1

INTRODUCTION TO FIBER OPTICS

Learning Outcomes

When you finish this module, you will be able to do the following:

1. *Describe the term fiber optics and fiber-optic communications.*
2. *List the parts of a fiber-optic data link.*
3. *Understand the function of each portion of a fiber-optic data link.*
4. *Outline the history of fiber optics technology.*
5. *Describe the trade-offs in fiber properties and component selection in the design of fiber-optic systems.*
6. *List the advantages of fiber-optic systems compared to electrical communications systems.*

Fiber optics is the branch of photonics that deals with the transmission of light through fibers. As such, fiber optics covers wide range of applications, from basic optical fiber manufacturing and fiber network installation and testing to design of complex fiber communication systems. **Fiber-optic communication** is based on sending information from a source to a recipient by means of light pulses over the fiber-optic data links. It is a growing field that enters almost every aspect of our life and is considered "the technology of the 21st century". Some of the applications include residential and industrial Ethernet, SCADA systems, cellular networks, cable access TV (CATV), security systems, medical applications, and so on.

Optical Spectrum

The main difference between conventional copper-based communication systems and fiber-optic systems is in the way that data is sent over the communication channel. Fiber-optic communication systems transmit signals in optical spectrum via glass fibers. Optical spectrum includes infrared, visible, and ultraviolet frequencies. Conventional electronic systems are operating at frequencies lower than the optical spectrum. Radio frequency and microwave communication (including satellite links) rely on radio waves and microwaves traveling through open space or air. Figure 1.1 shows the entire electromagnetic spectrum, while Figure 1.2 draws comparisons between various types of electromagnetic waves from different aspects—such as their ability to penetrate Earth's atmosphere (important for satellite links), correlation between electromagnetic wave radiation and temperature (black body radiation), etc. The frequency and the wavelength of an electromagnetic wave are related to each other through the following equation:

$$v = \lambda \cdot f \tag{1.1}$$

where v represents the speed of the electromagnetic wave in given medium.

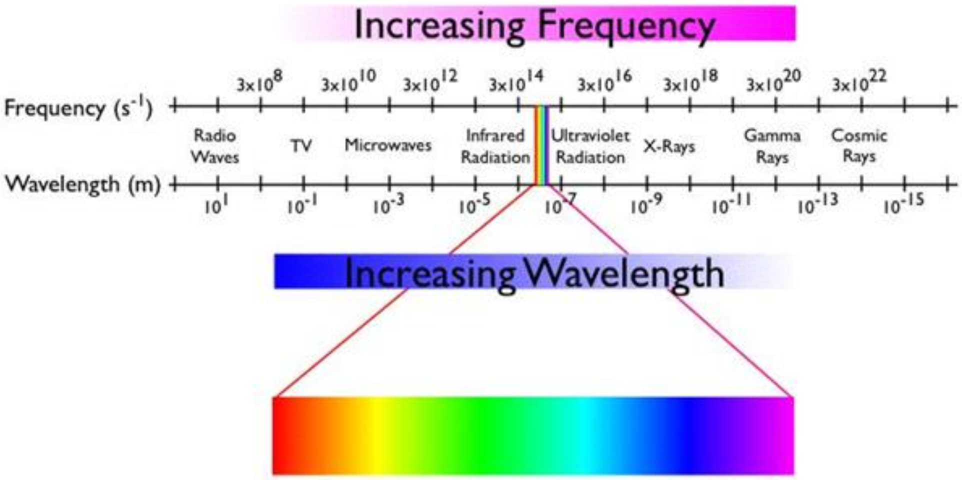

FIGURE 1.1 Distribution of frequencies and wavelengths in the electromagnetic spectrum.

