A Fiber Optic Primer

Introduction

As mankind's technological development progresses, the demand to transmit more and more information over longer and longer distances increases. In the early part of the 20th century, simple copper wire sufficed. As technology matured these soon gave way to coaxial cable and more recently, fiber optic cable has become the media whereby high density and long distance signals are propagated. The almost unlimited bandwidth and unique advantages of fiber optic cable compared to copper wire assures that this will be the preferred propagation media for the foreseeable future.

Low-loss glass fiber optic cable offers distinct advantages over other methods as a transmission media for the following reasons:

1. The fiber will carry much more information and deliver it with greater fidelity than either copper wire or coaxial cable.

2. The fiber is totally immune to virtually all kinds of interference, including lightning, and will not conduct electricity. It can therefore come in direct contact with high voltage electrical equipment or power lines. It will also not create ground loops of any kind between both ends of a transmission system.

3. As the basic fiber is made of glass, it will not corrode and is unaffected by most chemicals. It can be buried directly in most kinds of soil or exposed to most corrosive atmospheres in chemical plants without significant concern.

4. Since the only carrier in a fiber is light, there is no possibility of a spark from a broken fiber. Therefore, even in the most explosive of atmospheres, there is no fire hazard nor is there any danger of electrical shock to personnel repairing broken fibers.

5. Fiber optic cables are virtually unaffected by outdoor atmospheric conditions and so can be lashed directly to telephone poles or existing electrical cables without concern for extraneous signal pickup.

6. A fiber optic cable, even one that contains many fibers, is usually much smaller and lighter in weight than a wire or coaxial cable with similar information carrying capacity. It is easier to handle and install, and uses

less duct space. In fact it can frequently be installed without the need for protective ducts.

7. Fiber optic cable is also very difficult to tap but very easy to monitor for potential eavesdropping making it ideal for secure communications systems. In addition, there is absolutely no electrical radiation from a fiber.

The Basic Fiber Optic Transmission System

As shown in figure 1, a basic fiber optic transmission system consists of an optical transmitter, the fiber optic cable and an optical receiver.

The **optical transmitter** converts an electrical analog or digital signal into a corresponding optical signal. The source of the optical signal can be either a light emitting diode, or a solid state laser diode. The most popular wavelengths of operation for optical transmitters are 850, 1310, or 1550 nanometers. Most ***Luxlink® and Litelink****®* transmission equipment manufactured by ***Liteway, Inc***. operates at wavelengths of 850 or 1310nm.

The fiber optic cable consists of one or more glass fibers, which act as waveguides for the optical signal. Fiber optic cable is similar to electrical cable in its construction, but provides special protection for the optical fiber within. For systems requiring transmission over distances of many kilometers, or where two or more fiber optic cables must be joined together, an optical splice is commonly used.

The optical receiver converts the optical signal back into a replica of the original electrical signal. The detector of the optical signal (in the receiver) is either a PIN-type photodiode or avalanche-type photodiode. Most fiber optic receiving equipment uses PIN-type photodiodes.

We will now examine each of the elements of the basic system in some detail to gain a better understanding of what is occurring.

Optical Transmitters

The basic optical transmitter converts electrical input signals into modulated light for transmission over an optical fiber. Depending on the nature of this signal, the resulting modulated light may be turned on and off or may be linearly varied in intensity between two predetermined levels. Figure 2 shows a graphic representation of these two basic schemes.

The most common devices used as the light source in optical transmitters are the light emitting diode (LED) and the laser diode (LD). In a fiber optic system, these devices are mounted in a package that enables an optical fiber to be placed in very close proximity to the light emitting region in order to couple as much light as possible into the fiber. In some cases, a tiny spherical lens is mounted directly over the emitter to collect and focus "every last drop" of light onto the fiber and in other cases, a fiber is "pigtailed" directly onto the actual surface of the emitter.

In either event it is obvious that the main goal is to couple as much light into the tiny optical fiber as possible. LEDs have relatively large emitting areas and as a result are not as good light sources as LDs. They are widely used for short to moderate transmission distances however because they are much more economical, quite linear in terms of light output versus electrical current input and stable in terms of light output versus ambient operating temperature. LDs, on the other hand, have very small light emitting surfaces and can couple many times more power to the fiber than LEDs. LDs are also linear in terms of light output versus electrical current input, but unlike LEDs they are not stable over wide operating temperature ranges and require more elaborate circuitry to achieve acceptable stability. In addition, their added cost makes them primarily useful for applications that require the transmission of signals over long distances.

LEDs and LDs operate in the infrared portion of the electromagnetic spectrum so that their light output is usually invisible to the human eye. Their operating wavelengths are chosen to be compatible with the lowest transmission loss wavelengths of glass fibers and highest sensitivity ranges of photodiodes. The most common wavelengths in use today are 850 nanometers, 1310 nanometers and 1550 nanometers. Both LEDs and LDs are available in all three wavelengths.

