersion is signal distortion resulting from some modes requiring more time to move through the fiber than others. In a digitally-modulated system, this causes the received pulse to be spread out in time. No power is lost due to dispersion, but the peak power has been reduced as shown in Figure 8. Dispersion distorts both analog and digital signals. Dispersion is normally specified in nanoseconds per kilometer.

The dispersion of optical energy falls into two categories: modal dispersion and spectral dispersion.

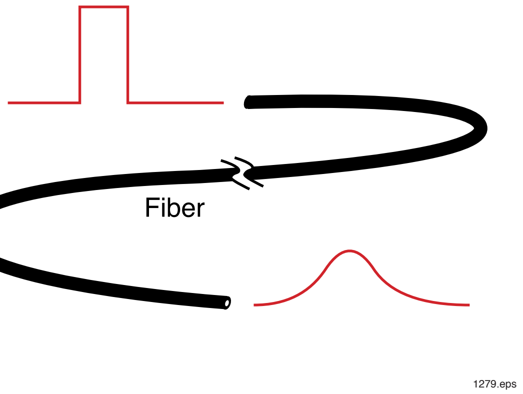


Figure 8. Dispersion in an optical fiber.

Modal Dispersion

Light travels a different path for each mode in a fiber. Each path varies the optical length of the fiber for each mode. In a long cable, the stretching and the summing of all a fiber's modes have a lengthening effect on the optical pulse.

Spectral Dispersion

As discussed previously, refractive index is inversely proportional to the speed that light travels in a medium and this speed varies with wavelength. Therefore, if two rays of different wavelengths are launched simultaneously along the same path, they will arrive at slightly different times. This causes the same effects as modal dispersion, spreading of the optical pulse. Spectral dispersion can be minimized by reducing the spectral width of the optical source. See Table 2, Page 11.

Cabling

Most optical fibers are packaged before use. Otherwise, any damage to the cladding causes degradation of the optical waveguide. Cabling, the outer protection structure for one or more optical fibers, protects the cladding and core from the environment and from mechanical damage or degradation. Fiber optic cables come in a wide variety of configurations. Important considerations in selecting a cable are:

- Tensile strength
- Ruggedness
- Environmental resistance
- Durability
- Flexibility
- Appearance
- Size
- Weight

Evaluation of these considerations depends on the application. No single cable will be suited for all applications. A cross section of an optical cable is shown in Figure 9.

Buffer - A protective layer around the cladding to protect it from damage. It also serves as the load-bearing member for the optical cable.

Strength Member - Material that is added to the cable to increase tensile strength. Common strengthen-ing materials are Kevlar, steel and fiber glass strands or rods.

Jacket - The outermost coating of the cable which provides protection from abrasion, acids, oil, water, etc. The choice of jacket depends upon the type of protection desired. The jacket may contain multiple layers.

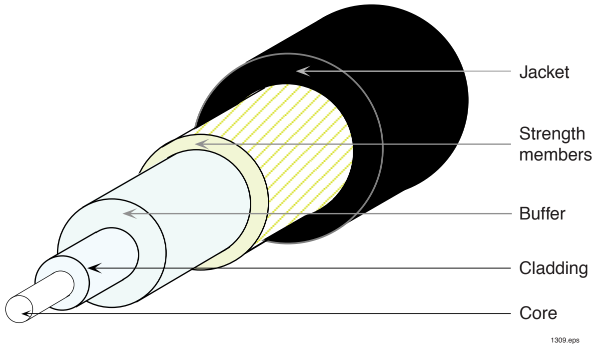


Figure 9. Cross-section of an optical cable.

Typical indoor fiber optic cables include:

- Simplex
- Duplex: Dual channel
- Multifiber
- Plenum-duty
- Undercarpet

Examples of outdoor cable:

- Overhead: Cables strung from poles
- Direct Burial: Cables buried in a trench
- Indirect Burial: Cable located underground inside conduit.
- Submarine: Underwater cable

Fiber Materials

The most common materials for making optical fibers are glass and plastic. Glass has superior optical qualities, but is more expensive per unit volume than plastic. Glass is used for high data rates and long distance transmission. For lower data rates over short distances, plastic fibers are more economical. A compromise option is plastic-clad glass fiber. The fiber core is high quality glass with an inexpensive plastic cladding.

Attenuation of an optical fiber is very dependent on the fiber core material and the wavelength of operation. Attenuation of a glass fiber (a) and of a plastic fiber (b) is shown in Figure 10.

The graphs in Figure 10 show that certain wavelengths are better suited for fiber optic trans-mission than others. Selecting the best wavelength for a fiber also depends on the available light sources and detectors.