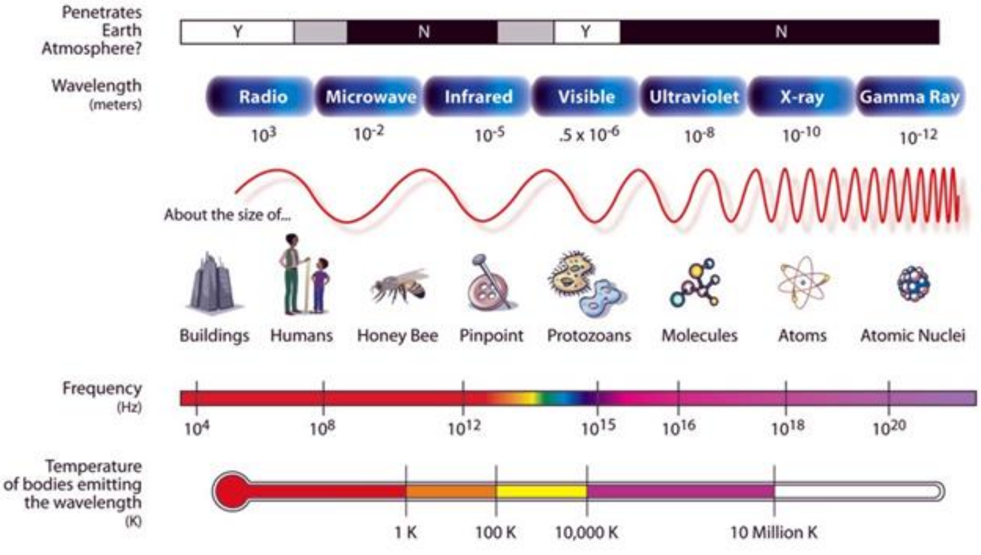

FIGURE 1.2 Important properties of various types of electromagnetic waves [1].

EXAMPLE 1. A light source launches light into an optical fiber. If the wavelength of light is 850 nm and if the light propagates through the fiber at a speed 2×10^8[m/s], calculate the frequency of the light in THz. Repeat the calculation for the other two typical wavelengths of propagation used in fiber-optic communications, 1310 [nm] and 1550 [nm].

Solution. Use formula (1.1) to calculate:

$$f = \frac{v}{\lambda} = \frac{2\cdot 10^{8}\left[\frac{\mathrm{m}}{\mathrm{s}}\right]}{850\cdot 10^{-9}[\mathrm{m}]} = 0.002353\cdot 10^{17}[\mathrm{Hz}] = 235.3\cdot 10^{12}[\mathrm{Hz}] = 235.3\ [\mathrm{THz}]$$

Similarly, for λ=1310 [nm] we get f=152.7 [THz] and for λ=1550 [nm] we get f=129 [THz]. Remember the three wavelengths given in this problem; they are extremely important in fiber-optic communications.

Review Questions

1. What is fiber optics?

2. What portions of the electromagnetic spectrum are included in the optical spectrum?

3. How are the wavelength and frequency of an electromagnetic wave related to each other?

Fiber-Optic Data Links

The main objective of a fiber-optic data link is to transmit an information-carrying signal through an optical fiber to a distant receiver. This objective is achieved through the three basic functions:

- Convert an electrical input signal to an optical signal at the transmit site
- Launch and send the optical signal over an optical fiber-based communication medium
- Convert the optical signal back to an electrical signal at the receive site

A fiber-optic data link consists of three parts—optical transmitter, optical fiber, and optical receiver. In addition to these three basic functional parts, an optical data link may also contain multiple connectors, terminations, and splices necessary to achieve corresponding interconnects.

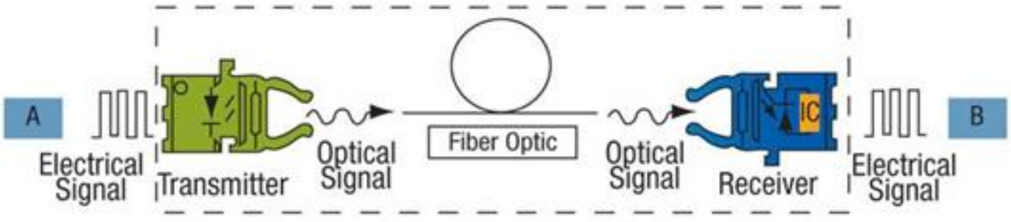

FIGURE 1.3 Important properties of various types of electromagnetic waves [2].

Figure 1.3 is an illustration of a fiber-optic data link connection. A fiber-optic data link needs a transmitter that can effectively convert an electrical input signal to an optical signal and launch the data-containing light down the optical fiber. There are three different types of optical transmitters [3]: light-emitting diodes (LEDs), Vertical Cavity Surface Emitting Lasers (VCSELS), and laser diodes.