LEDs and LDs, as previously stated, are modulated in one of two ways; on and off, or linearly. Figure 3 shows simplified circuitry to achieve either method with an LED or LD. As can be seen from Figure 3A, a transistor is used to switch the LED or LD on and off in step with an input digital signal. This signal can be converted from almost any digital format (by the appropriate circuitry) into the correct base drive for the transistor. Overall speed is then determined by the circuitry and the inherent speed of the LED or LD. Used in this manner, speeds of several hundred megahertz are readily achieved for LEDs and thousands of megahertz for LDs. Temperature stabilization circuitry for the LD has been omitted from this example for simplicity. LEDs, on the other hand do not normally require any temperature stabilization.

Linear modulation of an LED or LD is accomplished by the operational amplifier circuit of figure 3B. The inverting input is used to supply the modulating drive to the LED or LD while the non-inverting input supplies a DC bias reference. Once again temperature stabilization circuitry for the LD has been omitted from this example for simplicity.

Digital on/off modulation of an LED or LD can take a number of forms. The simplest, as we have already seen, is light-on for a logic "1", and light-off for a logic "0". Two other common forms are pulse width modulation and pulse rate modulation. In the former, a constant stream of pulses is produced with one width signifying a logic "1" and another width, a logic "0". In the latter, the pulses are all of the same width but the pulse rate changes to differentiate between logic "1" and logic "0".

Analog modulation can also take a number of forms. The simplest is intensity modulation where the brightness of an LED is varied in direct step with the variations of the transmitted signal. In other methods, an RF carrier is first frequency modulated with another signal or, in some cases, several RF carriers are separately modulated with separate signals, then all are combined and transmitted as one complex waveform. Figure 4 shows all of the above modulation methods as a function of light output.

The equivalent operating frequency of light, which is, after all, electromagnetic radiation, is extremely high – on the order of 1,000,000 GHz. The output bandwidth of the light produced by LEDs and Laser diodes is quite wide. Unfortunately today's technology does not allow this bandwidth to be selectively used in the way that conventional radio frequency transmissions are utilized. Rather, the entire optical bandwidth is turned on and off in the same way that early "spark transmitters" (in the infancy of radio), turned wide portions of the RF spectrum on and off. In time, however, researchers will overcome this obstacle and "coherent transmissions", as they are called, will become the direction in which the fiber optic field progresses.

The Optical Fiber: Launching the Light

Once the transmitter has converted the electrical input signal into whatever form of modulated light is desired, the light must be "launched" into the optical fiber. To understand the various factors that must be considered in this operation, as well as what happens to the light as it travels through the fiber, there are certain parameters that should be understood about fibers and light.

As previously mentioned, there are two methods whereby light is coupled into a fiber. One is by pigtailing. The other is by placing the fiber's tip in very close proximity to an LED or LD. When the proximity type of coupling is employed, the amount of light that will enter the fiber is a function of one of four factors: the intensity of the LED or LD, the area of the light emitting surface, the acceptance angle of the fiber, and the losses due to reflections and scattering. Following is a short discussion on each:

Intensity

The intensity of an LED or LD is a function of its design and is usually specified in terms of total power output at a particular drive current. Sometimes, this figure is given as actual power that is delivered into a particular type of fiber. All other factors being equal, more power provided by an LED or LD translates to more power "launched" into the fiber.

Area

The amount of light "launched" into a fiber is a function of the area of the light emitting surface compared to the area of the light accepting core of the fiber. The smaller this ratio is, the more light that is "launched" into the fiber.

Acceptance Angle

The acceptance angle of a fiber is expressed in terms of numeric aperture. The numerical aperture (NA) is defined as the sine of one half of the acceptance angle of the fiber. Typical NA values are 0.1 to 0.4 which correspond to acceptance angles of 11 degrees to 46 degrees. Optical fibers will only transmit light that enters at an angle that is equal to or less than the acceptance angle for the particular fiber.

Other Losses

Other than opaque obstructions on the surface of a fiber, there is always a loss due to reflection from the entrance and exit surface of any fiber. This loss is called the Fresnel Loss and is equal to about 4% for each transition between air and glass. There are special coupling gels that can be applied between glass surfaces to reduce this loss when necessary.

Other than the losses exhibited when coupling LEDs or LDs into a fiber, there are losses that occur as the light travels through the actual fiber.

The core of an optical fiber is made of ultra-pure low-loss glass. Considering that light has to pass through thousands of feet or more of fiber core, the purity of the glass must be extremely high. To appreciate the purity of this glass, consider the glass in common windowpanes. We think of windowpanes as "clear," allowing light to pass freely through, but this is because they are only 1/16 to ¼ inch thick. In contrast to this clear appearance, the edges of a broken windowpane look green and almost opaque. In this case, the light is passing edgewise into the glass, through several inches. Just imagine how little light would be able to pass through a thousand feet of window glass!