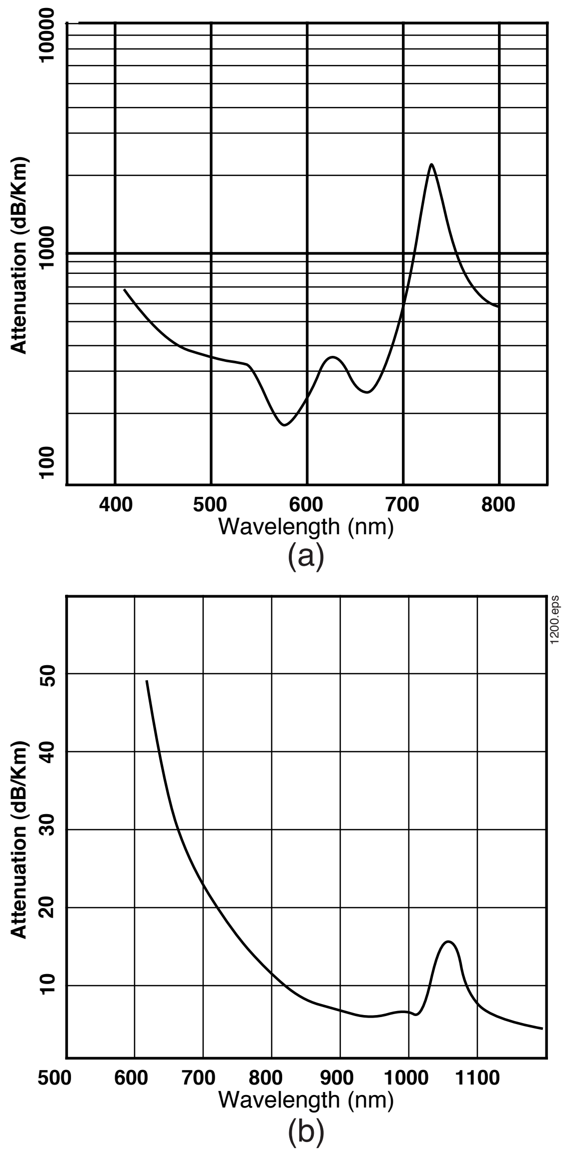


Figure 10. Attenuation of glass fiber (a), plastic fiber (b).

LIGHT SOURCES & THEIR CHARACTERISTICS

This section covers fiber optic light sources, those elements which emit light that can be directed into fiber cables. The rest of the transmitter will be discussed in the next section.

Two types of fiber optic sources supply greater than 95 percent of the communications market: light emitting diodes (LEDs) and laser diodes. (In industrial applications there may be other sources, but these will be covered in the section on industrial applications.) Both sources are made from semiconductor material and technology.

Both of these emitters are created from layers of p- and n-type semiconductor material, creating a junction. Applying a small voltage across the junction causes electrical current to flow, consisting of electrons and holes. Light photons are emitted from the junction when the electrons and holes combine inside the junction.

The best LED or laser for a fiber optic system is determined by several criteria:

- Output power
- Wavelength
- Speed
- Emission pattern
- Lifetime and reliability
- Drive current

Table 2. Typical characteristics of LEDs and lasers.

Characteristics	LED	Laser
Spectral width	20-60 nm	0.5-6 nm
Current	50 mA	150 mA
Output power	5 mW	100 mW
NA	0.4	0.25
Speed	100 MHz	2 GHz
Lifetime	10,000 hrs	50,000 hrs
Cost	$1.00-1500	$100-10 k

LED

LEDs are the simplest of the two sources and the most widely used in fiber optic systems for the following reasons:

- Sturdy
- Inexpensive
- Low input power
- Very long life expectancy

LEDs are made from a variety of materials. Color or emission wavelength depends upon the material. Table 3 shows some common LED materials, with corresponding colors and peak wavelengths.

Simple LEDs emit light in every direction and are constructed to optimize light coming from a particular surface. There are two types of LEDs, or packaging schemes for p-n junctions: surface-emitting LEDs and edge-emitting LEDs.

Surface-emitting LEDs

This is the most common LED packaging type. It is used in most of the visible LEDs and displays. Surface emitters are the easiest and cheapest to make. Figure 11(a) depicts typical surface emitter construction and a typical emission pattern.

Edge-emitting LED

The edge emitter, as shown in Figure 11(b), emits all of its light parallel to the p-n junction. The emission area is a stripe and the emission forms an elliptical beam. Edge-emitters can direct much more light into small fibers than do surface emitters. Because of the high price of fabricating edge-emitting LEDs there are very few being manufactured today. They are as expensive to make as laser diodes and more as compared to the laser diodes manufactured for CD players.

Table 3. Common materials used to make LEDs and laser diodes and their output characteristics.

Material	Color	Wavelength
Gallium phosphide	green	560 nm
Gallium arsenic phosphide	yellow-red	570-700 nm
Gallium aluminum arsenide	near-infrared	800-900 nm
Gallium arsenide	near-infrared	930 nm
Indium gallium arsenic phosphide	near-infrared	1300-1500 nm

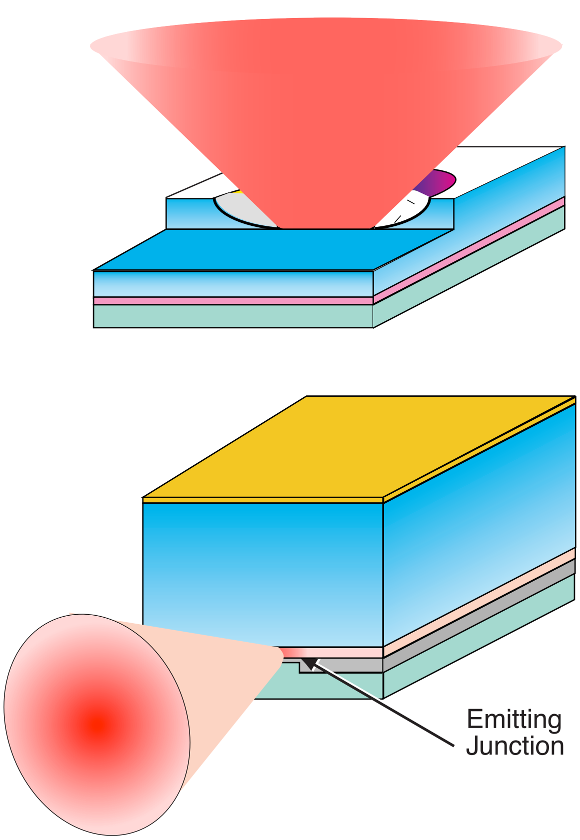


Figure 11. (a) Surface-emitting LED. (b) Edge-emitting LED.