A fiber-optic data link also needs a receiver whose role is to transform the optical signal back into its original form. This means that the electrical signal provided as data output should exactly match the electrical signal provided as data input. A variety of detector types are available. The most common is the photodiode, which produces current in response to incident light. Two types of photodiodes used extensively in fiber optics are the PIN photodiode and the avalanche photodiode (APD).

The transmitter and the receiver in a fiber-optic data link are connected through an optical fiber made out of a very thin glass rod surrounded by a plastic protective coating. As any other communication medium, optical fiber is also characterized by the loss per unit length (given in dB/km). This loss on the optical fiber plays a crucial role in all loss budget considerations associated with the fiber-optic data link. It is a common practice in telecommunications industry to perform power budget calculations on a logarithmic scale (in decibels). This approach allows for simple summation of various contributions to the budget. Relative power levels such as power gain and attenuation are expressed in dB according to the following formula

Power Gain or Attenuation (dB) = 10×log(Gain or Attenuation) =

= 10×log(Output Power/Input Power) (1.2)

Absolute power levels such as input power or output power are expressed in dBm according to the relationship:

Power (dBm) = 10×log(Power in milliWatts) (1.3)

Remember, absolute power levels are express in watts (W) while relative power levels are unitless.

EXAMPLE 2. A light source launches 0.5 W of input power into the single-mode fiber-optic cable. The fiber-optic cable has a loss of 0.5 dB/km and is 10 km long. Please (a) convert input power to dBm and explain (b) how much power in dBm exists the fiber on the receiving site.

Solution:

(a) First convert the power into mW: 0.5 W = 500 mW. Then use formula (1.3) to calculate:

$$\text{Power (dBm)}=10\times\log^{f()}(\text{Power in mW})=10\times\log^{f()}(500)=26.99\ [\text{dBm}]$$

The total loss of the cable is 0.5 [dB/km]×10 [km] = 5 [dB]

(b) The output power (dBm) = Input power - Cable Loss = 26.99 [dBm] - 5 [dB] = 21.99 [dBm]

Finally, a fiber-optic data link also includes various passive components and connections used to complete the construction of the link. These include optical splices, connectors (terminations), and couplers. Passive components used to make fiber connections affect the performance of the data link and must also be taken into consideration during the loss budget calculations. These components can also prevent the link from operating. Figure 1.4 shows various types of common connectors used on fiber-optic communication links.

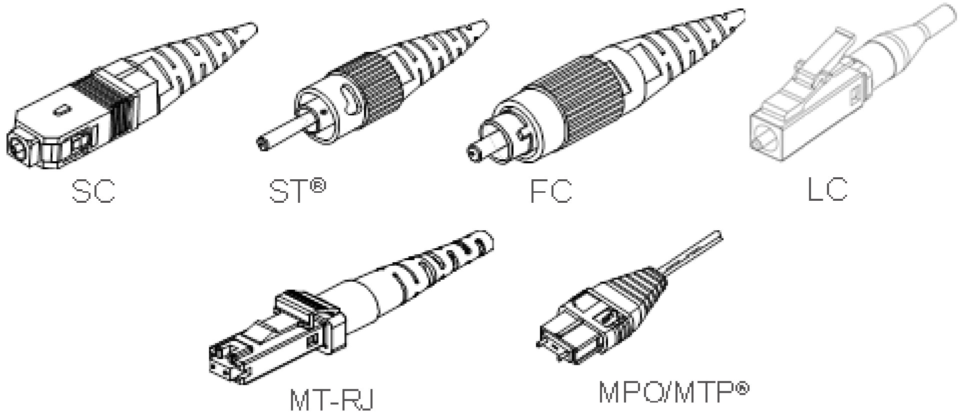

FIGURE 1.4 Various types of fiber-optic connectors.

Proof of link performance is an integral part of the design, fabrication, and installation of any fiber-optic system. Various measurement techniques are used to test individual parts of a data link. Each data link part is tested to be sure the link is operating properly. As the light signal travels through the fiber, it loses its power due to various effects such as absorption, scattering, etc. At some point, the attenuated light signal may become so weak that it cannot be successfully received and identified at the receiver. Figure 1.5 shows a typical plot that can be obtained for a fiber-optic data link. Slope of the curve corresponds to the loss per unit length of the cable while multiple and sudden drops (discontinuities) on the power loss curve represent connector and splice losses.

