Module
1.8

Fiber Optic Telecommunication

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Fiber optics is a major building block in the telecommunication infrastructure. Its high bandwidth capabilities and low attenuation characteristics make it ideal for gigabit transmission and beyond. In this module, you will be introduced to the building blocks that make up a fiber optic communication system. You will learn about the different types of fiber and their applications, light sources and detectors, couplers, splitters, wavelength-division multiplexers, and state-of-the-art devices used in the latest high-bandwidth communication systems. Attention will also be given to system performance criteria such as power and rise-time budgets.

Prerequisites

Before you work through this module, you should have completed Module 1-7, *Basic Principles of Fiber Optics*. In addition, you should be able to manipulate and use algebraic formulas, deal with units, and use basic trigonometric functions such as sine, cosine, and tangent. A basic understanding of wavelength, frequency, and the velocity of light is also assumed.

Objectives

When you finish this module, you will be able to:

- Identify the basic components of a fiber optic communication system
- Discuss light propagation in an optical fiber
- Identify the various types of optical fibers
- Determine the dispersion characteristics for the various types of optical fibersDescribe the various connector types
- Calculate decibel and dBm power
- Calculate the power budget for a fiber optic system
- Calculate the bandwidth of a fiber optic system
- Describe the operation and applications of the various types of fiber optic couplers
- Describe the operation and applications of light-emitting diodes (LEDs)
- Describe the operation and applications of laser diodes (LDs)
- Describe the operation and applications of distributed-feedback (DFB) lasers
- Discuss the differences between LEDs and laser diodes with respect to performance characteristics
- Discuss the differences between the various types of optical detectors with respect to performance characteristics
- Describe how pulse code modulation (PCM) is used in analog-to-digital conversion
- Describe the operation North American Digital Hierarchy
- Describe the difference between internal and external modulation
- Discuss the principles of time-division multiplexing (TDM)
- Discuss the principles of wavelength-division multiplexing (WDM)
- Discuss the principles of dense wavelength-division multiplexing (DWDM)
- Discuss the significance of the International Telecom Union grid (ITU grid)
- Discuss the use of erbium-doped fiber amplifiers (EDFA) for signal regeneration
- Describe the operation and applications of fiber Bragg gratings
- Describe the operation and application of fiber optic circulators
- Describe the operation of a typical fiber optic communication system and the components that make it up

Scenario—Using Fiber Optics in Telecommunication

Michael recently completed an associate degree in laser electro-optics technology at Springfield Technical Community College in Springfield, Massachusetts. Upon graduation he accepted a position as an electro-optics technician at JDS Uniphase Corporation in Bloomfield, Connecticut. The company makes high-speed fiber optic modulators and components that are used in transmitters for the telecommunication and cable television industry.

The company's main focus is on the precision manufacturing of these devices, which requires not only an in-depth knowledge of how the devices work but also an appreciation for the complex manufacturing processes that are required to fabricate the devices to exacting specifications. While Mike was in school, he took courses in optics, fiber optics, and electronics. The background he received, especially in the area of fiber optic testing and measuring, has proven to be invaluable in his day-to-day activities. On the job, Mike routinely works with fusion splicers, optical power meters, and laser sources and detectors, as well as with optical spectrum analyzers and other sophisticated electronic test equipment.

Mike was fortunate in that during his senior year in college he was awarded a full scholarship and internship at JDS Uniphase. The company allowed Mike to complete his degree while working part time. According to Mike, "the experience of working in a high-tech environment while going to school really helps you see the practical applications of what you are learning—which is especially important in a field that is so rapidly changing as fiber optics."

Opening Activities

The field of fiber optics, especially with respect to telecommunication, is a rapidly changing world in which, seemingly, each day a new product or technology is introduced. A good way to start learning about this field is to research the companies that are making major strides in this industry. The Internet is a tremendous source for valuable information on this subject. Try searching the Internet for companies such as:

- Lucent Technologies
- JDS Uniphase
- Ciena
- Alcatel
- Tyco Submarine Systems
- Corning
- AT&T
- Nortel Networks
- Cisco
- Others

Another way to obtain information is to search the Internet for specific topics in fiber optic telecommunication, such as

- Dense wavelength-division multiplexing
- Fiber optic communication
- Dispersion-shifted fiber
- Erbium-doped fiber amplifier
- Fiber optic transmitters
- Fiber optic modulators
- Optical networks
- SONET
- Fiber optic cable

Introduction

Since its invention in the early 1970s, the use of and demand for optical fiber have grown tremendously. The uses of optical fiber today are quite numerous. With the explosion of information traffic due to the Internet, electronic commerce, computer networks, multimedia, voice, data, and video, the need for a transmission medium with the bandwidth capabilities for handling such vast amounts of information is paramount. Fiber optics, with its comparatively infinite bandwidth, has proven to be the solution.

Companies such as AT&T, MCI, and U.S. Sprint use optical fiber cable to carry plain old telephone service (POTS) across their nationwide networks. Local telephone service providers use fiber to carry this same service between central office switches at more local levels, and sometimes as far as the neighborhood or individual home. Optical fiber is also used extensively for transmission of data signals. Large corporations, banks, universities, Wall Street firms, and others own private networks. These firms need secure, reliable systems to transfer computer and monetary information between buildings, to the desktop terminal or computer, and around the world. The security inherent in optical fiber systems is a major benefit. Cable television or community antenna television (CATV) companies also find fiber useful for video services. The high information-carrying capacity, or bandwidth, of fiber makes it the perfect choice for transmitting signals to subscribers.

The *fibering* of America began in the early 1980s. At that time, systems operated at 90 Mb/s. At this data rate, a single optical fiber could handle approximately 1300 simultaneous voice channels. Today, systems commonly operate at 10 Gb/s and beyond. This translates to over 130,000 simultaneous voice channels. Over the past five years, new technologies such as dense wavelength-division multiplexing (DWDM) and erbium-doped fiber amplifiers (EDFA) have been used successfully to further increase data rates to beyond a *terabit per second* (>1000 Gb/s) over distances in excess of 100 km. This is equivalent to transmitting 13 million simultaneous phone calls through a single hair-size glass fiber. At this speed, one can transmit 100,000 books coast to coast in 1 second!

The growth of the fiber optics industry over the past five years has been explosive. Analysts expect that this industry will continue to grow at a tremendous rate well into the next decade and beyond. Anyone with a vested interest in telecommunication would be all the wiser to learn more about the tremendous advantages of fiber optic communication. With this in mind, we hope this module will provide the student with a rudimentary understanding of fiber optic communication systems, technology, and applications in today's information world.

I. BENEFITS OF FIBER OPTICS

Optical fiber systems have many advantages over metallic-based communication systems. These advantages include:

- **Long-distance signal transmission**
  The low attenuation and superior signal integrity found in optical systems allow much longer intervals of signal transmission than metallic-based systems. While single-line,

voice-grade copper systems longer than a couple of kilometers (1.2 miles) require in-line signal for satisfactory performance, it is not unusual for optical systems to go over 100 kilometers (km), or about 62 miles, with no active or passive processing.

- **Large bandwidth, light weight, and small diameter**
  Today's applications require an ever-increasing amount of bandwidth. Consequently, it is important to consider the space constraints of many end users. It is commonplace to install new cabling within existing duct systems or conduit. The relatively small diameter and light weight of optical cable make such installations easy and practical, saving valuable conduit space in these environments.
- **Nonconductivity**
  Another advantage of optical fibers is their dielectric nature. Since optical fiber has no metallic components, it can be installed in areas with electromagnetic interference (EMI), including radio frequency interference (RFI). Areas with high EMI include utility lines, power-carrying lines, and railroad tracks. All-dielectric cables are also ideal for areas of high lightning-strike incidence.
- **Security**
  Unlike metallic-based systems, the dielectric nature of optical fiber makes it impossible to remotely detect the signal being transmitted within the cable. The only way to do so is by accessing the optical fiber. Accessing the fiber requires intervention that is easily detectable by security surveillance. These circumstances make fiber extremely attractive to governmental bodies, banks, and others with major security concerns.
- **Designed for future applications needs**
  Fiber optics is affordable today, as electronics prices fall and optical cable pricing remains low. In many cases, fiber solutions are less costly than copper. As bandwidth demands increase rapidly with technological advances, fiber will continue to play a vital role in the long-term success of telecommunication.

II. BASIC FIBER OPTIC COMMUNICATION SYSTEM

Fiber optics is a medium for carrying information from one point to another in the form of light. Unlike the copper form of transmission, fiber optics is not electrical in nature. A basic fiber optic system consists of a transmitting device that converts an electrical signal into a light signal, an optical fiber cable that carries the light, and a receiver that accepts the light signal and converts it back into an electrical signal. The complexity of a fiber optic system can range from

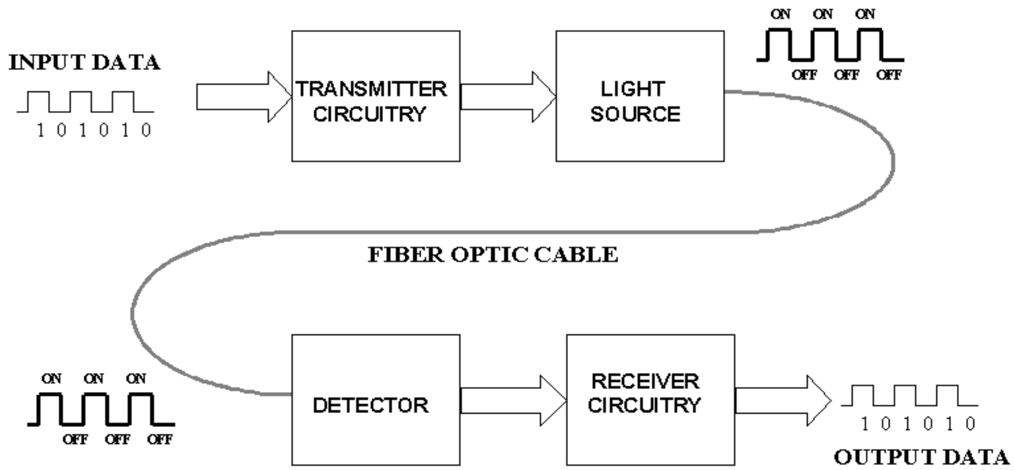


Figure 8-1 *Basic fiber optic communication system*

very simple (i.e., local area network) to extremely sophisticated and expensive (i.e., long-distance telephone or cable television trunking). For example, the system shown in Figure 8-1 could be built very inexpensively using a visible LED, plastic fiber, a silicon photodetector, and some simple electronic circuitry. The overall cost could be less than $20. On the other hand, a typical system used for long-distance, high-bandwidth telecommunication that employs wavelength-division multiplexing, erbium-doped fiber amplifiers, external modulation using DFB lasers with temperature compensation, fiber Bragg gratings, and high-speed infrared photodetectors could cost tens or even hundreds of thousands of dollars. The basic question is "how much information is to be sent and how far does it have to go?" With this in mind we will examine the various components that make up a fiber optic communication system and the considerations that must be taken into account in the design of such systems.