Lasers

Laser is an acronym for light amplification by stimulated emission of radiation. The main difference between an LED and a laser is that a laser has an optical cavity, which is required for lasing. This cavity is called a Fabry-Perot cavity. It is formed by cleaving the opposite ends of the edge-emitting chip to form highly parallel, reflective mirror-like finishes.

At low electrical drive current lasers act as LEDs. As the drive current increases, it reaches a threshold, above which lasing occurs. A laser diode relies on a very high current density to stimulate lasing. At high current densities, many electrons are in the excited state. As in LEDs, holes and electrons combine inside the laser, creating photons, which are confined to the optical cavity. Photons can travel only along the length of the optical cavity, and as they travel they collide with other electrons, generating new photons. These photons are clones of the first photons; they travel the same direction, have the same phase and wavelength. The first light photon amplified itself by stimulating an electron to emit another photon.

Both ends of the laser diode can be 100 percent reflective or there would be no optical output. Usually, one end has a partially reflecting facet to allow some optical power to escape to be used in fiber optic systems.

The stimulated emission process is very fast; laser diodes have been modulated at up to 16 gigabits per second.

Producing a laser diode is much more difficult than the simple description just given. Many material properties must all simultaneously occur. The very complex fabrication process causes laser diodes to be higher priced than surface-emitting LEDs.

Power

Both LEDs and lasers have voltage versus current curves similar to those of regular silicon diodes. The typical forward voltage drop across LEDs and laser diodes, made from Gallium Arsenid, is 1.7 volts.

In general, the output power of sources decreases in the following order: laser diodes, edge-emitting LEDs, surface emitting LEDs. Figure 12 shows some curves of relative output power versus input current for LEDs and lasers.

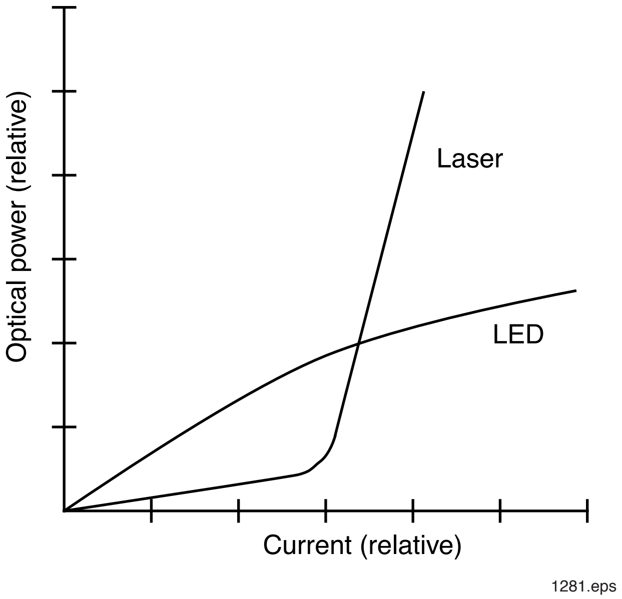


Figure 12. Output optical power versus current for LEDs and laser diodes.

Wavelength

Because optical fibers are sensitive to wavelength, the spectral (optical) frequency of the fiber optic source is important. Lasers and LEDs do not emit a single wavelength; they emit a range of wavelengths. The spectral width is the optical bandwidth at which the intensity of emission falls to 50 percent of the peak —sometimes known as full width half maximum [FWHM]. The spectral width of a laser is 0.5 to 6 nm; the width of LEDs is several times wider, typically between 20 and 60 nm.

Speed

A light source must turn on and off fast enough to meet the bandwidth requirements of the fiber optic system. Source speeds are specified by rise and fall times. Laser diodes have rise time less than 1 nanosecond, whereas LEDs have slower rise times, typically 5 nanoseconds or greater. A rough approximation of bandwidth of a device, given the rise time, is

$$B_w = \frac{0.35}{t_r} \qquad \text{Equation 10}$$

where B_w is bandwidth in Hz and t_r is rise time in seconds.

Lifetime

The expected operating lifetime of a source can run into thousands of hours. Over time, the output power decreases due to increasing internal defects. The specified lifetime of a source is the time for the output power to decrease to 50 percent of initial value. LEDs have a much longer lifetime than lasers. The conditions under which lasing occurs cause greater thermal stress, promoting growth of internal defects in the device, decreasing longevity.

Usage

Although a laser provides better optical performance than an LED, it is also more expensive, less reliable and harder to use. Lasers often require more complex electrical driving circuits. For example, the output power of a laser changes significantly with temperature. Therefore, to maintain proper output levels and prevent damage to the laser, special circuitry is needed to detect changes in temperature or optical output and adjust the electrical drive current according to temperature or output power.

Safety

Light from lasers or other light sources can cause eye damage just as directly looking at the sun can. Particularly with fiber optics systems, the light is infrared and not visible to the eye. Infrared radiation can be very dangerous because the normal human blink response will not protect the eye, nor can it be visibly seen.

Generally, light from LEDs is not intense enough to cause eye damage, but the emission from laser diodes can be harmful. Users should be especially conscious of collimated light beams from LEDs or lasers.

Because most fiber optic communications systems have very low optical power, eye safety is not usually a problem, but do not take it for granted. If you do not know, ask! The precautions are simple:

- **Do not look directly into an LED or laser diode**
- **Avoid all eye contact with all collimated beams**
- **Before working with fiber optics become familiar with pertinent safety standards**

For more information about safety, contact the Laser Society of America or OSHA. See section titled *References* for safety information.

TRANSMITTER COMPONENTS

The light source is the most important component of a transmitter, but it is not sufficient by itself. A housing is required to mount and protect the light source and to interface with the electronic signal source and transmitting optical fiber. Internal components may be necessary to optimize light coupling into the optical fiber. Electrical drive circuitry is needed and output monitoring may be crucial for sophisticated laser diodes.