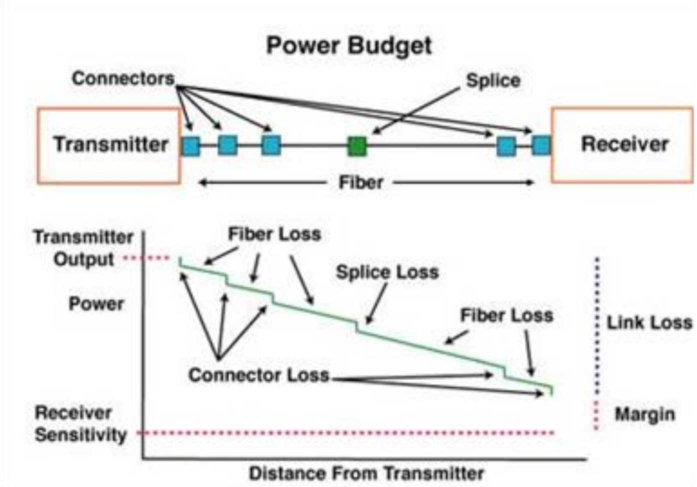

FIGURE 1.5 Power budget considerations on a fiber-optic data link.

In addition to the signal attenuation explained above, there are two other important factors that affect the performance of the fiber-optic link bandwidth and dispersion [4]. The optical fiber is characterized by certain range of frequencies that can be passed through this medium. This range of frequencies is known as the bandwidth of the fiber. This quantity is extremely important as it limits the information carrying capacity of the link. Dispersion represents the phenomenon of broadening of light pulses as they are traveling in the fiber. Dispersion also limits the information carrying capacity at very high transmission speeds over long distances.

Review Questions

1. Describe the basic functions of a fiber-optic data link.

2. List the four parts of a fiber-optic data link.

3. What types of transmitters are used in a fiber-optic network?

4. What types of receivers are used in a fiber-optic network?

5. Define units dB and dBm.

6. Define loss.

7. What type of loss is described by the slope of the power loss curve?

Brief History of Fiber Optics Technology

The earliest attempts to communicate via light undoubtedly go back thousands of years [3]. Early long distance communication techniques, such as “smoke signals” developed by native North Americans and the Chinese were, in fact, optical communication links. A larger scale version of this optical communication technique was the “optical telegraph” developed by Claude Chappe and deployed in France in the late 18th century. However, the development of fiber-optic communication awaited the discovery of TIR (Total Internal Reflection) and a host of additional electronic and optical innovations.

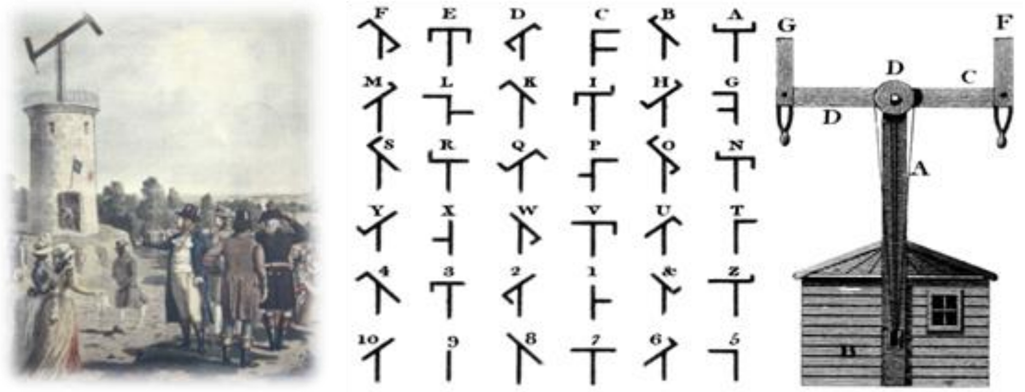

FIGURE 1.6 Optical telegraph developed by C. Chappe [5].

In 1854, John Tyndall, using a jet of water that flowed from one container to another and a beam of light, demonstrated that light used internal reflection to follow a specific path. As water poured out through the spout of the first container, Tyndall directed a beam of sunlight at the path of the water. The light, as seen by the audience, followed a zigzag path inside the curved path of the water. This simple experiment, illustrated in Figure 1.7, marked the first research into the guided transmission of light.