III. TRANSMISSION WINDOWS

Optical fiber transmission uses wavelengths that are in the near-infrared portion of the spectrum, just above the visible, and thus undetectable to the unaided eye. Typical optical transmission wavelengths are 850 nm, 1310 nm, and 1550 nm. Both lasers and LEDs are used to transmit light through optical fiber. Lasers are usually used for 1310- or 1550-nm single-mode applications. LEDs are used for 850- or 1300-nm multimode applications.

There are ranges of wavelengths at which the fiber operates best. Each range is known as an operating window. Each window is centered on the typical operational wavelength, as shown in Table 8.1.

Table 8.1: Fiber Optic Transmission Windows

Window	Operating Wavelength
800 – 900 nm	850 nm
1250 – 1350 nm	1310 nm
1500 – 1600 nm	1550 nm

These wavelengths were chosen because they best match the transmission properties of available light sources with the transmission qualities of optical fiber.

IV. FIBER OPTIC LOSS CALCULATIONS

Loss in a system can be expressed as the following:

$$\boxed{\text{Loss} = \frac{P_{\text{out}}}{P_{\text{in}}}} \tag{8-1}$$

where P_{in} is the input power to the fiber and P_{out} is the power available at the output of the fiber. For convenience, *fiber optic loss* is typically expressed in terms of decibels (dB) and can be calculated using Equation 8-2a.

$$\boxed{\text{Loss}_{\text{dB}} = 10 \log \frac{P_{\text{out}}}{P_{\text{in}}}} \tag{8-2a}$$

Oftentimes, loss in optical fiber is also expressed in terms of decibels per kilometer (dB/km)

Example 1

A fiber of 100-m length has $P_{\text{in}} = 10\ \mu\text{W}$ and $P_{\text{out}} = 9\ \mu\text{W}$. Find the loss in dB/km.

From Equation 8-2

$$\text{Loss}_{\text{dB}} = 10 \log \left(\frac{9\ \mu\text{W}}{10\ \mu\text{W}} \right) = -0.458\ \text{dB}$$

and since

$$100\ \text{m} = 0.1\ \text{km}$$

the loss is

$$\text{Loss(dB/km)} = \frac{-0.458\ \text{dB}}{0.1\ \text{km}} = -4.58\ \text{dB/km}$$

$\therefore$ The negative sign implies <u>loss</u>.

Example 2

A communication system uses 10 km of fiber that has a 2.5-dB/km loss characteristic. Find the output power if the input power is 400 mW.

Solution:

From Equation 8-2, and making use of the relationship that $y = 10^x$ if $x = \log y$,

$$\text{Loss}_{\text{dB}} = 10 \log\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)$$

$$\frac{\text{Loss}_{\text{dB}}}{10} = \log\left(\frac{P_{\text{out}}}{P_{\text{in}}}\right)$$

which becomes, then, $$10^{\frac{\text{Loss}_{\text{dB}}}{10}} = \left(\frac{P_{\text{out}}}{P_{\text{in}}}\right).$$

So, finally, we have

$$P_{\text{out}} = P_{\text{in}} \times 10^{\frac{\text{Loss}_{\text{dB}}}{10}} \tag{8-2b}$$

For 10 km of fiber with 2.5-dB/km loss characteristic, the loss_{dB} becomes

$$\text{Loss}_{\text{dB}} = 10 \text{ km} \times (-2.5 \text{ dB/km}) = -25 \text{ dB}$$

Plugging this back into Equation 8-2b,

$$P_{\text{out}} = (400 \text{ mW}) \times 10^{\frac{-25}{10}} = 1.265 \text{ mW}$$

Optical power in fiber optic systems is typically expressed in terms of dBm, which is a decibel term that assumes that the input power is 1 mwatt. Optical power here can refer to the power of a laser source or just to the power somwhere in the system. If P in Equation 8-3 is in milliwatts, Equation 8-3 gives the power in dBm, referenced to an input of one milliwatt:

$$\boxed{P(\text{dBm}) = 10 \log\left(\frac{P}{1 \text{ mW}}\right)} \tag{8-3}$$

With optical power expressed in dBm, output power anywhere in the system can be determined simply by expressing the power input in dBm and subtracting the individual component losses, also expressed in dB. It is important to note that an optical source with a power input of 1 mW can be expressed as 0 dBm, as indicated by Equation 8-3. For every 3-dB loss, the power is cut in half. Consequently, for every 3-dB increase, the optical power is doubled. For example, a 3-dBm optical source has a P of 2 mW, whereas a –6-dBm source has a P of 0.25 mW, as can be verified with Equation 8-3.

Example 3

A 3-km fiber optic system has an input power of 2 mW and a loss characteristic of 2 dB/km. Determine the output power of the fiber optic system.

Solution:

Using Equation 8-3, we convert the source power of 2 mW to its equivalent in dBm:

$$\text{Input power}_{\text{dBm}} = 10\log\left(\frac{2\text{ mW}}{1\text{ mW}}\right) = +3\text{ dBm}$$

The loss_{dB} for the 3-km cable is,

$$\text{Loss}_{\text{dB}} = 3\text{ km} \times 2\text{ dB/km} = 6\text{ dB}$$

Thus, power in dB is $\quad (\text{Output power})_{\text{dB}} = +3\text{ dBm} - 6\text{ dB} = -3\text{ dBm}$

Using Equation 8-3 to convert the output power of –3 dBm back to milliwatts, we have

$$P(\text{dBm}) = 10\log\frac{P(\text{mW})}{1\text{ mW}}$$

so that

$$P(\text{mW}) = 1\text{ mW}\times 10^{\frac{P(\text{dBm})}{10}}$$

Plugging in for P(dBm) = –3 dBm, we get for the output power in milliwatts

$$P(\text{mW}) = 1\text{ mW}\times 10^{\frac{-3}{10}} = 0.5\text{ mW}$$

Note that one can also use Equation 8-2a to get the same result, where now P_{in} = 2 mW and Loss_{dB} = –6 dB:

$$P_{\text{out}} = P_{\text{in}}\times 10^{\frac{\text{Loss}_{\text{dB}}}{10}}$$

or

$$P_{\text{out}} = 2\text{ mW}\times 10^{\frac{-6}{10}} = 0.5\text{ mW, the same as above.}$$

V. TYPES OF FIBER

Three basic types of fiber optic cable are used in communication systems:

1. Step-index multimode
2, Step-index single mode
3, Graded-index

This is illustrated in Figure 8-2.

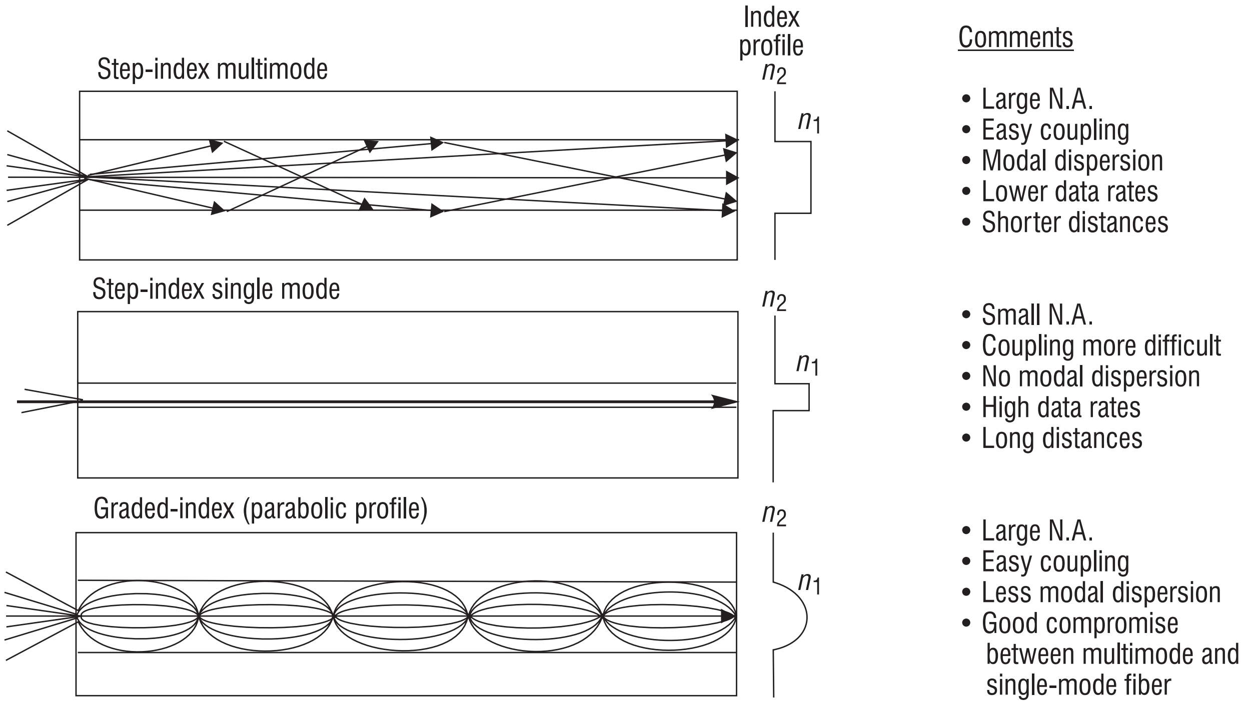


Figure 8-2 *Types of fiber*

Step-index multimode fiber has an index of refraction profile that "steps" from low to high to low as measured from cladding to core to cladding. Relatively large core diameter and numerical aperture characterize this fiber. The core/cladding diameter of a typical multimode fiber used for telecommunication is 62.5/125 μm (about the size of a human hair). The term "multimode" refers to the fact that multiple *modes* or *paths* through the fiber are possible. Step-index multimode fiber is used in applications that require high bandwidth (< 1 GHz) over relatively short distances (< 3 km) such as a local area network or a campus network backbone.

The major benefits of multimode fiber are: (1) it is relatively easy to work with; (2) because of its larger core size, light is easily coupled to and from it; (3) it can be used with both lasers and LEDs as sources; and (4) coupling losses are less than those of the single-mode fiber. The drawback is that because many modes are allowed to propagate (a function of core diameter, wavelength, and numerical aperture) it suffers from *modal dispersion*. The result of modal dispersion is bandwidth limitation, which translates into lower data rates.

Single-mode step-index fiber allows for only one path, or mode, for light to travel within the fiber. In a multimode step-index fiber, the number of modes M_n propagating can be approximated by

$$\boxed{M_n = \frac{V^2}{2}} \qquad (8\text{-}4)$$

Here V is known as the normalized frequency, or the ***V*-number**, which relates the fiber size, the refractive index, and the wavelength. The V-number is given by Equation (8-5)

$$\boxed{V = \left[\frac{2\pi\, a}{\lambda}\right] \times \text{N.A.}} \qquad (8\text{-}5)$$

or by Equation 8-6.

$$\boxed{V = \frac{2\pi a}{\lambda} \times n_1 \times (2 \times \Delta)^{\frac{1}{2}}} \qquad (8\text{-}6)$$

In either equation, a is the fiber core radius, λ is the operating wavelength, N.A. is the numerical aperture, n_1 is the core index, and Δ is the relative refractive index difference between core and cladding.