Most general purpose optical fiber exhibits losses of 4 to 6 dB per km (a 60% to 75% loss per km) at a wavelength of 850nm. When the wavelength is changed to 1310nm, the loss drops to about 3 to 4 dB (50% to 60%) per km. At 1550nm, it is even lower. Premium fibers are available with loss figures of 3 dB (50%) per km at 850nm and 1 dB (20%) per km at 1300nm. Losses of 0.5 dB (10%) per km at 1550 nm are not uncommon. These losses are primarily the result of random scattering of light and absorption by actual impurities within the glass.

Another source of loss within the fiber is due to excessive bending, which causes some of the light to leave the core area of the fiber. The smaller the bend radius, the greater the loss. Because of this, bends along a fiber optic cable should have a turning radius of at least an inch.

Bandwidth

All of the above attenuation factors result in simple attenuation that is independent of bandwidth. In other words, a 3 dB loss means that 50% of the light will be lost whether it is being modulated at 10 Hz or 100 MHz. There is an actual bandwidth limitation of optical fiber however, and this is measured in MHz per km. The easiest way to understand why this loss occurs is to refer to Figure 6. A ray of light that enters a fiber at a small angle (M1) has a shorter path through the fiber than light entering at an angle close to the maximum acceptance angle (M2). As a result, different "rays" (or modes) of light reach the end of the fiber at different times, even though the original source is the same LED or LD. This produces a "smearing" effect or uncertainty as to where the start and end of a pulse occurs at the output end of the fiber – which in turn limits the maximum frequency that can be transmitted. In short, the less modes, the higher the bandwidth of the fiber. The way that the number of modes is reduced is by making the core of the fiber as small as possible. Single-mode fiber, with a core measuring only 8 to 10 microns in diameter, has a much higher bandwidth because it allows only a few modes of light to propagate along its core. Fibers with a wider core diameter, such as 50 and 62.5 microns, allow many more modes to propagate and are therefore referred to as "multimode" fibers.

Typical bandwidths for common fibers range from a few MHz per km for very large core fibers, to hundreds of MHz per km for standard multimode fiber, to thousands of MHz per km for single-mode fibers. As the length of fiber increases, its bandwidth will decrease proportionally. For example, a fiber cable that can support 500 MHz bandwidth at a distance of one kilometer will only be able to support 250 MHz at 2 kilometers and 100 MHz at 5 kilometers. Because single-mode fiber has such a high inherent bandwidth, the "bandwidth reduction as a function of length" factor is not a real issue of concern when using this type of fiber. However, it is a consideration when using multimode fiber, as its maximum bandwidth often falls within the range of the signals most often used in point-to-point transmission systems.

Fiber Optic Cable Construction

Fiber optic cable comes in all sizes and shapes. Like coaxial cable, its actual construction is a function of its intended application. It also has a similar "feel" and appearance. Figure 7 is a sketch of a typical fiber optic cable.

The basic optical fiber is provided with a buffer coating which is mainly used for protection during the manufacturing process. This fiber is then enclosed in a central PVC loose tube which allows the fiber to flex and bend, particularly when going around corners or when being pulled through conduits. Around the loose tube is a braided Kevlar yarn strength member which absorbs most of the strain put on the fiber during installation. Finally, a PVC outer jacket seals the cable and prevents moisture from entering.

Basic optical fiber is ideal for most inter-building applications where extreme ruggedness is not required. In addition to the "basic" variety, it is also available for just about any application, including direct buried, armored, rodent resistant cable with steel outer jacket, and UL approved plenum grade cable. Color-coded, multi-fiber cable is also available.

The Optical Fiber: Other Types of Fibers

Two additional types of fiber – very large core diameter silica fiber and fiber made completely of plastic – are normally not employed for data transmission.

Silica fiber it typically used in applications involving high power lasers and sensors, such as medical laser-surgery.

All-plastic fiber is useful for very short data links within equipment because it may be used with relatively inexpensive LEDs. An isolation system for use as part of a high voltage power supply would be a typical example of an application for plastic fiber.

Optical Connectors

Optical connectors are the means by which fiber optic cable is usually connected to peripheral equipment and to other fibers. These connectors are similar to their electrical counterparts in function and outward appearance but are actually high precision devices. In operation, the connector centers the small fiber so that its light gathering core lies directly over and in line with the light source (or other fiber) to tolerances of a few ten thousandths of an inch. Since the core size of common 62.5 micron multimode fiber is only 0.0025 inches and single-mode fiber is 9 microns (0.00035 inches) the need for such extreme tolerances is obvious.

There are many different types of optical connectors in use today. The SMA connector, which was first developed before the invention of single-mode fiber, was the most popular type of connector until recently. Figure 8 shows an exploded view of the parts of this connector.

The most popular type of multimode connector in use today is the ST connector. Initially developed by AT&T for telecommunications purposes, this connector uses a twist lock type of design and provides lower overall losses than the SMA. A typical mated pair of ST connectors will exhibit less than 1 dB (20%) of loss and does not require alignment sleeves or other similar devices. The inclusion of an "anti-rotation tab" assures that every time the connectors are mated, the fibers always return to the same rotational position assuring constant, uniform performance.