People have used light to transmit information for hundreds of years. However, it was not until the 1960s, with the invention of the laser that widespread interest in optical (light) systems for data communications began. The invention of the laser prompted researchers to study the potential of fiber optics for data communications, sensing, and other applications. Laser systems could send a much larger amount of data than telephone, microwave, and other electrical systems. The first experiment with the laser involved letting the laser beam transmit freely through the air. Researchers also conducted experiments letting the laser beam transmit through different types of waveguides. Glass fibers, gas-filled pipes, and tubes with focusing lenses are examples of optical waveguides.

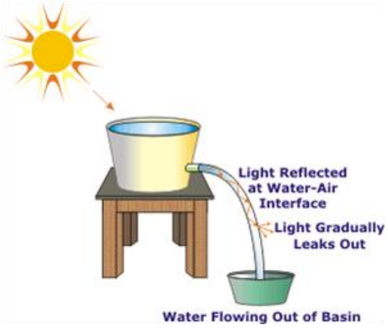

FIGURE 1.7 Tyndall's experiment with the light guidance.

Charles Kao and Charles Hockham, working at the Standard Telecommunication Laboratory in England in 1966, published a landmark paper proposing that optical fiber might be a suitable transmission medium if its attenuation could be kept under 20 decibels per kilometer (dB/km). At the time of this proposal, optical fibers exhibited losses of 1,000 dB/ km or more. Even at a loss of only 20 dB/km, 99% of the light would still be lost over only 3,300 feet. In other words, only 1/100th of the optical power that was transmitted reached the receiver. But, even with this loss, the power was enough to drive the receiver. The problem was developing a process in glass manufacturing to achieve the 20 dB threshold. Intuitively, researchers postulated that the current, higher optical losses were the result of impurities in the glass and not the glass itself. An optical loss of 20 dB/km was within the capability of the electronics and optoelectronic components of the day.

Intrigued by Drs. Kao and Hockham's proposal, glass researchers began to work on the problem of purifying glass. In 1970, Drs. Robert Maurer, Donald Keck, and Peter Schultz of Corning Glass Works succeeded in developing a glass fiber that exhibited attenuation at less than 20 dB/km, the threshold for making fiber optics a viable technology. It was the purest glass ever made. In 1972, Corning made a high silica-core multimode optical fiber with 4 dB/km minimum loss. Currently, multimode fibers can have losses as low as 0.5 dB/km at wavelengths around 1300 nm. Single-mode fibers are available with losses lower than 0.25 dB/km at wavelengths around 1500 nm.

The early work on fiber-optic light sources and detectors was slow and often had to borrow technology developed for other reasons. For example, the first fiber-optic light sources were derived from visible indicator LED's. As demand grew, light sources were developed for fiber optics that offered higher switching speed, more appropriate wavelengths, and higher output power.

Fiber optics developed over the years in a series of generations that can be closely tied to wavelength. Figure 1.8 shows three curves. The top, dashed, curve corresponds to early 1980s fiber, the middle, dotted, curve corresponds to late 1980s fiber, and the bottom, solid, curve corresponds to modern optical fiber. The earliest fiber-optic systems were developed at an operating wavelength of about 850 nm. This wavelength corresponds to the so-called "first window" in a silica-based optical fiber. This window refers to a wavelength region that offers low optical loss. It sits between several large absorption peaks caused primarily by moisture in the fiber and Rayleigh scattering. The 850 nm region was initially attractive because the technology for light emitters at this wavelength had already been perfected in visible indicator and infrared (IR) LED's. Low-cost silicon detectors could also be used at the 850 nm wavelength. As the technology progressed, the first window became less attractive because of its relatively high 3 dB/km loss limit.

Most companies jumped to the "second window" at 1310 nm with lower attenuation of about 0.5 dB/km. In late 1977, Nippon Telegraph and Telephone (NTT) developed the "third window" at 1550 nm. It offered the theoretical minimum optical loss for silica-based fibers, about 0.2 dB/km. Today, 850 nm, 1310 nm, and 1550 nm systems are all manufactured and deployed along with very low-end, short distance, systems using visible wavelengths near 660 nm. Each wavelength has its advantage. Longer wavelengths offer higher performance, but always come with higher cost. The shortest link lengths can be handled with wavelengths of 660 nm or 850 nm. The longest link lengths require 1625 nm wavelength systems. This fourth window was developed in 2007.