The analysis of how the V-number is derived is beyond the scope of this module, but it can be shown that by reducing the diameter of the fiber to a point at which the V-number is less than 2.405, higher-order modes are effectively extinguished and single-mode operation is possible.

Example 4

What is the maximum core diameter for a fiber if it is to operate in single mode at a wavelength of 1550 nm if the N.A. is 0.12?

From Equation 8-5,

$$V = \left[\frac{2\pi\, a}{\lambda}\right] \times \text{N.A.}$$

Solving for a yields

$$a = (V)(\lambda)/(2\pi \text{N.A.})$$

For single-mode operation, V must be 2.405 or less. The maximum core diameter occurs when $V = 2.405$. So, plugging into the equation, we get

$$a_{\text{max}} = (2.405)(1550\ \text{nm})/[(2\pi)(0.12)] = 4.95\ \mu\text{m}$$

or

$$d_{\text{max}} = 2 \times a = 9.9\ \mu\text{m}$$

The core diameter for a typical single-mode fiber is between 5 μm and 10 μm with a 125-μm cladding. Single-mode fibers are used in applications in which low signal loss and high data rates are required, such as in long spans where repeater/amplifier spacing must be maximized. Because single-mode fiber allows only one mode or ray to propagate (the lowest-order mode), it does not suffer from modal dispersion like multimode fiber and therefore can be used for higher bandwidth applications. However, even though single-mode fiber is not affected by modal dispersion, at higher data rates *chromatic* dispersion can limit the performance. This problem can be overcome by several methods. One can transmit at a wavelength in which glass has a fairly constant index of refraction (~1300 nm), use an optical source such as a distributed-feedback laser (DFB laser) that has a very narrow output spectrum, use special dispersioncompensating fiber, or use a combination of all these methods. In a nutshell, single-mode fiber is used in high-bandwidth, long-distance applications such as long-distance telephone trunk lines, cable TV head-ends, and high-speed local and wide area network (LAN and WAN) backbones. The major drawback of single-mode fiber is that it is relatively difficult to work with (i.e., splicing and termination) because of its small core size. Also, single-mode fiber is typically used only with laser sources because of the high coupling losses associated with LEDs.

Graded-index fiber is a compromise between the large core diameter and N.A. of multimode fiber and the higher bandwidth of single-mode fiber. With creation of a core whose index of refraction decreases parabolically from the core center toward the cladding, light traveling through the center of the fiber experiences a higher index than light traveling in the higher modes. This means that the higher-order modes travel faster than the lower-order modes, which allows them to "catch up" to the lower-order modes, thus decreasing the amount of modal dispersion, which increases the bandwidth of the fiber.

VI. DISPERSION

Dispersion, expressed in terms of the symbol Δt, is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser linewidth cause the pulse to broaden. This poses a limitation on the overall bandwidth of the fiber as demonstrated in Figure 8-3.

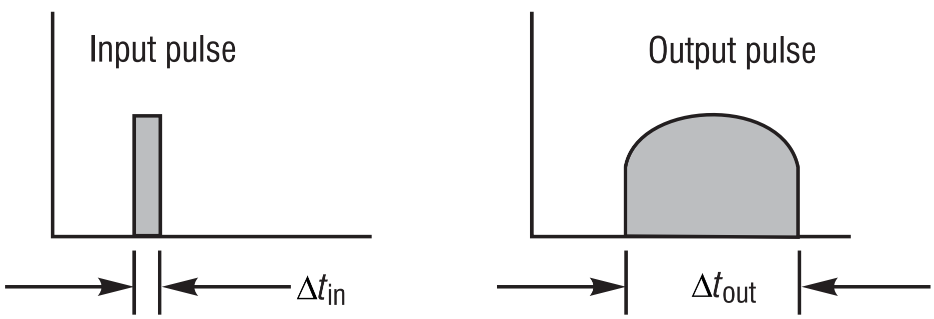


Figure 8-3 *Pulse broadening caused by dispersion*

Dispersion Δt can be determined from Equation 8-7.

$$\boxed{\Delta t = (\Delta t_{out} - \Delta t_{in})^{1/2}} \tag{8-7}$$

and is measured in time, typically nanoseconds or picoseconds. Total dispersion is a function of fiber length. The longer the fiber, the more the dispersion. Equation 8-8 gives the total dispersion per unit length.

$$\boxed{\Delta t_{total} = L \times (\text{Dispersion/km})} \tag{8-8}$$

The overall effect of dispersion on the performance of a fiber optic system is known as *intersymbol interference* (Figure 8-4). Intersymbol interference occurs when the pulse spreading caused by dispersion causes the output pulses of a system to overlap, rendering them undetectable. If an input pulse is caused to spread such that the rate of change of the input exceeds the dispersion limit of the fiber, the output data will become indiscernible.

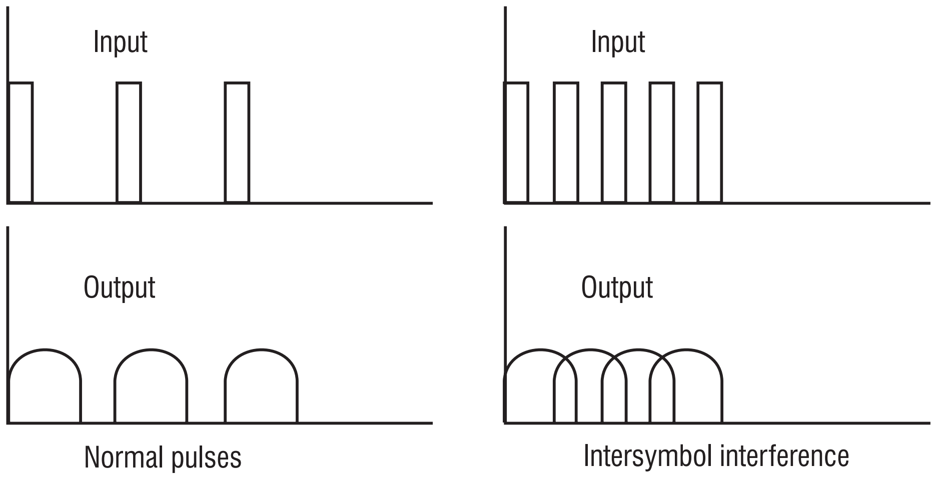


Figure 8-4 *Intersymbol interference*

Dispersion is generally divided into two categories: *modal dispersion* and *chromatic dispersion*.

Modal dispersion is defined as pulse spreading caused by the time delay between lower-order modes (modes or rays propagating straight through the fiber close to the optical axis) and higher-order modes (modes propagating at steeper angles). This is shown in Figure 8-5. Modal dispersion is problematic in multimode fiber, causing bandwidth limitation, but it is not a problem in single-mode fiber where only one mode is allowed to propagate.

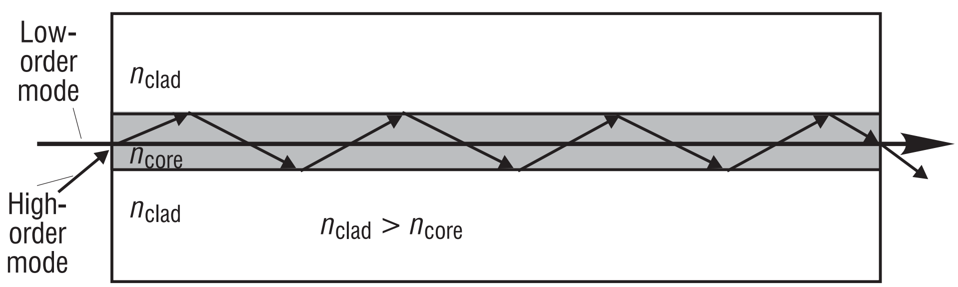


Figure 8-5 *Mode propagation in an optical fiber*

Chromatic dispersion is pulse spreading due to the fact that different wavelengths of light propagate at slightly different velocities through the fiber. All light sources, whether laser or LED, have finite linewidths, which means they emit more than one wavelength. Because the index of refraction of glass fiber is a wavelength-dependent quantity, different wavelengths propagate at different velocities. Chromatic dispersion is typically expressed in units of nanoseconds or picoseconds per (km-nm).

Chromatic dispersion consists of two parts: material dispersion and waveguide dispersion.

$$\boxed{\Delta t_{\text{chromatic}} = \Delta t_{\text{material}} + \Delta t_{\text{waveguide}}} \tag{8-9}$$

Material dispersion is due to the wavelength dependency on the index of refraction of glass. Waveguide dispersion is due to the physical structure of the waveguide. In a simple step-index-profile fiber, waveguide dispersion is not a major factor, but in fibers with more complex index profiles, waveguide dispersion can be more significant. Material dispersion and waveguide dispersion can have opposite signs depending on the transmission wavelength. In the case of a step-index single-mode fiber, these two effectively cancel each other at 1310 nm, yielding zero-dispersion. This makes very high-bandwidth communication possible at this wavelength. However, the drawback is that, even though dispersion is minimized at 1310 nm, attenuation is not. Glass fiber exhibits minimum attenuation at 1550 nm. Coupling that with the fact that erbium-doped fiber amplifiers (EDFA) operate in the 1550-nm range makes it obvious that, if the zero-dispersion property of 1310 nm could be shifted to coincide with the 1550-nm transmission window, high-bandwidth long-distance communication would be possible. With this in mind, *zero-dispersion-shifted fiber* was developed.

When considering the total dispersion from different causes, we can approximate the total dispersion by Δt_{tot}.

$$\boxed{\Delta_{\text{tot}} = \left[(\Delta t_1)^2 + (\Delta t_2)^2 + \ldots + (\Delta t_n)^2\right]^{1/2}} \tag{8-10}$$

where Δt_n represents the dispersion due to the various components that make up the system. The transmission capacity of fiber is typically expressed in terms of *bandwidth* × *distance*. For example, the bandwidth × distance product for a typical 62.5/125-µm (core/cladding diameter) multimode fiber operating at 1310 nm might be expressed as 600 MHz•km. The approximate bandwidth of a fiber can be related to the total dispersion by the following relationship

$$\boxed{\text{BW} = 0.35/\Delta t_{\text{total}}} \tag{8-11}$$

Example 5

A 2-km-length multimode fiber has a modal dispersion of 1 ns/km and a chromatic dispersion of 100 ps/km•nm. If it is used with an LED of linewidth 40 nm, (a) what is the total dispersion? (b) Calculate the bandwidth (BW) of the fiber.

a. $\Delta t_{\text{modal}} = 2\text{ km} \times 1\text{ ns/km} = 2\text{ ns}$

$\Delta t_{\text{chromatic}} = (2\text{ km}) \times (100\text{ ps/km}\cdot\text{nm}) \times (40\text{ nm}) = 8000\text{ ps} = 8\text{ ns}$

$\Delta t_{\text{total}} = ((2\text{ ns})^2 + (8\text{ ns})^2)^{1/2} = 8.24\text{ ns}$

b. $\text{BW} = 0.35/\Delta t_{\text{total}} = 0.35/8.24\text{ ns} = 42.48\text{ MHz}$

Expressed in terms of the product (BW• km), we get (BW•km) = (42.5 MHz)(2 km) $\simeq$ 85 MHz•km.