ST connectors are available for both multimode and single-mode fibers, the primary difference being the overall tolerances. Note that multimode ST connectors will only perform properly with multimode fibers. More expensive single-mode ST connectors will perform properly with both single-mode and multimode fibers. The installation procedure for the ST connector is very similar to that of the SMA and requires approximately the same amount of time. Figure 9 shows some of the major features of the typical ST connector.

Optical Splices

While optical connectors can be used to connect fiber optic cables together, there are other methods that result in much lower loss splices. Two of the most common and popular are the mechanical splice and the fusion splice. Both are capable of splice losses in the range of 0.15 dB (3%) to 0.1 dB (2%).
In a mechanical splice, the ends of two pieces of fiber are cleaned and stripped, then carefully butted together and aligned using a mechanical assembly. A gel is used at the point of contact to reduce light reflection and keep the splice loss at a minimum. The ends of the fiber are held together by friction or compression, and the splice assembly features a locking mechanism so that the fibers remained aligned.

A fusion splice, by contrast, involves actually melting (fusing) together the ends of two pieces of fiber. The result is a continuous fiber without a break. Fusion splices require special expensive splicing equipment but can be performed very quickly, so the cost becomes reasonable if done in quantity. As fusion splices are fragile, mechanical devices are usually employed to protect them.

Optical Receivers

The basic optical receiver converts the modulated light coming from the optical fiber back into a replica of the original signal applied to the transmitter.

The detector of this modulated light is usually a photodiode of either the PIN or the Avalanche type. This detector is mounted in a connector similar to the one used for the LED or LD. Photodiodes usually have a large sensitive detecting area that can be several hundred microns in diameter. This relaxes the need for special precautions in centering the fiber in the receiving connector and makes the "alignment" concern much less critical than it is in optical transmitters.

Since the amount of light that exits a fiber is quite small, optical receivers usually employ high gain internal amplifiers. Because of this, optical receivers can be easily overloaded. For this reason, it is important only to the size fiber specified for use with a given system. If, for example, a transmitter/receiver pair designed for use with single-mode fiber were used with multimode fiber, the large amount of light present at the output of the fiber (due to over-coupling at the light source) would overload the receiver and cause a severely distorted output signal. Similarly, if a transmitter/receiver pair designed for use with multimode fiber was used with single-mode fiber, not enough light would reach the receiver, resulting in either an excessively noisy output signal or no signal at all.
The only time any sort of receiver "mismatching" might be considered is when there is so much excessive loss in the fiber that the extra 5 to 15 dB of light coupled into a multimode fiber by a single-mode light source is the only chance to achieve proper operation. However, this is an extreme case and is not normally recommended.

As in the case of transmitters, optical receivers are available in both analog and digital versions. Both types usually employ an analog preamplifier stage, followed by either an analog or digital output stage (depending on the type of receiver). Figure 10 is a functional diagram of a simple analog optical receiver.

The first stage is an operational amplifier connected as a current-to-voltage converter. This stage takes the tiny current from the photodiode and converts it into a voltage, usually in the millivolt range. The next stage is a simple operational voltage amplifier. Here the signal is raised to the desired output level.

Figure 11 is a functional diagram of a simple digital optical receiver. As in the case of the analog receiver, the first stage is a current-to-voltage converter. The output of this stage, however, is fed to a voltage comparator, which produces a clean, fast rise-time digital output signal. The trigger level adjustment, when it is present, is used to "touch up" the point on the analog signal where the comparator switches. This allows the symmetry of the recovered digital signal to be trimmed as accurately as desired.

Additional stages are often added to both analog and digital receivers to provide drivers for coaxial cables, protocol converters or a host of other functions in efforts to reproduce the original signal as accurately as possible.

It is important to note that while fiber optic cable is immune to all forms of interference, the electronic receiver is not. Because of this, normal precautions, such as shielding and grounding, should be taken when using fiber optic electronic components.

Designing a Fiber Optic System

Designing a fiber optic transmission system (as you now should realize) requires that many factors be considered. As a result, the following step-by-step procedure is provided to assure that you do not fail to consider the major ones.

1. Determine the correct optical transmitter and receiver combination based upon the signal to be transmitted (analog, digital, audio, video, RS-232, RS-422, RS-485, etc.).

2. Determine the operating power available (AC, DC, etc.) and be sure it is compatible with the system chosen.

3. Determine the fiber type to be used and the operating optical wavelength according to the chart below

4. Determine the special modifications (if any) necessary (impedances, bandwidths, special connectors, etc.).

5. Calculate the total optical loss (in dB) in the system by adding the cable loss, splice loss, and connector loss. These parameters should be available from the manufacturer of the connectors and fiber optic cable.

6. Compare the total loss figure obtained in Step 4 with the allowable optical loss budget of the transmitter/receiver combination specified by the manufacturer. Be certain to add a safety margin factor of at least 3 dB to the entire system.