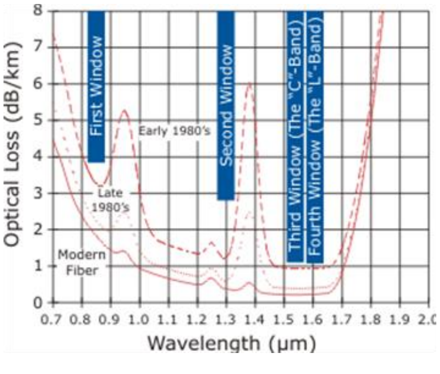

FIGURE 1.8 Four wavelength regions of optical fiber.

The U.S. military moved quickly to use fiber optics for improved communications and tactical systems. In 1973, the U.S. Navy installed a fiber-optic telephone link aboard the U.S.S. Little Rock. The Air Force followed suit by developing its Airborne Light Optical Fiber Technology (ALOFT) program in 1976. Encouraged by the success of these applications, military R&D programs were funded to develop stronger fibers, tactical cables, ruggedized, high-performance components, and numerous demonstration systems ranging from aircraft to undersea applications.

Commercial applications followed soon after. In 1977, both AT&T and GTE installed fiber-optic telephone systems in Chicago and Boston respectively. These successful applications led to the increase of fiber-optic telephone networks. By the early 1980s, single-mode fiber operating in the 1310 nm and later the 1550 nm wavelength windows became the standard fiber installed for these networks. Initially, computers, information networks, and data communications were slower to embrace fiber, but today they too find use for a transmission system that has lighter weight cable, resists lightning strikes, and carries more information faster and over longer distances.

In the commercial industry broadband services allow transmission of voice, video, and data. Services include television, data retrieval, video word processing, electronic mail, banking, and shopping. Fiber to the home or FTTH is being rolled out to neighborhoods throughout the country. The bundled packages now include television, phone and internet. Figure 1.9 shows an example of cable access TV over optical fiber.

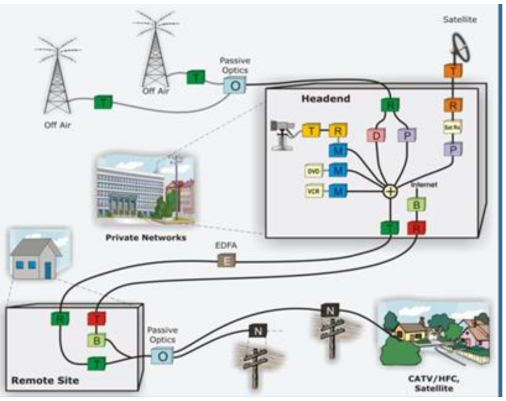

FIGURE 1.9 Cable Access TV (CATV) over fiber.

Fiber optics has changed the world we live in. The ability to use debit and credit cards everywhere occurs because of fiber-optic storage networks. Even in the age of wireless communications (cell phones) the only reason they work is because of the world-wide web or fiber-optic network. Figure 1.9 shows the current development state of the optical network worldwide.

The transmitter in your cell phone broadcasts your voice a short distance to the nearest cell tower. Once received at the tower, it is converted to pulses of light that are sent across the country (or world) through various switches and fibers to a cell tower closest to your intended recipient. That tower converts your voice back to a wireless transmission and broadcasts it out. It is received by the cell phone it was intended to go to. Basically no matter where you are 99.99 percent of the distance your voice travels is through a fiber-optic network.

Review Questions

1. What wavelengths are used in the typical fiber-optic system?

2. What are the two basic types of optical fibers?

3. When was the first commercial fiber-optic network installed?

Advantages and Disadvantages of Fiber Optics

Fiber-optic systems have several attractive features that are superior relative to other communication systems [4]:

1. Optical signal can be sent through fiber over long distances a few hundreds of kilometers) without the need for signal regeneration
2. Fiber-optical data links are not sensitive to external noise such as traffic, high power lines, etc.
3. Optical fibers do not conduct electricity and are therefore immune to any noise at high frequencies (RF). In addition, they provide for an increased information security, although optical signals can also be tapped for surveillance.
4. Fiber-optic systems provide much greater capacity than copper, coaxial and other conventional means of information transfer
5. Optical fibers are lighter and smaller than other transmission lines (copper, coaxial). Fiber-optic cables can literally contain hundreds of single fibers
6. Optical fibers are characterized by a high reliability, extreme flexibility, and have a lifetime of over 25 years
7. Operating temperatures for optical fibers vary but they are typically ranging from -40ºC to +80ºC.