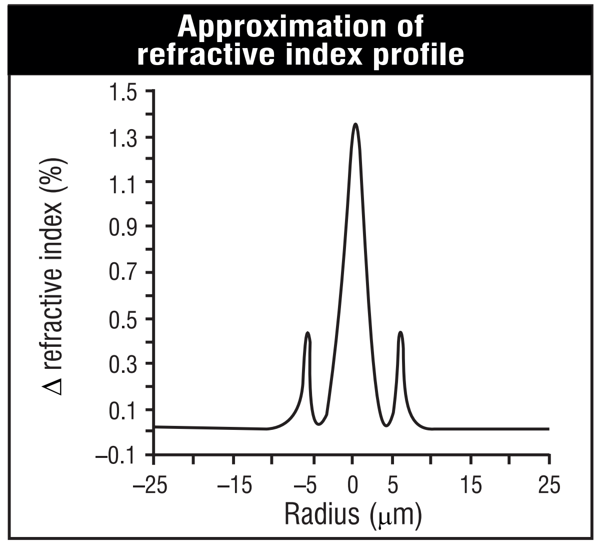


Figure 8-6 *W-profile fiber*

Dispersion-shifted fiber: By altering the design of the waveguide, we can increase the magnitude of the waveguide dispersion o as to shift the zero-dispersion wavelength to 1550 nm. This type of fiber has an index profile that resembles a "W" and hence is sometimes referred to as W-profile fiber (Figure 8-6). Although this type of fiber works well at the zero-dispersion wavelength, in systems in which multiple wavelengths are transmitted, such as in wavelength-division multiplexing, signals transmitted at different wavelengths around 1550 nm can interfere with one another, resulting in a phenomenon called *four-wave mixing,* which degrades system performance. However, if the waveguide structure of the fiber is modified so that the waveguide dispersion is further increased, the zero-dispersion point can be pushed past 1600 nm (outside the EDFA operating window). This means that the total chromatic dispersion can still be substantially lowered in the 1550-nm range without having to worry about performance problems. This type of fiber is known as *nonzero-dispersion-shifted fiber*. Figure 8-7 compares the material chromatic and wavelength dispersions for single-mode fiber and dispersion-shifted fiber.

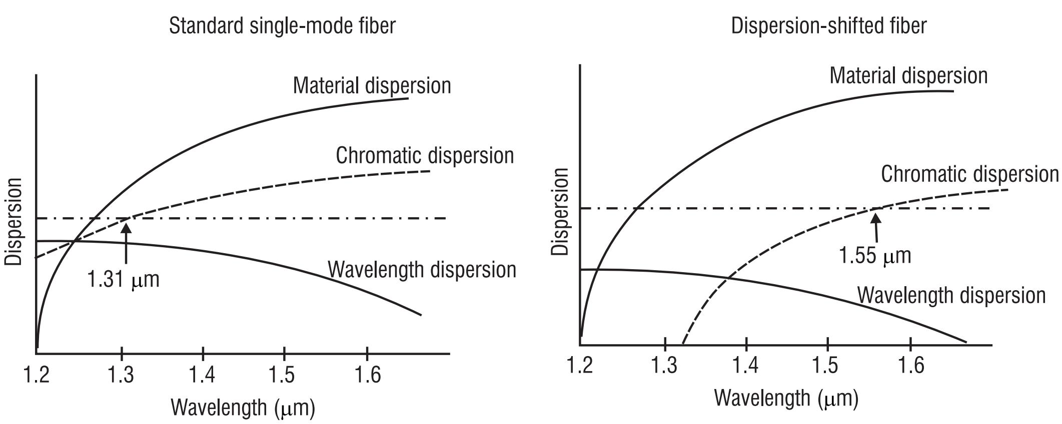


Figure 8-7 *Single-mode versus dispersion-mode versus dispersion-shifted fiber*

VII. ANALOG VERSUS DIGITAL SIGNALS

Information in a fiber optic system can be transmitted in one of two ways: *analog* or *digital* (see Figure 8-8). An analog signal is one that varies continuously with time. For example, when you speak into the telephone, your voice is converted to an analog voltage that varies continuously. The signal from your cable TV company is also analog. A digital signal is one that exists only at discrete levels. For example, in a computer, information is represented as zeros and ones (0 and

5 volts). In the case of the telephone, the analog voice signal emanating from your handset is sent through a pair of wires to a device called a concentrator, which is located either on a utility pole, in a small service box, or in a manhole. The concentrator converts the analog signal to a digital signal that is combined with many other telephone signals through a process called multiplexing. In telecommunication, most signals are digitized. An exception is cable TV, which still transmits video information in analog form. With the advent of digital and high-definition television (HDTV), cable TV will eventually also be transmitted digitally.

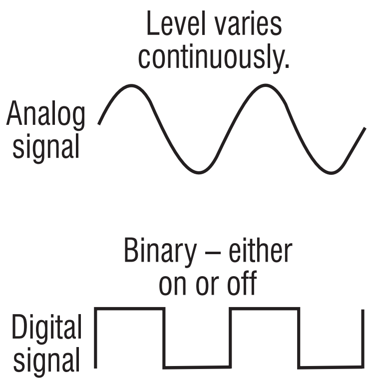


Figure 8-8 *Analog and digital signals*

Digital transmission has several advantages over analog transmission. First, it is easier to process electronically. No conversion is necessary. It is also less susceptible to noise because it operates with discrete signal levels. The signal is either on or off, which makes it harder to corrupt. Digital signals may also be encoded to detect and correct transmission errors.

VIII. PULSE CODE MODULATION

Pulse code modulation (PCM) is the process of converting an analog signal into a 2^n-digit binary code. Consider the block diagram shown in Figure 8-9. An analog signal is placed on the input of a *sample and hold*. The *sample and hold* circuit is used to "capture" the analog voltage long enough for the conversion to take place. The output of the sample and hold circuit is fed into the *analog-to-digital converter* (A/D). An A/D converter operates by taking periodic discrete samples of an analog signal at a specific point in time and converting it to a 2^n-bit binary number. For example, an 8-bit A/D converts an analog voltage into a binary number with 2^8 discrete levels (between 0 and 255). For an analog voltage to be successfully converted, it must be sampled at a rate at least *twice* its maximum frequency. This is known as the *Nyquist sampling rate*. An example of this is the process that takes place in the telephone system.
A standard telephone has a bandwidth of 4 kHz. When you speak into the telephone, your 4-kHz bandwidth voice signal is sampled at twice the 4-kHz frequency or 8 kHz. Each sample is then converted to an 8-bit binary number. This occurs 8000 times per second. Thus, if we multiply

$$8 \text{ k samples/s} \times 8 \text{ bits/sample} = 64 \text{ kbits/s}$$

we get the standard bit rate for a single voice channel in the North American DS1 System, which is 64 kbits/s. The output of the A/D converter is then fed into a driver circuit that contains the appropriate circuitry to turn the light source on and off. The process of turning the light source on and off is known as modulation and will be discussed later in this module. The light then travels through the fiber and is received by a photodetector that converts the optical signal into an electrical current. A typical photodetector generates a current that is in the micro- or nanoamp range, so amplification and/or signal reshaping is often required. Once the digital signal has been reconstructed, it is converted back into an analog signal using a device called a *digital-to-analog converter* or DAC. A digital storage device or buffer may be used to temporarily store the digital codes during the conversion process. The DAC accepts an n-bit digital number and outputs a continuous series of discrete voltage "steps." All that is needed to smooth the stair-step voltage out is a simple low-pass filter with its cutoff frequency set at the maximum signal frequency as shown in Figure 8-10.