Practical boundaries between transmitters and light sources can be vague. Simple LED sources can be mounted in a case with optical and electronic connections, with little or no drive circuitry. On the other hand, a high-performance laser may be packaged as a transmitter in a case that also houses an output monitor and thermoelectric cooler.

Elements of a Transmitter

The basic elements commonly found in transmitters and shown in Figure 13 are:

- Housing
- Electronic interface
- Electronic preprocessing
- Drive circuits
- Light sources
- Optical interface
- Temperature sensing and control
- Optical monitor

<u>Housing</u>

The simplest housing for a fiber optic transmitter is an adequately sized box that can be conveniently mounted with screws or other means to a printed wiring board or other electrical interface. Some transmitters are built inside a mechanical box, with only electrical and optical connections exposed.

<u>Electronic Interface</u>

Electronic interfaces can be wires, pins, or standard electrical connections. Transmitters containing a LED may only have two simple electrical connections. Others may be more complex, requiring electrical power, feedback interfaces resulting in circuits and up to 16 or more interconnects.

<u>Drive Circuits</u>

The type of drive circuit depends upon the application requirements, data format and light source. LEDs are best driven by a current source. (Most electronic signals are voltages and must be converted to current.) Some LEDs work better with special drive circuitry to tailor the electric current input. For example, the proper drive waveform can effectively reduce the rise time of an inexpensive LED and allow its use at higher-than-specified bandwidths.

Semiconductor lasers are generally pre-biased at a current level near lasing threshold.

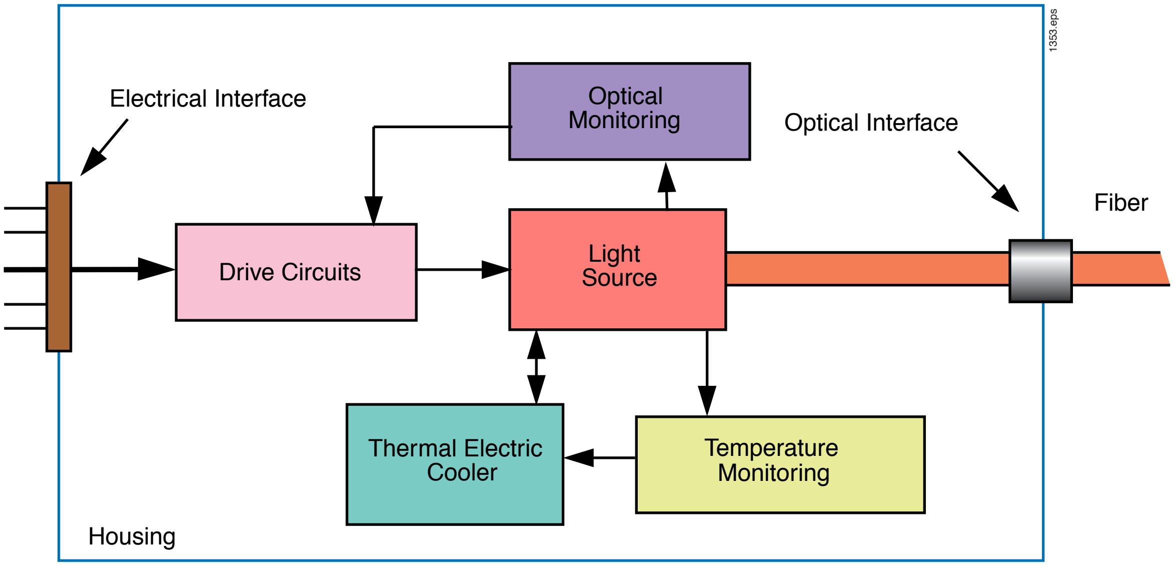


Figure 13. Block diagram of elements commonly found in a fiber optic transmitter.

Light Source

Fiber optic light sources are either LEDs or laser diodes. We discussed these two components in the previous section.

Optical Interface

The two forms of optical interfaces are the fiber optic connector as shown in Figure 14, and a short fiber optic pigtail coupled to the light source and brought outside the housing. The pigtail can be spliced or connected to an external fiber.

Temperature Sensing and Control

These circuits are primarily found in transmitters with laser diodes, because their output is very temperature-dependent. A temperature sensing element senses the device temperature, compares it to a reference, and then adapts the electric heat pump to control the laser diode temperature. (The most common heat pump is the thermal electric [TE] cooler.) Stabilizing the temperature of laser diodes has the additional benefit of increasing their reliability and lifetime.

Optical Monitor

Some transmitters include optical output stabilization circuits. Such circuits sample a small amount of optical energy with a photodetector and convert it to an electrical signal. The signal is then used to adjust input drive current, stabilizing output power.

Requirements

No single fiber optic transmitter will fulfill all the needs of the many fiber optic designs. There are just too many options that must be considered when making a design. Following is a list of important design criteria to consider when selecting a fiber optic transmitter:

- Modulation type
- Speed
- Output power
- Optical interface
- Electronic interface
- Housing
- Cost

In most cases, fiber optic system engineers do not design their own transmitters, but rather use completed assemblies. For information on Industrial Fiber Optics transmitter components, please see our Web site at
www.i-fiberoptics.com

Figure 14. Fiber optic FDDI transceiver.

DETECTORS FOR FIBER OPTIC RECEIVERS

In a receiver, the detector is comparable to the light source in the transmitter. The detector performs the reciprocal function of the source, converting optical energy to electrical current. This section will cover the types of semi-conductor photodetectors.

Fiber optic detectors are fabricated from semiconductor materials similar to those found in LEDs and lasers.