EXPERIMENT 1. Making a Light Guide

GOAL: To construct a simple light guide using water and transparent plastic (vinyl) tubing, to demonstrate the effectiveness of a simple light guide in transferring the light energy from the source to the load, and to analyze the effects of bent guide on the loss of optical signal

EQUIPMENT: A red LED, phototransistor, 5" long vinyl tubing, 150 Ω resistor, and variable voltage power supply.

PROCEDURE:

1. Insert the red LED into one end of the vinyl tubing making sure a tight fit is achieved.

2. Insert the phototransistor into the other end of the tubing ensuring a tight fit.

3. Build a circuit on your breadboard as shown in Figure 1.10. Measure the current through the phototransistor. Record the measured current here: I (LED OFF, AIR) = ________________

4. Adjust the variable voltage supply to 5V and turn it on. At this point red light produced by LED should be visible. Measure the current through the phototransistor and record it here: I (LED ON, AIR) = ________________.

5. Do you observe a difference in the current in the two cases above? Why?

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6. Now remove the vinyl tubing from the breadboard, open the end where LED is placed, and fill the tubing in with the distilled water using eyedropper. Place red LED back into the tubing and ensure a tight fit to prevent any water leakage. Reconnect the circuit onto the breadboard as per Figure 1.10.

7. Measure the current through the phototransistor when LED is off. Record the measured current here: I (LED OFF, WATER) = _________________

8. Adjust the variable voltage supply to 5V and turn it on. At this point red light produced by LED should be visible. Measure the current through the phototransistor and record it here: I (LED ON, WATER) = ________________.

9. Compare the measured values of four currents from steps 3-10. What can you conclude?

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10. Are there any other liquids that may be used instead of water to keep more light inside the tubing?

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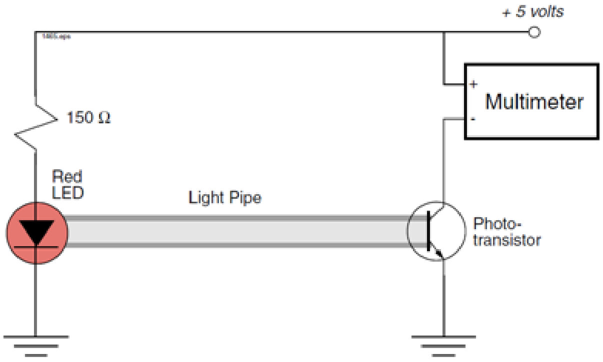

FIGURE 1.10 Test circuit for evaluating light guide.

Multiple Choice Questions for Practice

1. Fiber optics uses what medium to send information?

   A. Electrons
   B. Phonons
   C. Link 11
   D. Light

2. What are the four parts of a fiber-optic data link?

   A. Transmitter, optical fiber, connectors/splices, receiver
   B. Transmitter, optical fiber, data, optical connectors
   C. Optical fiber, data, optical connectors, receiver
   D. Optical fiber, optical connectors, optical splices, data

3. The fiber-optic transmitter has which of the following functions?

   A. Amplifies the optical signal
   B. Converts the electrical input signal to an optical signal
   C. Converts the input optical signal to an electrical signal
   D. Amplifies the output electrical signal

4. Fiber-optic systems use what three types of optical sources?

   A. LEDs, LASERs and VCSELs
   B. PIN diodes, LASERs and LEDs
   C. LEDs and LASERs and diodes
   D. LASERs, diodes and APDs

5. The fiber-optic receiver performs which of the following functions?

   A. Amplifies the optical signal
   B. Amplifies the electrical signal
   C. Converts the electrical signal back into an optical signal

D. Converts the optical signal back into an electrical signal

6. What are the two types of optical detectors?

A. LEDs and APDs
B. PIN photodiodes and APDs
C. APDs and laser diodes
D. Laser diodes and PIN photodiodes

7. Of the following advantages, which one does NOT apply to fiber optics?

A. Lower signal attenuation
B. Increased bandwidth
C. Improved environmental
D. Reduced size and weight

8. To describe the nature of light, which of the following ways can be used?

A. Electromagnetic wave only
B. Particles of energy only
C. Electromagnetic wave and particles of energy
D. Element

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