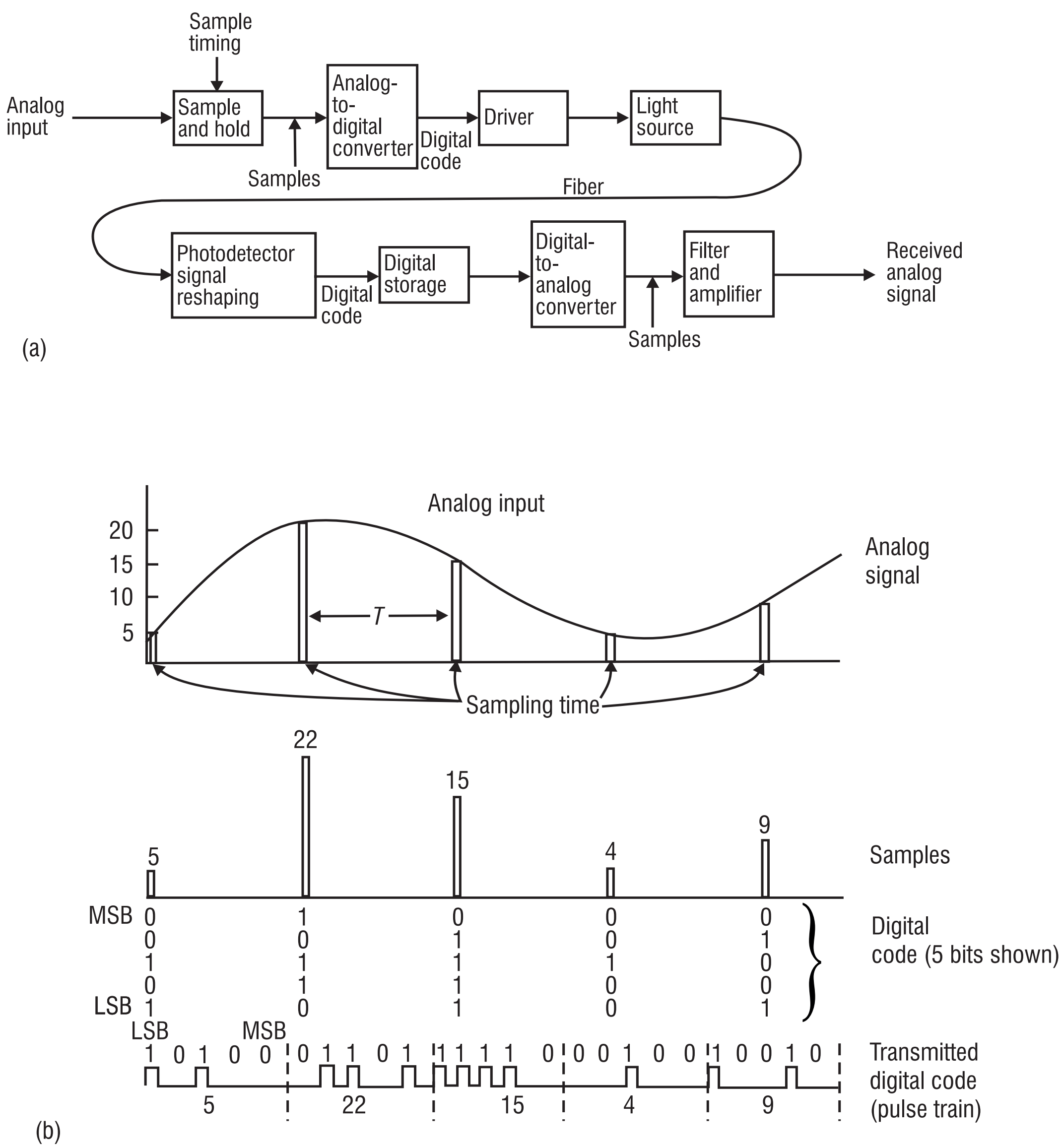


Figure 8-9 (a) *Block diagram* (b) *Digital waveforms*

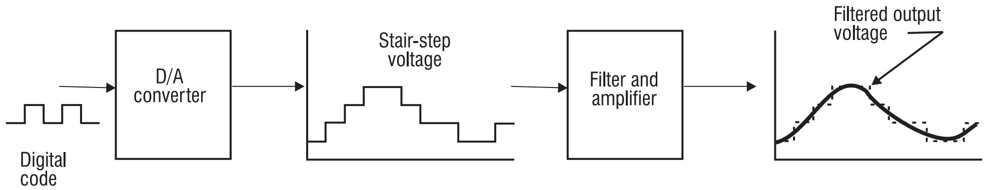
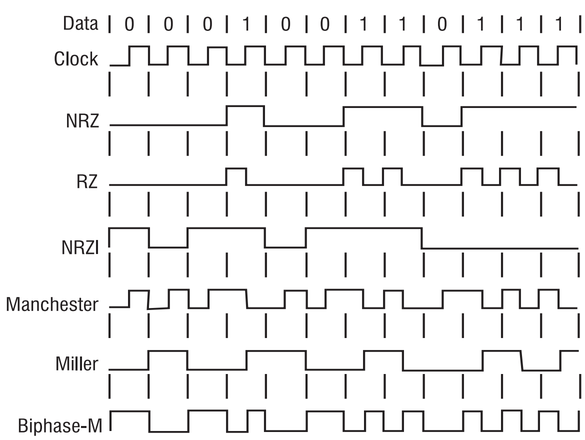


Figure 8-10 *D/A output circuit*

IX. DIGITAL ENCODING SCHEMES

Signal format is an important consideration in evaluating the performance of a fiber optic system. The signal format directly affects the detection of the transmitted signals. The accuracy of the reproduced signal depends on the intensity of the received signal, the speed and linearity of the receiver, and the noise levels of the transmitted and received signal. Many coding schemes are used in digital communication systems, each with its own benefits and drawbacks. The most common encoding schemes are the return-to-zero (RZ) and non-return-to-zero (NRZ). The NRZ encoding scheme, for example, requires only one transition per symbol, whereas RZ format requires two transitions for each data bit. This implies that the required bandwidth for RZ must be twice that of NRZ. This is not to say that one is better than the other. Depending on the application, any of the code formats may be more appropriate than the others. For example, in synchronous transmission systems in which large amounts of data are to be sent, clock synchronization between the transmitter and receiver must be ensured. In this case *Manchester encoding* is used. The transmitter clock is embedded in the data. The receiver clock is derived from the guaranteed transition in the middle of each bit. The various methods are illustrated in Figure 8-11.



Format	Symbols per Bit	Self-Clocking	Duty Factor Range (%)
NRZ	1	No	0-100
RZ	2	No	0-50
NRZI	1	No	0-100
Manchester (Biphase L)	2	Yes	50
Miller	1	Yes	33-67
Biphase M (Bifrequency)	2	Yes	50

Figure 8-11 *Different encoding schemes*

Digital systems are analyzed on the basis of rise time rather than on bandwidth. The rise time of a signal is defined as the time required for the signal to change from 10% to 90% of its maximum value. The system rise time is determined by the data rate and code format. Depending on which code format is used, the number of transitions required to represent the transmitted data may limit overall the data rate of the system. The system rise time depends on the combined rise time characteristics of the individual system components.

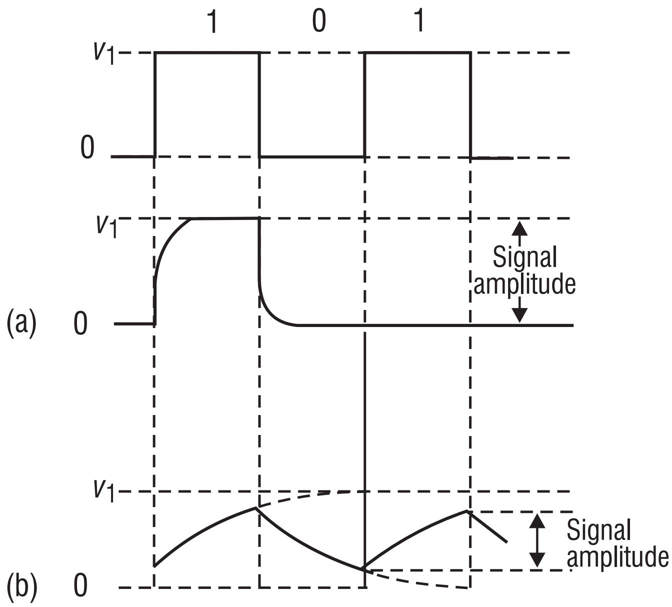
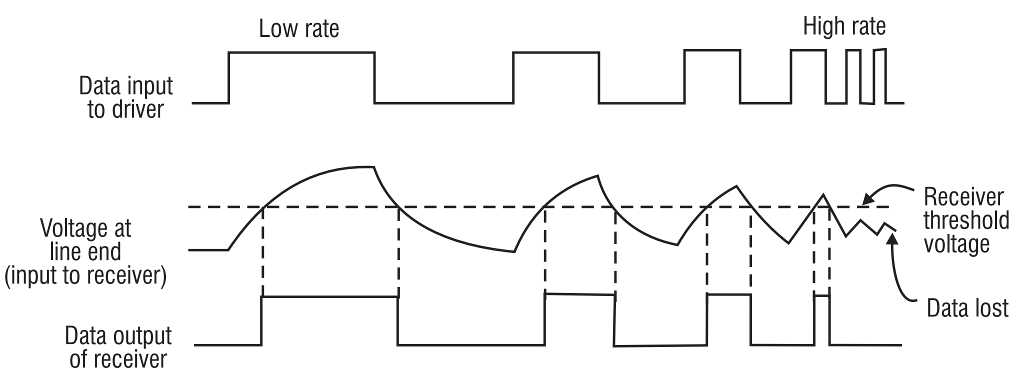


Figure 8-12 *Effect of rise time:* (a) *Short rise time* (b) *Long rise time*

The signal shown in Figure 8-12 (a) represents a signal with adequate rise time. Even though the pulses are somewhat rounded on the edges, the signal is still detectable. In Figure 8-12 (b), however, the transmitted signal takes too long to respond to the input signal. The effect is exaggerated in Figure 8-13, where, at high data rates, the rise time limitations cause the data to be distorted and thus lost.



Source: *The TTL Application Handbook,* August 1973f, p. 14-7.
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Figure 8-13 *Distortion of data bits by varying data rates*

To avoid this distortion, an acceptable criterion is to require that a system have a rise time t_s of no more than 70% of the pulse width T_p;

$$\boxed{t_s \le (0.7 \times T_p)} \tag{8-12}$$

For an RZ, T_p takes half the bit time T so that

$$\boxed{t_s \le (0.7 \times T)/2} \tag{8-13}$$

or

$$\boxed{t_s \le 0.35/B_r} \tag{8-14}$$

where $B_r = 1/T$ is the system bit rate.

For an NRZ format, $T_p = T$ and thus

$$\boxed{t_S \le 0.7/B_r} \tag{8-15}$$

∴ RZ transmission requires a larger-bandwidth system.

Figure 8-14 shows transmitted (a) RZ and (c) NRZ pulse trains and the effects of system rise time on (b) format RZ and (d) format NRZ.

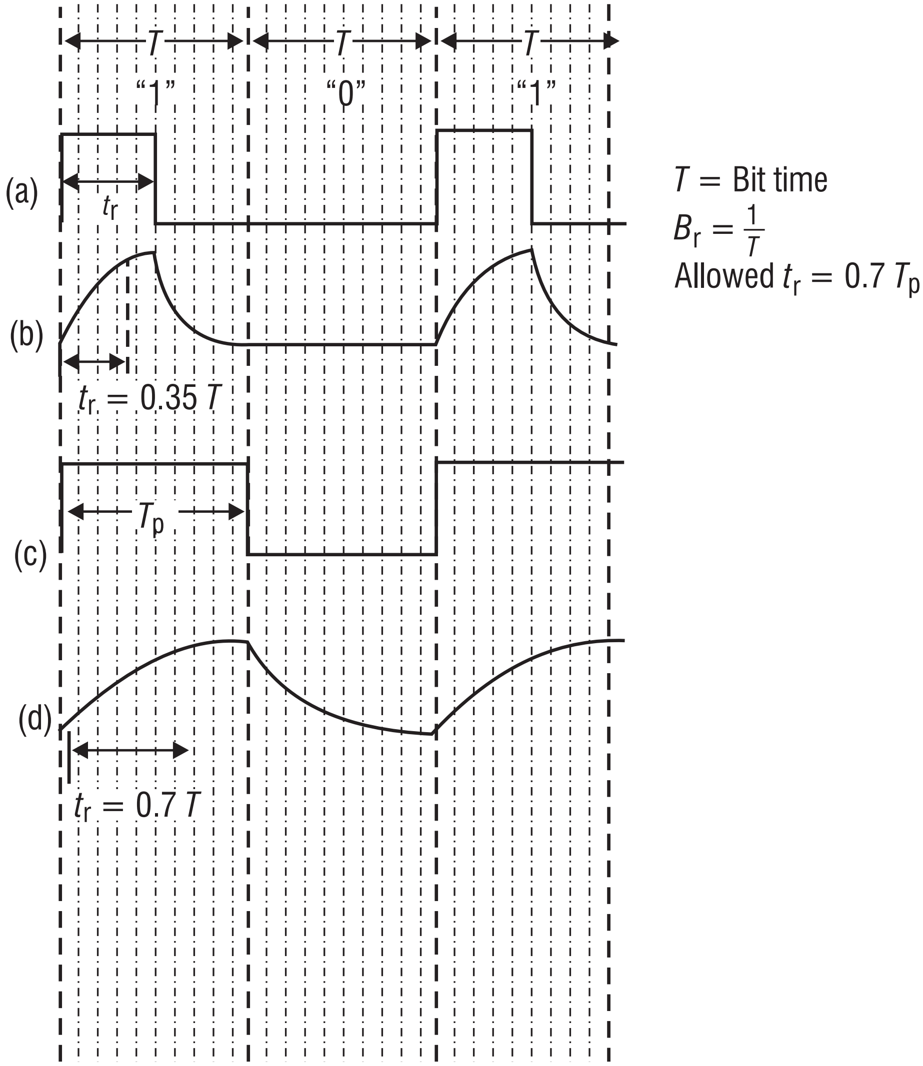


Figure 8-14 *Effects of system rise time for RZ format and NRZ format:*
a) *Transmitted RZ pulse train*
b) *Received RZ signal with allowable t_r.*
c) *Transmitted NRZ pulse train*
d) *Received NRZ pulse train with allowable t_r*

X. MULTIPLEXING

The purpose of multiplexing is to share the bandwidth of a single transmission channel among several users. Two multiplexing methods are commonly used in fiber optics:

1. Time-division multiplexing (TDM)
2. Wavelength-division multiplexing (WDM)

A. Time-Division Multiplexing (TDM)

In time-division multiplexing, time on the information channel, or fiber, is shared among the many data sources. The multiplexer MUX can be described as a type of "rotary switch," which rotates at a very high speed, individually connecting each input to the communication channel for a fixed period of time. The process is reversed on the output with a device known as a demultiplexer, or DEMUX. After each channel has been sequentially connected, the process repeats itself. One complete cycle is known as a *frame*. To ensure that each channel on the input is connected to its corresponding channel on the output, start and stop frames are added to synchronize the input with the output. TDM systems may send information using any of the digital modulation schemes described (analog multiplexing systems also exist). This is illustrated in Figure 8-15.