7. Check that the fiber bandwidth is adequate to pass the signal desired.

If, after performing the above calculations, it is discovered that the fiber bandwidth is inadequate for transmitting the required signal the necessary distance, it will be necessary either to select a different transmitter/receiver (wavelength) combination, or consider the use of a lower loss premium fiber.

Good Luck!

We hope this guide has helped you to better understand the basics of fiber optic technology and system design. The specification check sheet below and on the following pages can be used to help collect and organize the necessary information when actually designing a system.

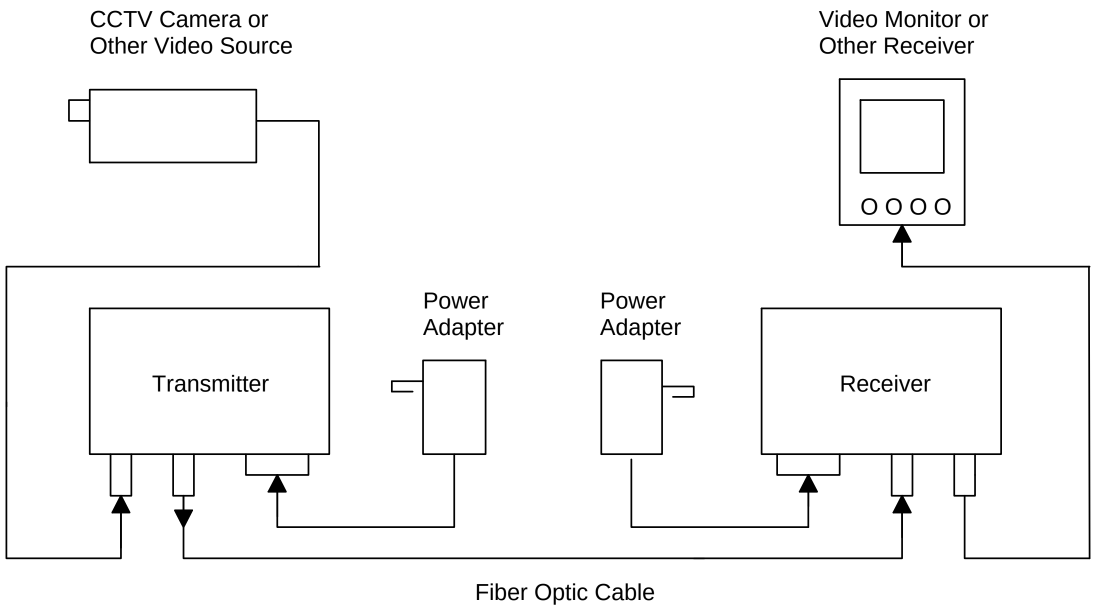


Figure 1, Basic Fiber Optic Transmission System

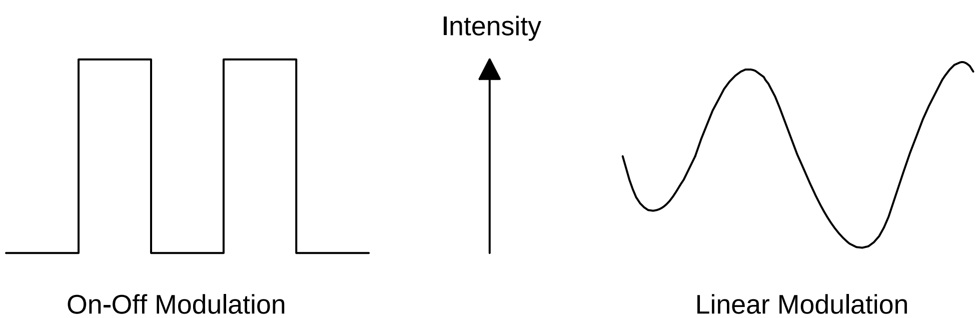


Figure 2. Basic Optical Modulation Methods

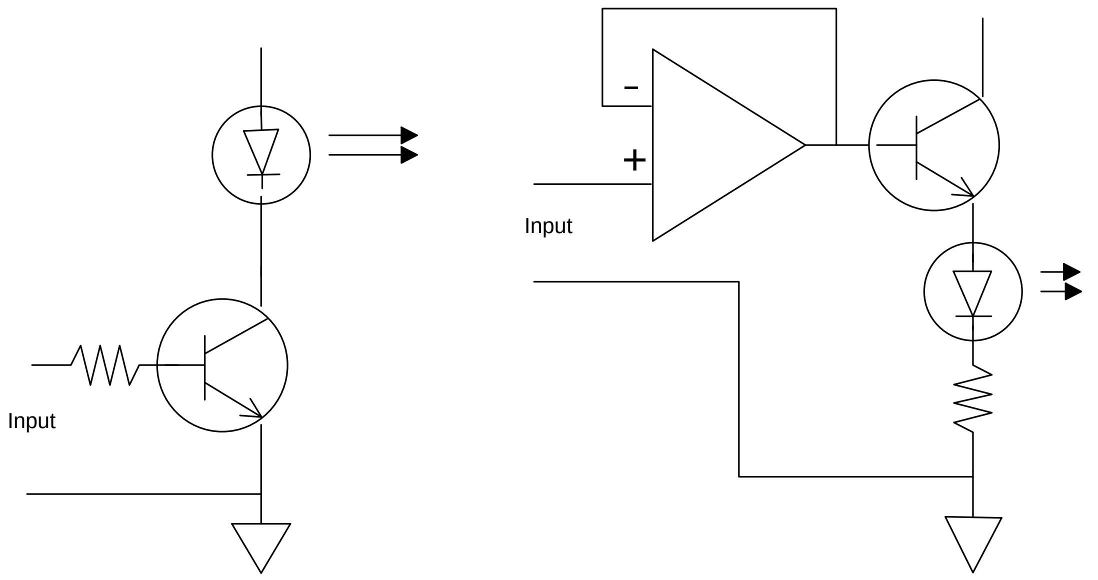