Table 4. Photodetector materials and active regions.

Material	Wavelength (nm)
Silicon	400 - 1050
Germanium	600 - 1600
Gallium arsenide	800 - 1000
Indium gallium arsenide	1000 - 1700
Indium arsenic phosphide	1100 - 1600

A circuit using a semiconductor photodetector is shown in Figure 15. The diode is reverse biased; little or no current flows in the absence of light. When light photons strike the detector, they create hole/electron pairs, causing current flow. The number of electron/hole pairs (current) is directly proportional to the amount of light incident upon the detector. This type of photodetector is called a photoconductive detector.

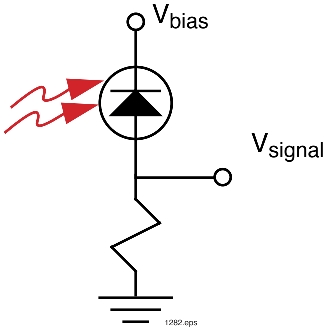


Figure 15. Circuit using an optical photodetector.

Types

The characteristics of four types of photoconductive photodetectors are listed in Table 5. The phototransistor and photodarlington have little use in most fiber optic systems due to their slow rise times. Photodiodes and avalanche photodiodes are the primary detectors for fiber optics.

Table 5. Characteristics of fiber optic detectors.

Device	Responsivity	Rise time
Phototransistor	18 A/W	2.5 us
Photodarlington	500 A/W	40 us
PIN photodiode	0.6 A/W	1 ns
Avalanche photodiode	60 A/W	1 ns

Photodiode

There are several types of photodiodes, also. The one most useful for fiber optics is the PIN photodiode. The name of the photodiode comes from the layering — positive, intrinsic, negative — PIN. See the cross-section shown in Figure 16.

The PIN photodiode has higher efficiency and a faster rise time than other photodiodes. In a PIN photodiode, one photon creates one hole/electron pair.

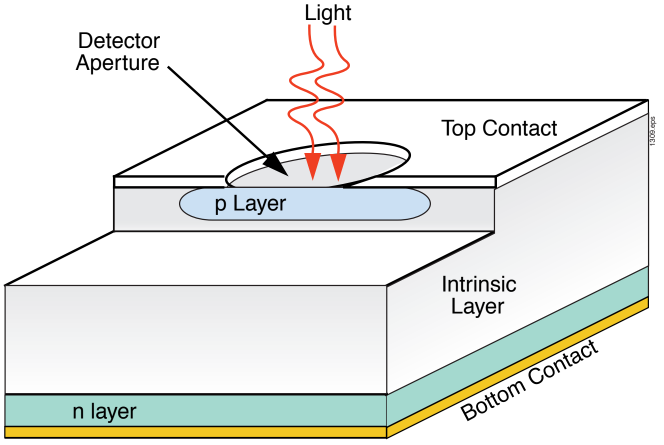


Figure 16. Cross-section of a PIN photodiode.

Avalanche Photodiode (APD)

The avalanche photodiode is similar to the laser diode. In a laser, a few primary carriers result in many emitted photons. In an avalanche photodiode, a few photons produce many carriers.

When an avalanche photodetector absorbs a photon, it creates a hole/electron pair in the intrinsic region. The APD is reversed biased, causing the holes and electrons to move in the electric field. In an avalanche photodiode this electric field is much stronger than in a PIN diode, due to higher bias voltage (typically 100 – 400 volts). The holes/electron pairs accelerate while traveling in this strong electric field. These pairs collide with electrons/holes, generating another set of carriers, i.e., avalanching.

The avalanche process amplifies the number of carriers generated from a single photon. Typical magnifications are 10 to 100.

Avalanche photodiodes are used in fiber optic systems because the system noise level is limited by the interface electronics which follow. The avalanche photodiode provides pre-electronics gain.

Disadvantages of using avalanche photodiodes:

- Gain variation with temperature
- High voltage power supply required
- Power dissipation
- Higher price

Responsivity

The responsivity of a detector is a measure of its efficiency. A good detector has an efficiency between 80 and 85 percent. A plot of silicon PIN photodiode responsivity versus wavelength is shown in Figure 17. The shape of the response is typical and consistent with solid state theory. It is beyond the depth of this course to discuss this, but suffice to say that a 100 percent efficient detector does not generate 1 Amp per watt. The typical responsivity of a silicon PIN diode is .6 A/W.

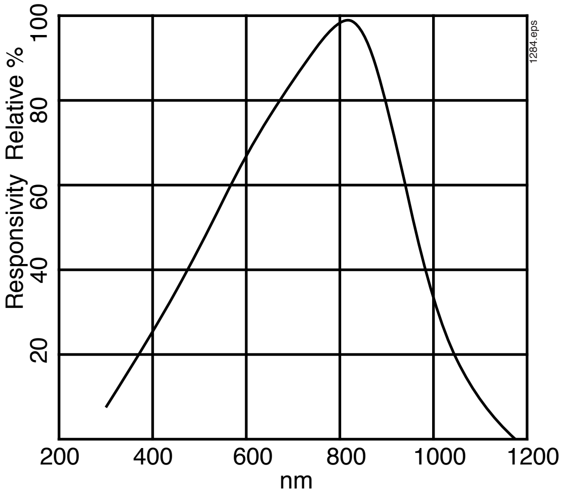


Figure 17. Responsivity of a silicon photodiode versus wavelength.

The shape of the curve shown in figure 17 is dependant upon the detector material. Above a certain wavelength, light photons will not contain enough energy to create a hole/electron pair (see Equation 2). This explains the sharp roll-off to the right of the peak. For the curve left of the peak, remember that if the optical power remains constant, the number of photons (per watt of energy) decreases as the wavelength gets shorter. In a detector each photon creates one hole/electron pair, thus the responsivity decreases with wavelength with constant energy. The remainder of the energy is converted to heat. Other effects also occur below 500 nm, but this is outside fiber optic normal operating regions.