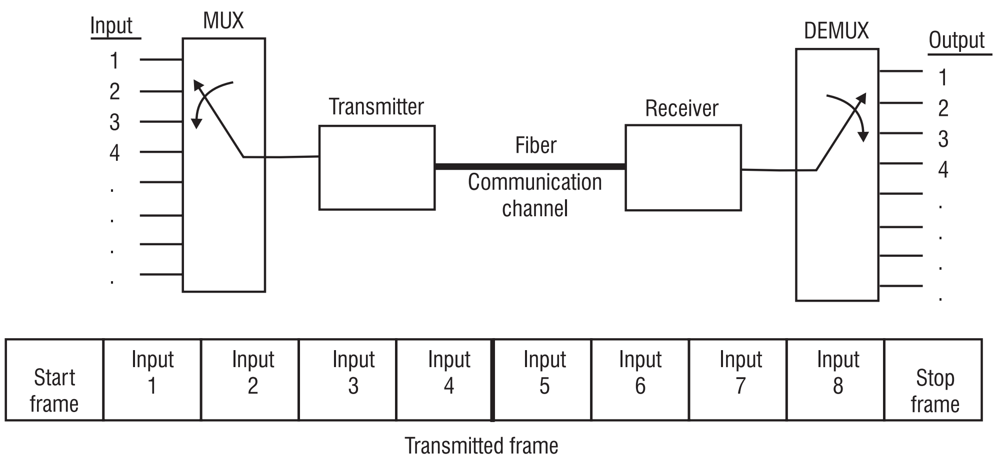


Figure 8-15 *Time-division multiplexing system*

The amount of data that can be transmitted using TDM is given by the MUX output rate and is defined by Equation 8-16.

$$\boxed{\text{MUX output rate} = N \times \text{Maximum input rate}} \qquad (8\text{-}16)$$

where N is the number of input channels and the maximum input rate is the highest data rate in bits/second of the various inputs. The bandwidth of the communication channel must be *at least equal* to the MUX output rate. Another parameter commonly used in describing the information capacity of a TDM system is the *channel-switching rate.* This is equal to the number of inputs visited per second by the MUX and is defined as

$$\boxed{\text{Channel switching rate} = \text{Input data rate} \times \text{Number of channels}} \qquad (8\text{-}17)$$

Example 6

A digital MUX operates with 8 sources. The rate of data in each source is 1000 bytes/s. Assume that 8-bits-per-byte data is transmitted byte by byte.

1. What is the data rate of the MUX output?
2. What is the channel switching rate?

Solution:

1. The data rate of each input channel is (8×1000) bits/s. The output data rate from Equation 8-16 is then:

$$\text{Output rate} = N \times \text{Input rate}$$
$$= 8 \times (8 \times 1000) = 64 \text{ kbits/s}$$

2. Each channel must have access to the MUX 1000 times each second, transmitting 1 byte at a time. From Equation 8-17, the channel switching rate is

$$8 \times 1000 = 8{,}000 \text{ channels/s}$$

The Digital Telephone Hierarchy

The North American digital telephone hierarchy defines how the low-data-rate telephone signals are multiplexed together onto higher-speed lines. The system uses pulse code modulation (PCM) in conjunction with time-division multiplexing to achieve this. The basic digital multiplexing standard established in the United States is called *the Bell System Level 1 PCM Standard* or the *Bell T1 Standard*. This is the standard used for multiplexing 24 separate 64-kbps (8 bits/sample × 8000 samples/s) voice channels together. Each 64-kbps voice channel is designated as *digital signaling level 0* or *DS-0*. Each frame in the 24-channel multiplexer consists of

$$8 \text{ bits/channel} \times 24 \text{ channels} + 1 \text{ framing bit} = 193 \text{ bits}$$

The total data rate when transmitting 24 channels is determined by:

$$193 \text{ bits/frame} \times 8000 \text{ frames/s} = 1.544 \text{ Mbps} = \text{T1 designation}$$

If four T1 lines are multiplexed together, we get

$$4 \times 24 \text{ channels} = 96 \text{ channels} = \text{T2 designation}$$

Multiplexing seven T2 lines together we get

$$7 \times 96 = 672 \text{ channels} = \text{T3 designation}$$

Figure 8-16 shows how the multiplexing takes place.

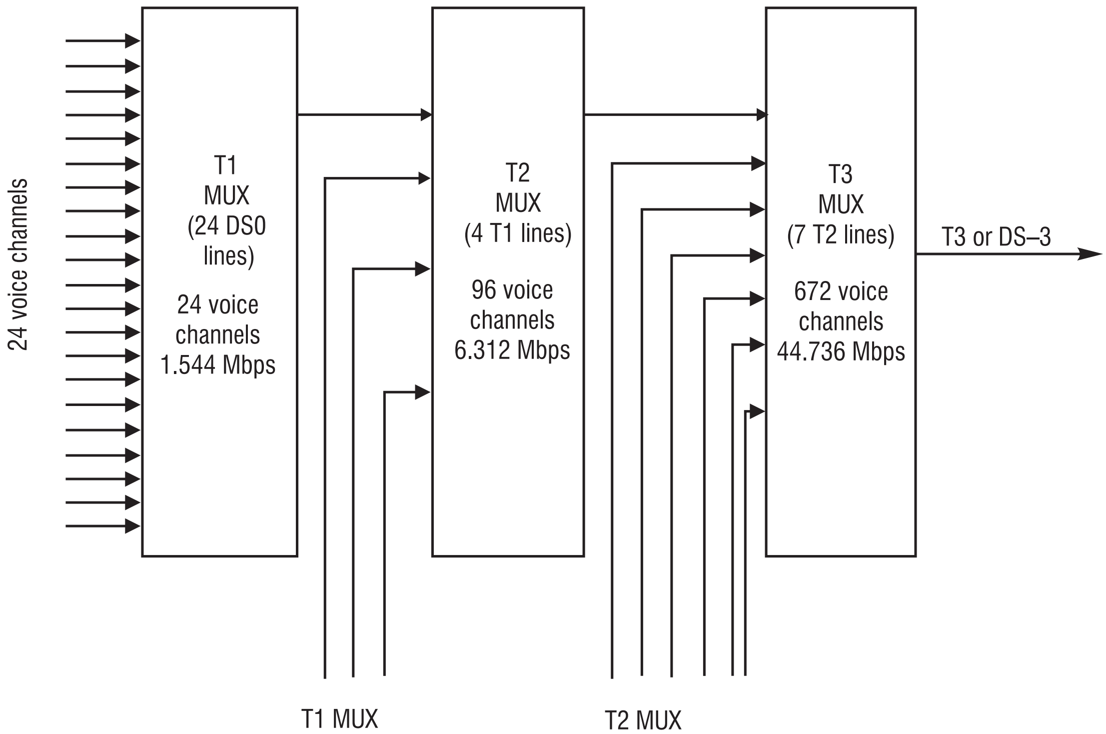


Figure 8-16 *The North American digital telephone hierarchy*

SONET

Fiber optics use *Synchronous Optical Network (SONET*) standards. The initial SONET designation is OC-1 (*optical carrier-1*). This level is known as synchronous transport level l (STS-1). It has a synchronous frame structure at a speed of 51.840 Mbps. The synchronous frame structure makes it easy to extract individual DS1 signals without disassembling the entire frame. OC-1 picks up where the DS3 signal (28 DSI signals or 672 channels) leaves off. With SONET standards any of these 28 T1 systems can be stripped out of the OC-1 signal.

The North American SONET rate is OC-48, which is 48 times the 51.840-Mbps OC-1 rate, or approximately 2.5 billion bits per second (2.5 Gbps). OC-48 systems can transmit 48 × 672 channels or 32,256 channels, as seen in Table 8-2. One fiber optic strand can carry all 32,256 separate 64-kbps channels. The maximum data rate specified for the SONET standard is OC-192 or approximately 9.9538 Gbps. At this data rate, 129,024 separate voice channels can be transmitted through a single fiber. Even though OC-192 is the maximum data rate specified by SONET, recent developments in technology allow for transmission as high as 40 Gbps. This, coupled with the availability of 32-channel wavelength-division multiplexers, has led to the development of systems capable of 1.2-terabit/s transmission. As can been seen, the data rates achievable through the use of fiber optics are dramatically greater than those achievable with copper. In addition, the distance between repeaters in a fiber optic system is considerably greater than that for copper, making fiber more reliable and, in most cases, more cost-effective.

Table 8-2 Digital Telephone Transmission Rates

Medium	Designation	Data Rate (Mbps)	Voice Channels	Repeater Spacing
Copper	DS-1	1.544	24	1-2 km
	DS-2	3.152	96	
	DS-3	44.736	672	
Fiber Optic	OC-1	51.84	672	50-100 km
	OC-3	155.52	2016	
	OC-12	622.08	8064	
	OC-18	933.12	12,096	
	OC-24	1244.16	16,128	
	OC-36	1866.24	24,192	
	OC-48	2488.32	32,256	
	OC-96	4976.64	64,512	
	OC-192	9953.28	129,024	

B. Wavelength-Division Multiplexing (WDM)

In wavelength-division multiplexing, each data channel is transmitted using a slightly different wavelength (different color). With use of a different wavelength for each channel, many channels can be transmitted through the same fiber without interference. This method is used to increase the capacity of existing fiber optic systems many times. Each WDM data channel may consist of a single data source or may be a combination of a single data source and a TDM (time-division multiplexing) and/or FDM (frequency-division multiplexing) signal. Dense wavelength-division multiplexing (DWDM) refers to the transmission of multiple closely spaced wavelengths through the same fiber. For any given wavelength λ and corresponding frequency f, the International Telecommunications Union (ITU) defines standard frequency spacing Δf as 100 GHz, which translates into a $\Delta\lambda$ of 0.8-nm wavelength spacing. This follows from the relationship $\Delta\lambda = \frac{\lambda\,\Delta f}{f}$. (See Table 8-3.) DWDM systems operate in the 1550-nm window because of the low attenuation characteristics of glass at 1550 nm and the fact that erbium-doped fiber amplifiers (EDFA) operate in the 1530-nm–1570-nm range. Commercially available systems today can multiplex up to 128 individual wavelengths at 2.5 Gb/s or 32 individual wavelengths at 10 Gb/s (see Figure 8-17). Although the ITU grid specifies that each transmitted wavelength in a DWDM system is separated by 100 GHz, systems currently under development have been demonstrated that reduce the channel spacing to 50 GHz and below (< 0.4 nm). As the channel spacing decreases, the number of channels that can be transmitted increases, thus further increasing the transmission capacity of the system.