Figure 3. Methods of Modulating LEDs or Laser Diodes

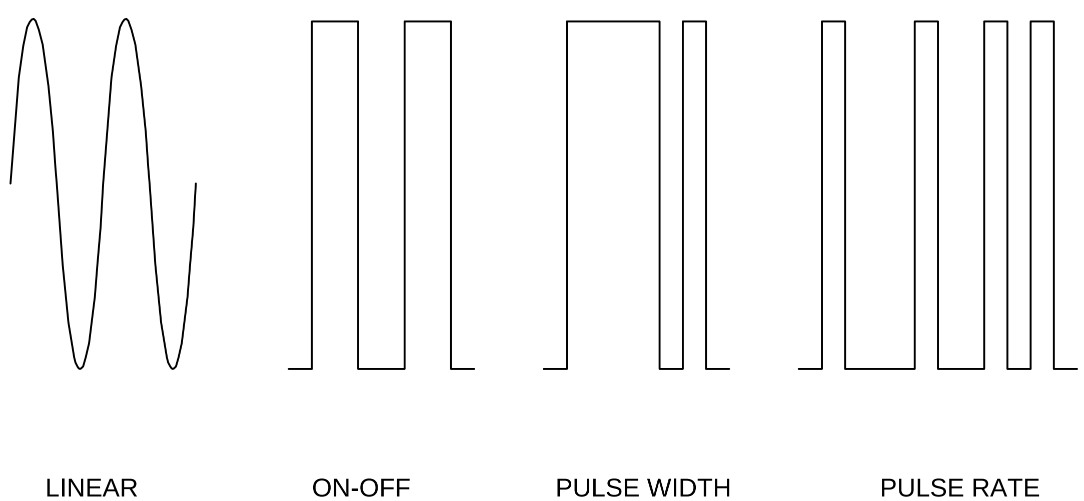


Figure 4, Various Methods to Optically Transmit Analog Signals

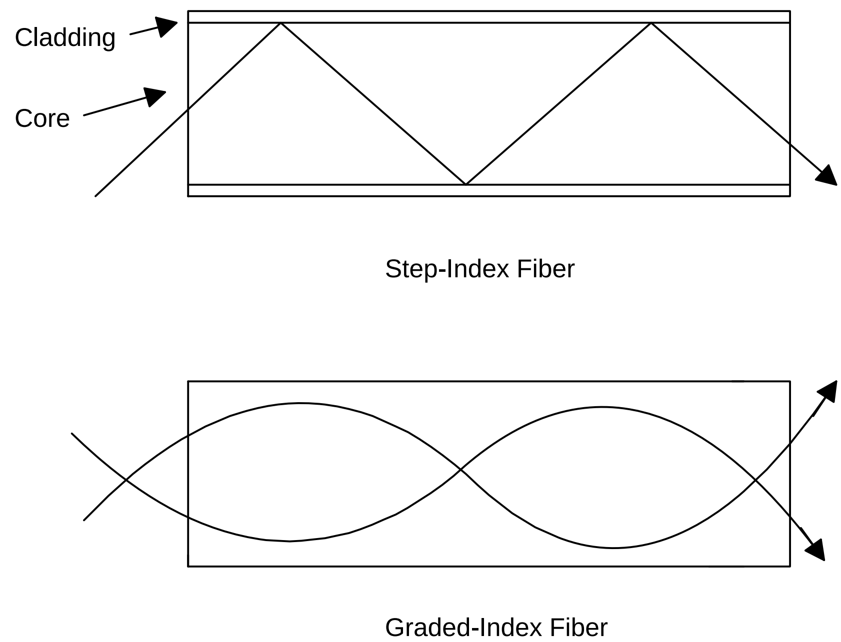


Figure 5, Light Propogation Through Step And Graded-Index Fiber

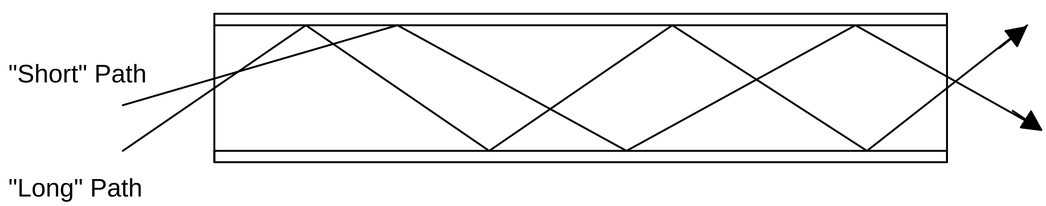


Figure 6, Different Light Paths Determine the Bandwidth of a Fiber

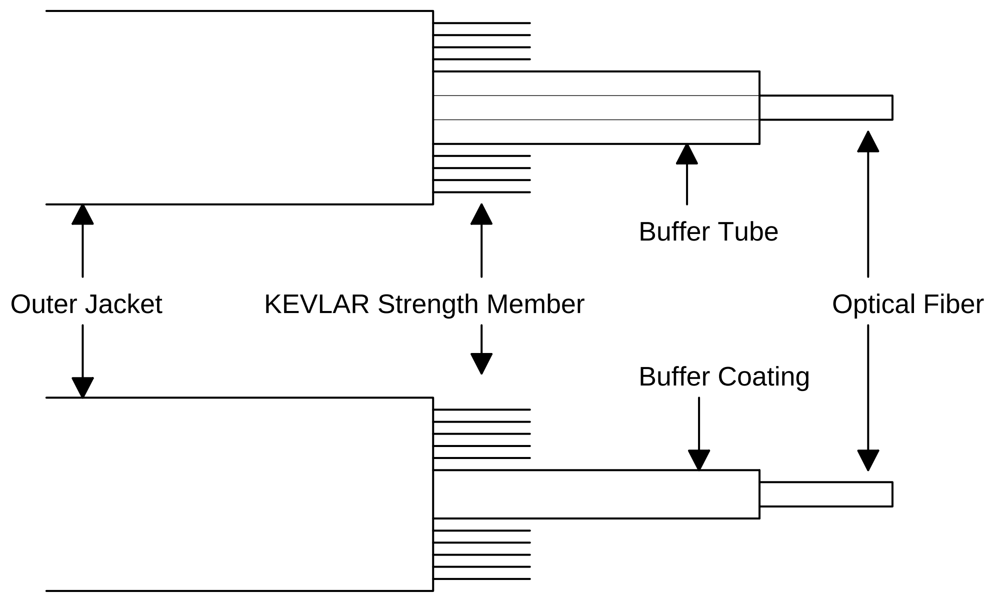
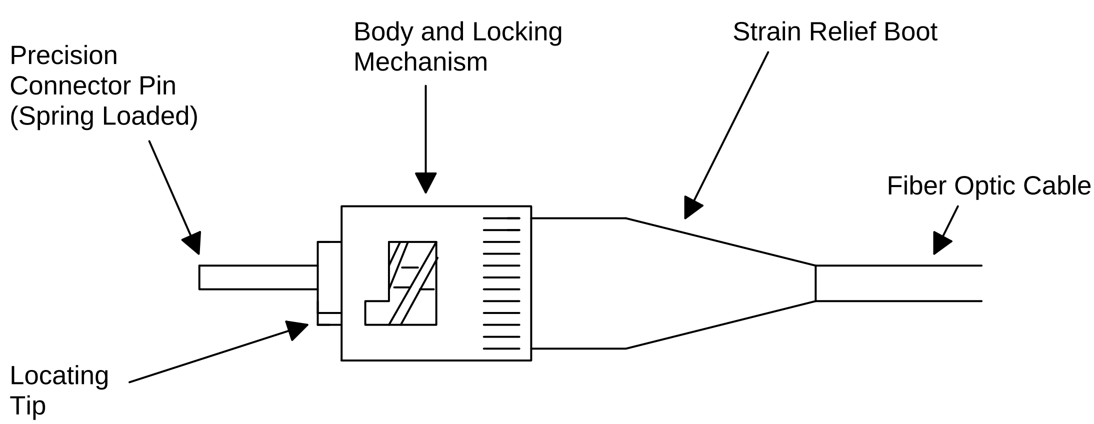