Dark Current

Dark current is the current flowing through a detector in the absence of any light when in an operational circuit. This value is normally specified on the manufacturer’s device data sheets as a worst-case condition at a given temperature. The dark current in silicon PIN photodiodes or APDs doubles every 10° C.

Rise time

A fiber optic system's bandwidth is very dependent on the photodetector bandwidth or rise time. Equation 10 applies to detectors as well. Rise time is furnished on the manufacturer's data sheets. Rise times can be dependent on the bias voltage applied to the photodetector. The rise and fall times are very comparable in PIN photodetectors and avalanche photodiodes.

Bias Voltage

Both photodiodes and avalanche photodiodes are reverse biased. Typical bias voltage for photodiodes is 5 to 100 volts. Photodiodes operating with a low bias voltage will have more internal capacitance which slows down rise and fall times.

Avalanche photodiodes require a much higher voltage, typically 100 to 400 volts. The bias voltage of avalanche photodiodes determines the responsivity of the device, as shown in Figure 18.

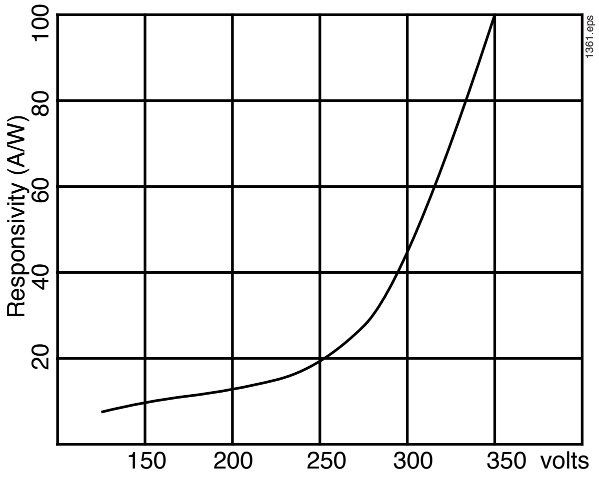


Figure 18. Responsivity versus voltage for an APD.

ELEMENTS OF FIBER OPTIC RECEIVERS

Preamplifier

The receiver is as essential an element of any fiber optic system as the fiber or light source. The receiver converts the optical signal transmitted through the optical fiber to an electrical form. Again, the boundary between receivers and detectors is variable, depending on the system requirements.

Receiver Elements

Fiber optic receivers come in many varieties, from simple packaged photodetectors to sophisticated systems for high speed transmission. The description of a receiver is a little more complicated than the transmitter because there are two types of receivers, analog and digital. The basic elements of all receivers are:

- Housing
- Electronic interface
- Optical interface
- Detector
- Low-noise preamplifier
- Main amplifier
- Signal processor

The information pertaining to the housing, electronic interface, and optical interface covered in the section on transmitters applies equally to receivers.

The preamplifier sets the two most important performance levels in a fiber optic system: minimal detectable signal and electrical bandwidth. At the preamplifier, the signal is the weakest and the most susceptible to extraneous sources. Typical input-current levels to preamplifier are 0.1- 100 µA.

The transfer function of a fiber optic preamplifier has the dimensions of volts per Amp. (Most electronic amplifiers have transfer functions of volts/volt.) This unusual dimension of these preamplifiers gives them an alternate name, transimpedance amplifiers.

Main Amplifier

The main amplifier further amplifies the transimpedance amplifier signals to higher levels. Typical values would be 0.7 to 3.4 volts in a digital TTL system. In an analog system, the main amplifier could be a power amplifier for driving a 50 ohm load

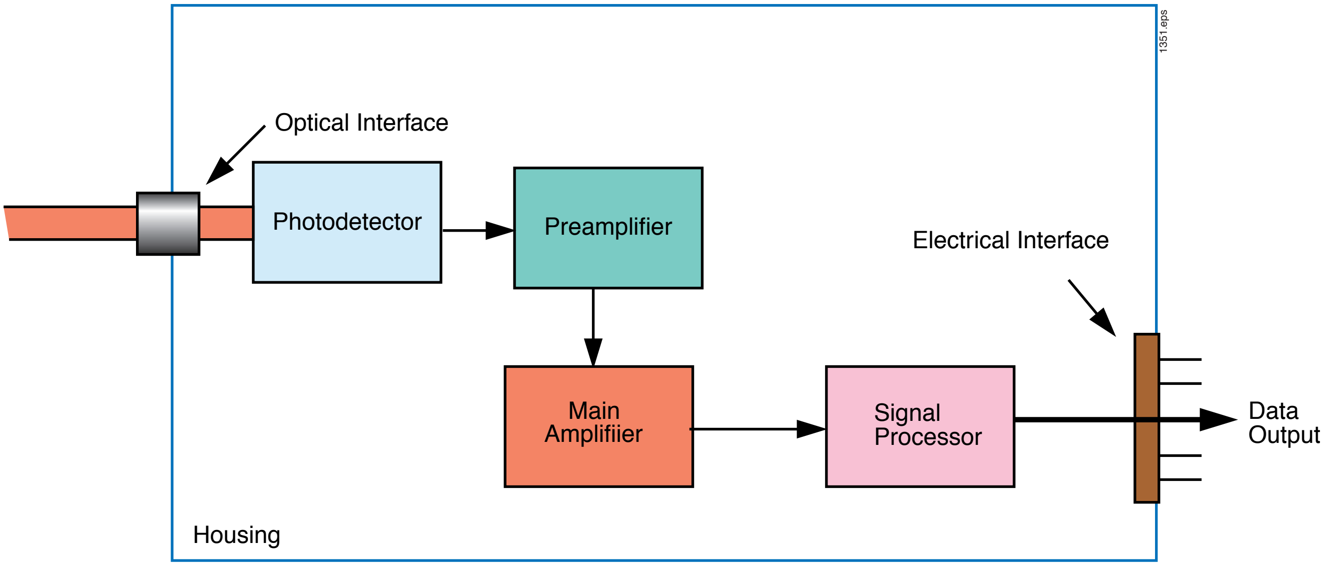
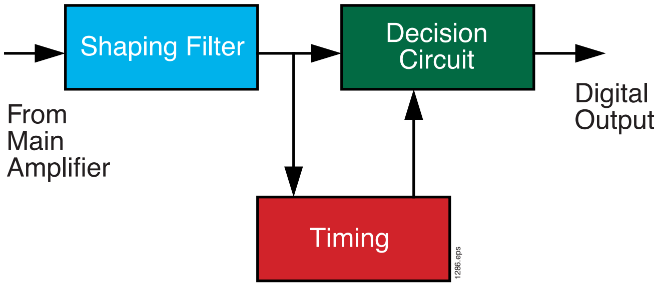