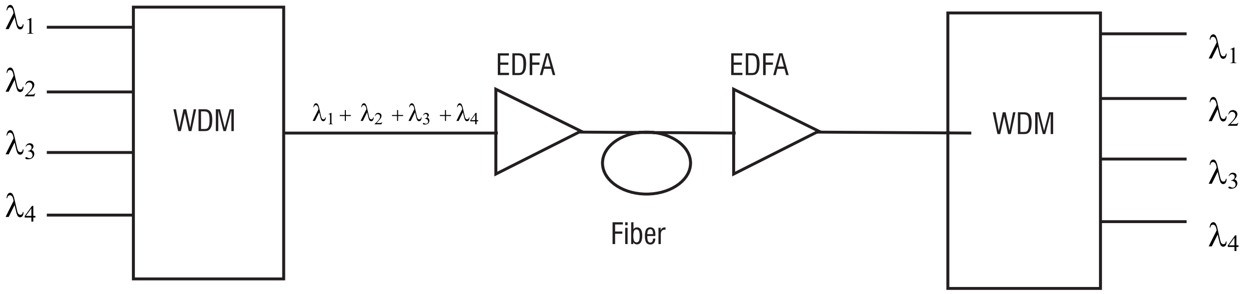


Figure 8-17 *Wavelength-division multiplexing*

Table 8-3 ITU GRID

Center Wavelength – nm (vacuum)	Optical Frequency (THz)
1530.33	195.9
1531.12	195.8
1531.90	195.7
1532.68	195.6
1533.47	195.5
1534.25	195.4
1535.04	195.3
1535.82	195.2
1536.61	195.1
1537.40	195.0
1538.19	194.9
1538.98	194.8
1539.77	194.7
1540.56	194.6
1541.35	194.5
1542.14	194.4
1542.94	194.3
1543.73	194.2
1544.53	194.1
1545.32	194.0
1546.12	193.9
1546.92	193.8
1547.72	193.7
1548.51	193.6
1549.32	193.5
1550.12	193.4
1550.92	193.3
1551.72	193.2
1552.52	193.1
1553.33	193.0
1554.13	192.9
1554.93	192.8
1555.75	192.7
1556.55	192.6
1557.36	192.5
1588.17	192.4
1558.98	192.3
1559.79	192.2
1560.61	192.1
1561.42	192.0
1562.23	191.9
1563.05	191.8
1563.86	191.7

XI. COMPONENTS—FIBER OPTIC CABLE

In most applications, optical fiber must be protected from the environment using a variety of different cabling types based on the type of environment in which the fiber will be used. Cabling provides the fiber with protection from the elements, added tensile strength for pulling, rigidity for bending, and durability. In general, fiber optic cable can be separated into two types: indoor and outdoor.

Indoor Cables

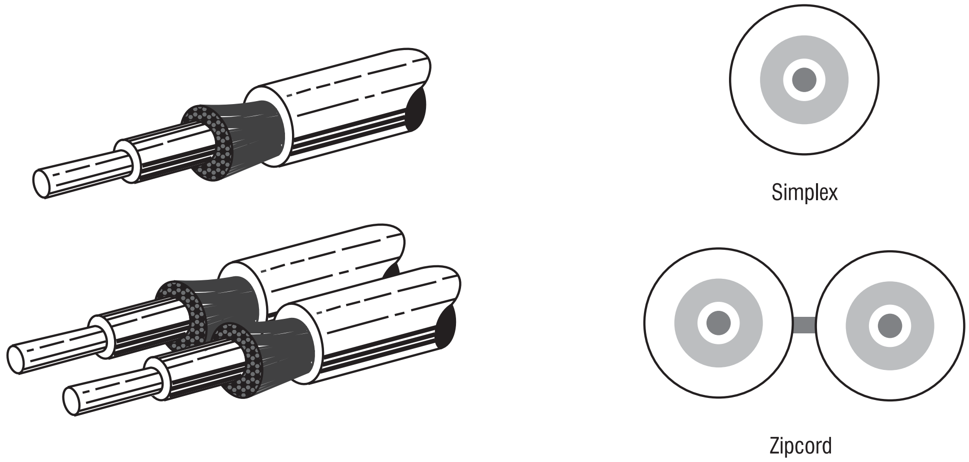
- *Simplex cable*—contains a single fiber for one-way communication
- *Duplex cable*—contains two fibers for two-way communication
- *Multifiber cable*—contains more than two fibers. Fibers are usually in pairs for duplex operation. A ten-fiber cable permits five duplex circuits.
- *Breakout cable*—typically has several individual simplex cables inside an outer jacket. The outer jacket includes a zipcord to allow easy access
- *Heavy-, light-, and plenum-duty and riser cable*
  - Heavy-duty cables have thicker jackets than light-duty cable, for rougher handling.
  - Plenum cables are jacketed with low-smoke and fire-retardant materials.
  - Riser cables run vertically between floors and must be engineered to prevent fires from spreading between floors.

Outdoor Cables

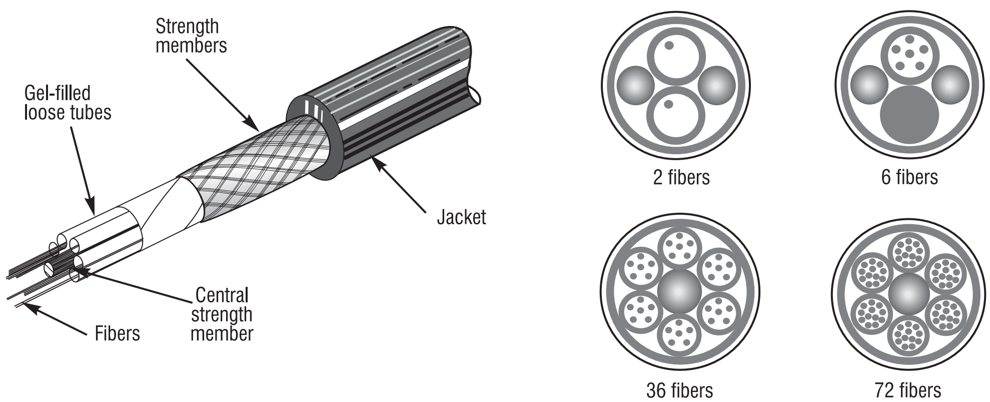
Outdoor cables must withstand harsher environmental conditions than indoor cables. Outdoor cables are used in applications such as:

- *Overhead*—cables strung from telephone lines
- *Direct burial*—cables placed directly in trenches
- *Indirect burial*—cables placed in conduits
- *Submarine*—underwater cables, including transoceanic applications

Sketches of indoor and outdoor cables are shown in Figure 8-18.



a) Indoor simplex and duplex cable (Courtesy of General Photonics)



b) Outdoor loose buffer cable (Courtesy of Siecor)

Figure 8-18 *Indoor and outdoor cable*

Cabling Example

Figure 8-19 shows an example of an interbuilding cabling scenario

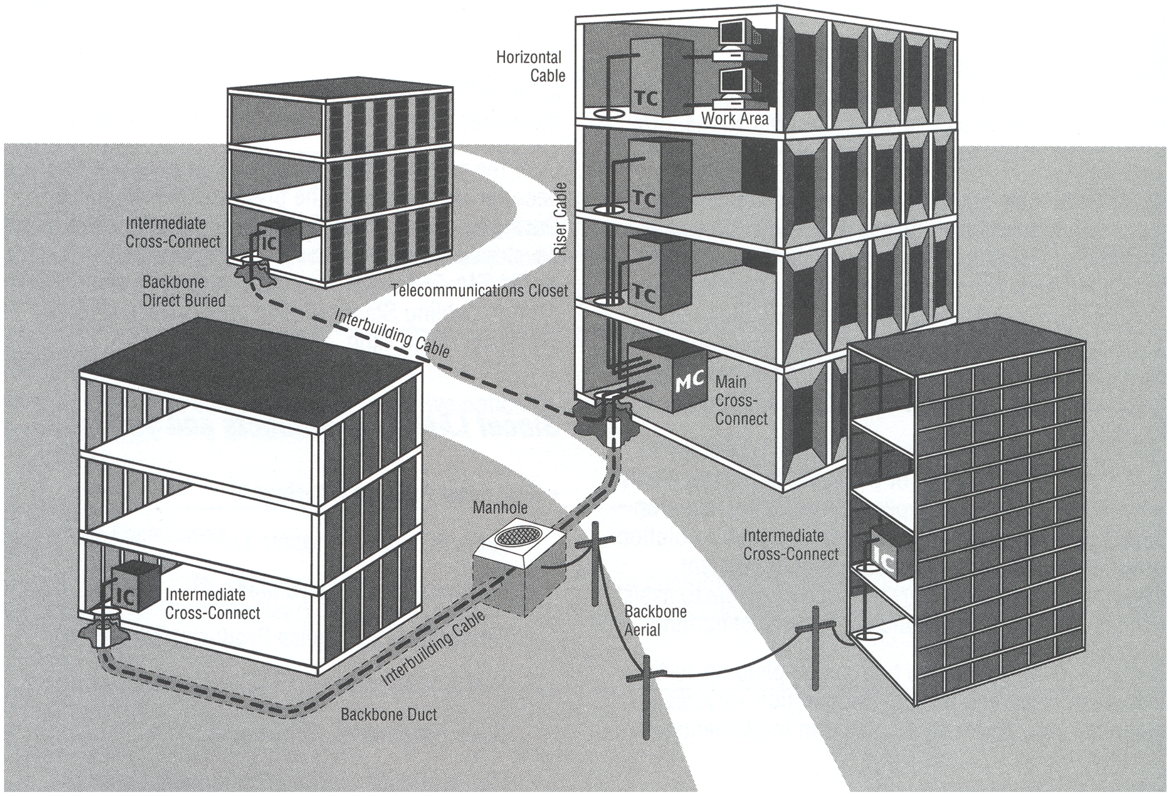


Figure 8-19 *Interbuilding cabling scenario* (Courtesy of Siecor)

XII. FIBER OPTIC SOURCES

Two basic light sources are used for fiber optics: laser diodes (LD) and light-emitting diodes (LED). Each device has its own advantages and disadvantages as listed in Table 8-4.

Table 8-4 LED Versus Laser

Characteristic	LED	Laser
Output power	Lower	Higher
Spectral width	Wider	Narrower
Numerical aperture	Larger	Smaller
Speed	Slower	Faster
Cost	Less	More
Ease of operation	Easier	More difficult

Fiber optic sources must operate in the low-loss transmission windows of glass fiber. LEDs are typically used at the 850-nm and 1310-nm transmission wavelengths, whereas lasers are primarily used at 1310 nm and 1550 nm.

LEDs are typically used in lower-data-rate, shorter-distance multimode systems because of their inherent bandwidth limitations and lower output power. They are used in applications in which data rates are in the hundreds of megahertz as opposed to GHz data rates associated with lasers. Two basic structures for LEDs are used in fiber optic systems: *surface-emitting* and *edge-emitting* as shown in Figure 8-20.