Figure 7, Basic Fiber Optic Cable Construction



Commonly used for multi-mode fiber

Figure 8, The ST-style Optical Connector

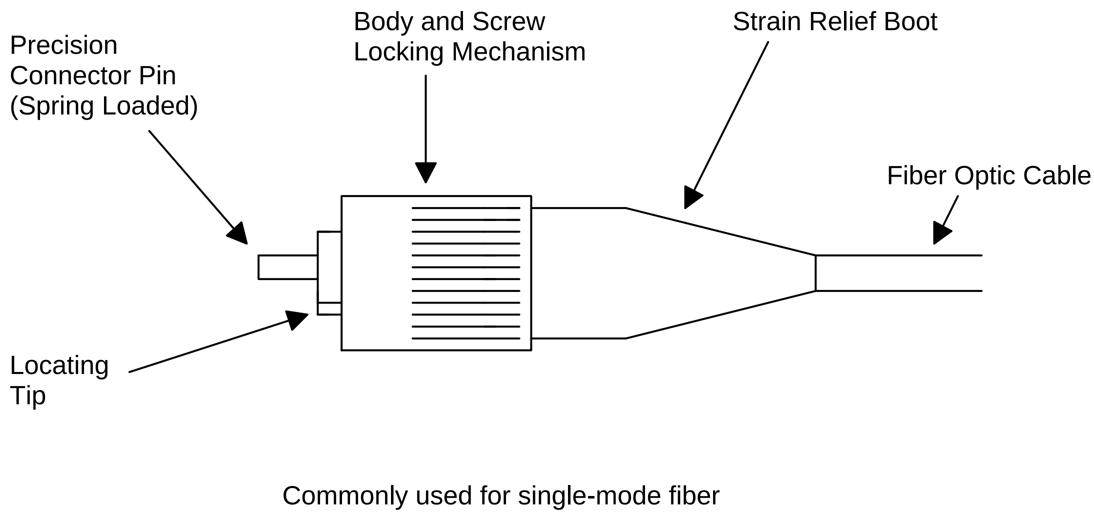


Figure 9, The FCPC-style Optical Connector

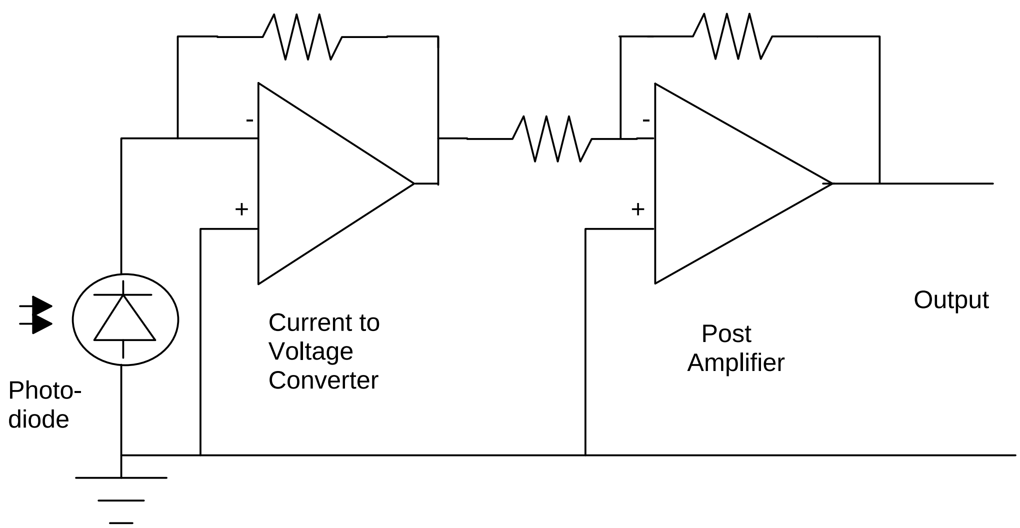


Figure 10, Block Diagram of Typical Analog Fiber Optic Receiver

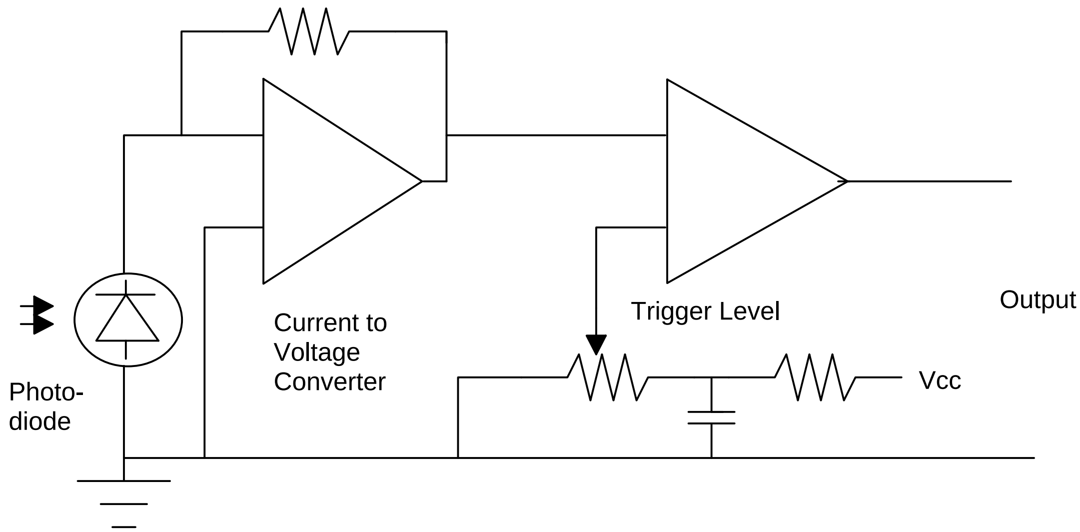


Figure 11, Block Diagram of Typical Digital Fiber Optic Receiver