Figure 19. Typical elements of a fiber optic receiver.

Signal Processor

The detector, preamplifier, and main amplifier are the same for both analog and digital receivers, but the signal processors are different. See Figure 20.

Analog processor



Digital processor

Figure 20. Analog and digital fiber optic receiver signal processors.

Requirements

Fiber optic receiver requirements are so different that a single device cannot fit every need. Besides selecting between analog and digital receivers, there are many other options. Following is a list of the more important features in a receiver:

- Modulation
- Bandwidth
- Noise
- Dynamic range
- Optical interface
- Electronic interface
- Housing
- Cost

Fiber optic engineers, in most cases, do not design their own receivers, but rather use completed assemblies. Details of receiver design will be left to more advanced classes, but a brief discussion of the two most critical receiver parameters follows.

Noise in Fiber Optic Receivers

Every component in a fiber optic receiver generates electrical noise. This noise has a Gaussian distribution. The amplitude depends on the receiver bandwidth and associated components, but the detector and preamplifier are the major sources.

The noise current generated in a photodiode is called shot noise. It can be calculated by Equation 11,

$$i_s^2 = 2\ e\ I\ \mathrm{B} \qquad \text{Equation 11}$$

in which e is the charge of an electron, 1.6 X 10^{-19} coulombs, B is system electrical bandwidth in Hz, and I is the dc current flowing through photodiode in amps.

Shot noise generation is due to the statistical nature of electron flow across the p-n junction.

Thermal noise or Johnson noise is caused by noise generated in resistors and electronics, and can be calculated from Equation 12.

$$i_{th}^2 = \frac{4\ \mathrm{K}\ \ \mathrm{T\,B}}{Req} \qquad \text{Equation 12}$$

K is Boltzman's Constant (1.38 E-23 joules/° K), T is the absolute temperature (°Kelvin) and Req is the equivalent resistance of the transimpedance amplifier.

The total noise current of a photodiode and preamplifier can be summed up by Equation 13.

$$i_{\mathrm{noise}}^2 = i_{\mathrm{shot}}^2 + i_{th}^2 \qquad \text{Equation 13}$$

Receiver Bandwidth

The electrical bandwidth of most fiber optic receivers is set by the preamplifier. Generally, photodiodes and avalanche photodiodes with wide bandwidths are easier to find than wide bandwidth, low-noise preamplifiers.

The fiber optic receiver in Figure 19 has a series of elements that each can reduce system bandwidth or rise time. Calculation of overall system rise time can be done with Equation 14. Bandwidth can be computed with Equation 10.

Equation 14

$$t_r(system) = \left(t_r^2(transmitter) + t_r^2(\mathrm{det}\,ector) + t_r^{\,2}(preamp) + \ldots\right)^{0.5}$$

PASSIVE OPTICAL INTERCONNECTIONS

Interconnecting the various components of a fiber optic system is a vital part of system performance. This section discusses the mechanics and requirements for fiber optic connections and distribution. The three most important interconnects involve connectors, splices and couplers.

The losses in a fiber optic interconnect can be separated into two categories.

Intrinsic, or fiber-related, losses caused by variations in the fiber itself, such as numerical aperture mismatch, concentricity, ellipticity and core/cladding mismatches.

Extrinsic, or interface-related, factors contributed by the interface itself. The main causes of these losses are lateral displacement, end separation, angular misalignment and surface roughness.

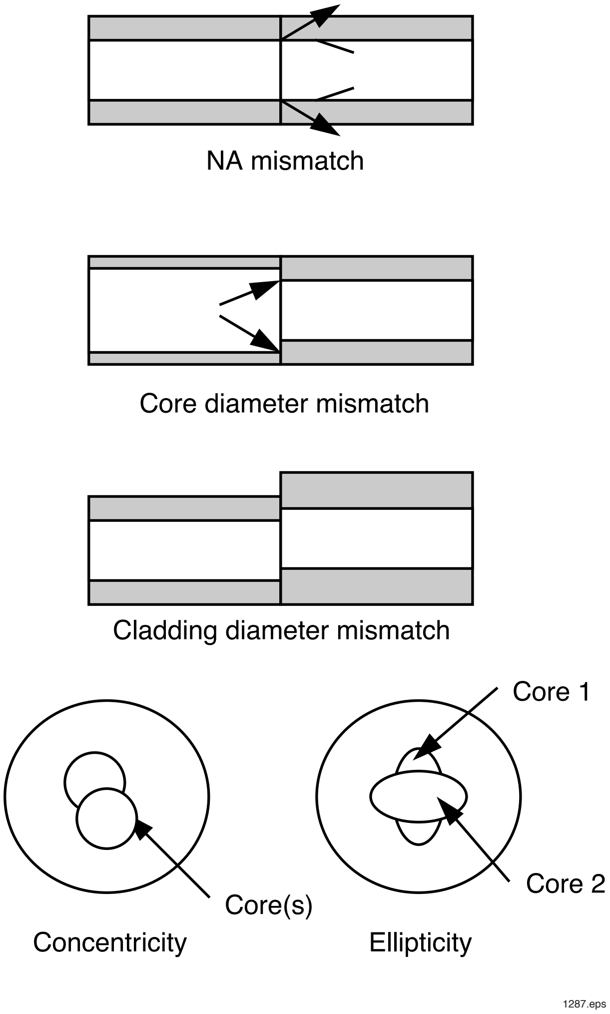


Figure 21. Intrinsic fiber optic losses.

Connectors

The fiber optic connector is a non-permanent disconnectable device used to connect a fiber to a source, detector, or another fiber. It is designed to be easily connected and disconnected repeatedly. Listed below are some of the desirable features in a connector:

- Low loss
- Easy installation
- Repeatability (low variations in loss after disconnection)
- Consistency (between connectors)
- Economical

It is very difficult to design a connector to meet every requirement. A low-loss connector may be more expensive, take longer to install, or require high-priced tooling than a higher-loss connector.

The many different kinds of connectors include:

- SMA
- ST
- Bi-conic
- LC

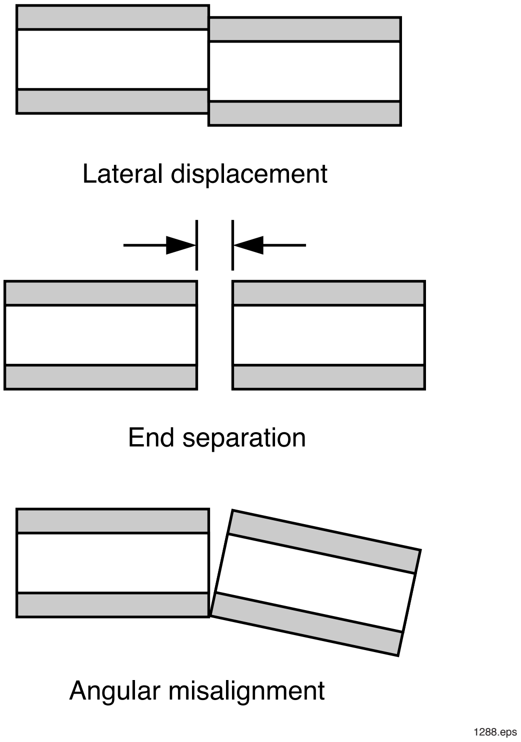


Figure 22. Extrinsic fiber optic losses.

The SMA fiber optic connector is the oldest type of connector, evolving from the SMA electrical interface. The ST, Bi-conic and LC are connectors recently designed specifically for fiber cable using small core fiber, having low loss and meeting environmental considerations.

The installation of a fiber optic connector is similar to that of electrical connectors, but it does require more care, special tools and little more time. The steps in making a fiber optic connection are outlined below:

- Open cable
- Remove jacketing and buffer layers to expose fiber
- Insert fiber cable into connector
- Attach connector to fiber with crimp or epoxy
- Scripe fiber
- Polish or smooth the fiber end
- Inspect fiber ends with microscope

Splices

Unlike connectors, splices are a permanent connection between two fibers. Table 6 presents a comparison of connectors and splices.

The main concerns in a fiber optic splice are:

- Losses in splice
- Physical durability
- Ease of making splice

The losses in a fiber optic splice are identical to those in a connector — intrinsic and extrinsic. However, the methods used to make fiber optic splices produce tighter tolerances, and therefore lower attenuation. Some sources of loss are reduced; others are eliminated.

Because most fiber optic splices are made in the field, the ease with which splices can be made is very important. This has led to development of very specialized fiber splices and equipment.

A splice is made by either fusing (melting), gluing, or mechanically holding two fibers together. Unlike wire splices, a carefully made fusion splice can withstand roughly the same stress as an unspliced fiber. Wire splices will nearly always fail in the joint.

Fusion Splices

The fusion splice, the most common fiber splice, is formed by heating two ends of fiber and welding them together.

A splice begins with cleaving the ends of both fibers. (A fiber cleave is made by scribing or nicking the fiber and putting it under tension by pulling or bending. This causes the fiber to break along the crystalline structure. Ideal cleaves are perfect — no discontinuities.) The ends are cleaned and prepared with a preform electrical arc, then the fibers are aligned with micropositioners and a microscope or an automatic alignment processor. A final fusion completes the splice process. The electrical arc raises the fiber temperature to 2000° C, melting the glass. Time duration and energy in the arcs can be controlled, which allows optimal splices for many different types of fibers.

Mechanical Splice

Mechanical splices join two fiber ends by clamping them within a structure or by gluing them together. Because tolerances in mechanical splices are looser than fusion splicing, this approach is used more often with multimode than single-mode fiber. Mechanical splices are easy to perform and do not require expensive splicing equipment. Losses are generally higher in mechanical splices than in fusion splices.

Table 6. Comparison of fiber optic connectors and splices.

Connectors	Splices
Non-permanent	Permanent
Factory installable on cables	Easier to get low loss in field
Easy reconfiguration	Lower attenuation
Simple to use	Spliced fibers can fit inside conduit
Field installable	Some are hermetically sealed
Less expensive per interconnect	Stronger junction