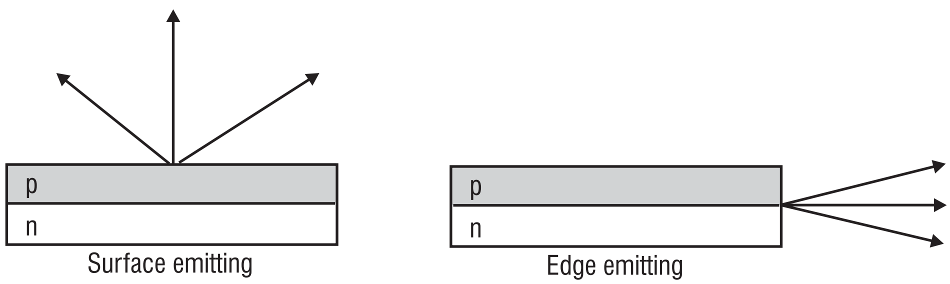
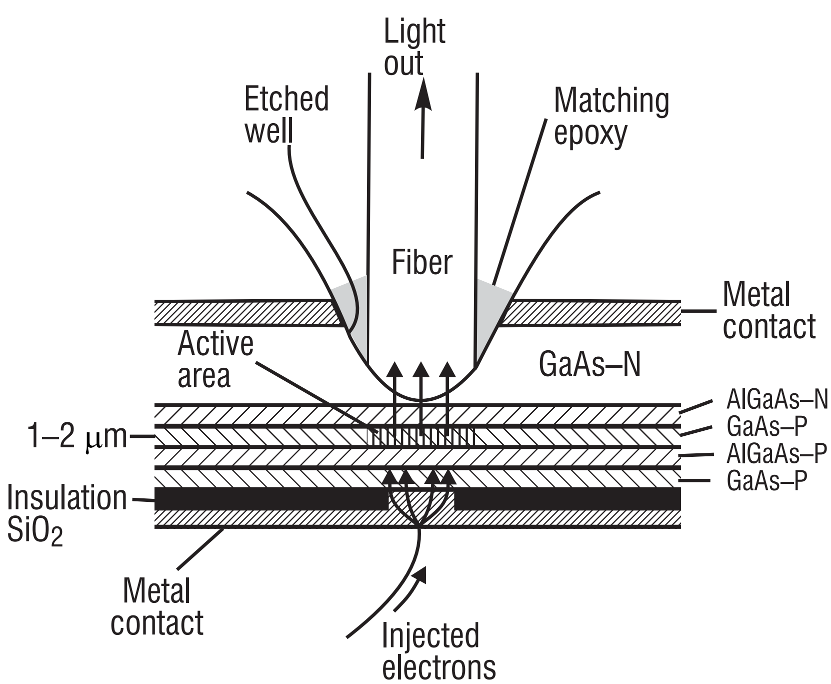


Figure 8-20 *Surface-emitting versus edge-emitting diodes*

In surface-emitting LEDs the radiation emanates from the surface. An example of this is the Burris diode as shown in Figure 8-21. LEDs typically have large numerical apertures, which



Source: C. A. Burrus and B. I. Miller, "Small Area Double-Heterostructure Aluminum Gallium Arsenide Electroluminescent Diode Sources for Optical Fiber Transmission Lines," *Optical Communications* 4:307-69 (1971).

Figure 8-21 *Burrus diode*

makes light coupling into single-mode fiber difficult due to the fiber's small N.A. and core diameter. For this reason LEDs are most often used with multimode fiber. LEDs are used in lower-data-rate, shorter-distance multimode systems because of their inherent bandwidth limitations and lower output power. The output spectrum of a typical LED is about 40 nm, which limits its performance because of severe chromatic dispersion. LEDs operate in a more linear fashion than do laser diodes. This makes them more suitable for analog modulation. Figure 8-22 shows a graph of typical output power versus drive current for LEDs and laser diodes. Notice that the LED has a more linear output power, which makes it more suitable for analog modulation. Often these devices are pigtailed, having a fiber attached during the manufacturing process. Some LEDs are available with connector-ready housings that allow a connectorized fiber to be directly attached. They are also relatively inexpensive. Typical applications are local area networks, closed-circuit TV, and transmitting information in areas where EMI may be a problem.

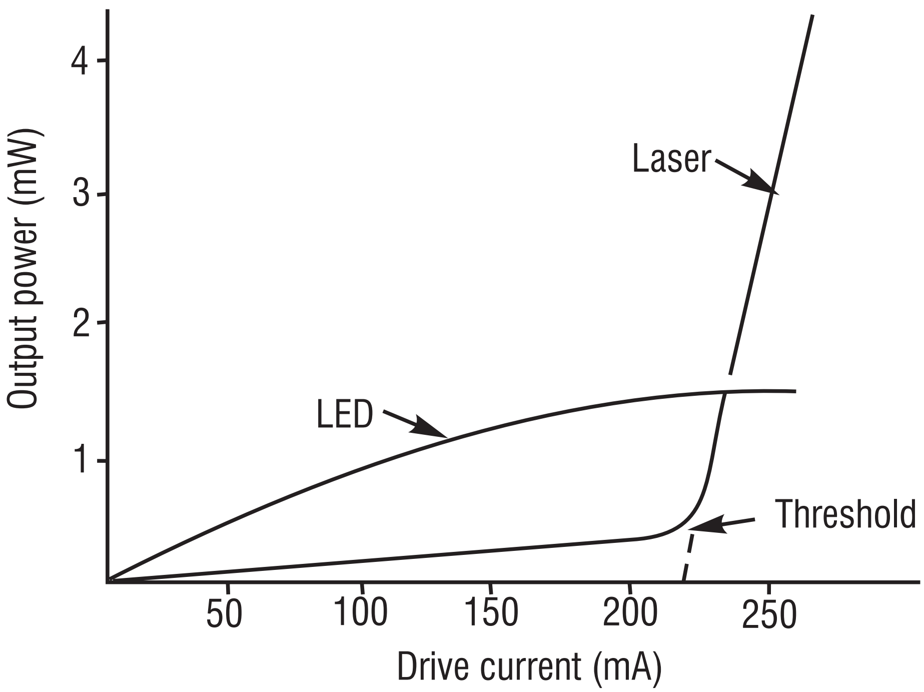


Figure 8-22 *Drive current versus output power for LED and laser* (Courtesy of AMP, Inc.)

Laser diodes (LD) are used in applications in which longer distances and higher data rates are required. Because an LD has a much higher output power than an LED, it is capable of transmitting information over longer distances. Consequently, and given the fact that the LD has a much narrower spectral width, it can provide high-bandwidth communication over long distances. The LD's smaller N.A. also allows it to be more effectively coupled with single-mode fiber. The difficulty with LDs is that they are inherently nonlinear, which makes analog transmission more difficult. They are also very sensitive to fluctuations in temperature and drive current, which causes their output wavelength to drift. In applications such as wavelength-division multiplexing in which several wavelengths are being transmitted down the same fiber, the stability of the source becomes critical. This usually requires complex circuitry and feedback mechanisms to detect and correct for drifts in wavelength. The benefits, however, of high-speed transmission using LDs typically outweigh the drawbacks and added expense.

Laser diodes can be divided into two generic types depending on the method of confinement of the lasing mode in the lateral direction.

- *Gain-guided* laser diodes work by controlling the width of the drive-current distribution; this limits the area in which lasing action can occur. Because of different confinement mechanisms in the lateral and vertical directions, the emitted wavefront from these devices has a different curvature in the two perpendicular directions. This astigmatism in the output beam is one of the unique properties of laser-diode sources. Gain-guided injection laser diodes usually emit multiple longitudinal modes and sometimes multiple transverse modes. The optical spectrum of these devices ranges up to about 2 nm in width, thereby limiting their coherence length.
- *Index-guided* laser diodes use refractive index steps to confine the lasing mode in both the transverse and vertical directions. Index guiding also generally leads to both single transverse-mode and single longitudinal-mode behavior. Typical linewidths are on the order of 0.01 nm. Index-guided lasers tend to have less difference between the two perpendicular divergence angles than do gain-guided lasers.

Single-frequency laser diodes are another interesting member of the laser diode family. These devices are now available to meet the requirements for high-bandwidth communication. Other advantages of these structures are lower threshold currents and lower power requirements. One variety of this type of structure is the *distributed-feedback (DFB)* laser diode (Figure 8-23). With introduction of a corrugated structure into the cavity of the laser, only light of a very specific wavelength is diffracted and allowed to oscillate. This yields output wavelengths that are extremely narrow—a characteristic required for DWDM systems in which many closely spaced wavelengths are transmitted through the same fiber. Distributed-feedback lasers have been developed to emit light at fiber optic communication wavelengths between 1300 nm and 1550 nm.

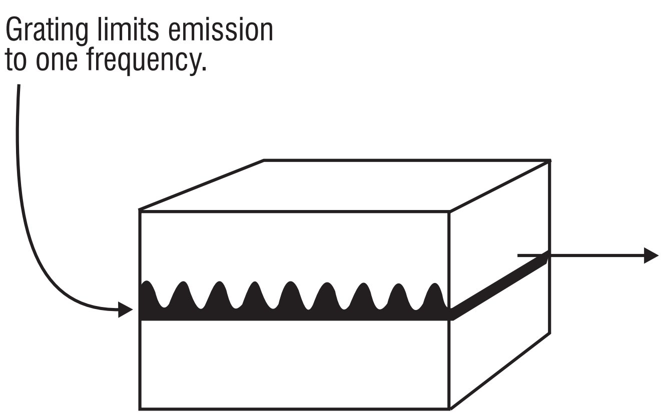


Figure 8-23 *Distributed-feedback laser*

XIII. PACKAGING

Laser diodes are available in a variety of packages. Most have monitoring photodiodes integrated with the packages. Because lasers inherently emit light from both ends of the cavity, a photodiode can be placed on one end to monitor and maintain the output power at a certain level. One of the most popular types of packages is the TO-can style (Figure 8-24) available in both 5.6-mm and 9-mm-diameter sizes. Either style can be purchased with connectorized fiber pigtails for convenience. Devices used in telecommunication typically come in either 14-pin *butterfly* or *dual-in-line* (DIL) packages as shown in Figures 8-25 and 8-26. These devices typically include thermoelectric coolers (TEC) and mounting plates for heat-sinking.

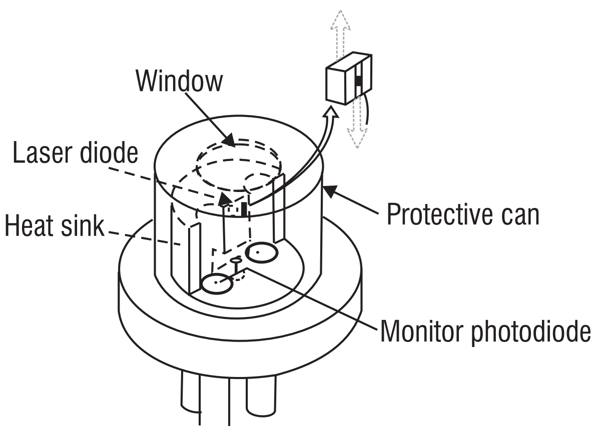


Figure 8-24 *Laser diode in TO-can style package* (Courtesy of Newport Corp.)

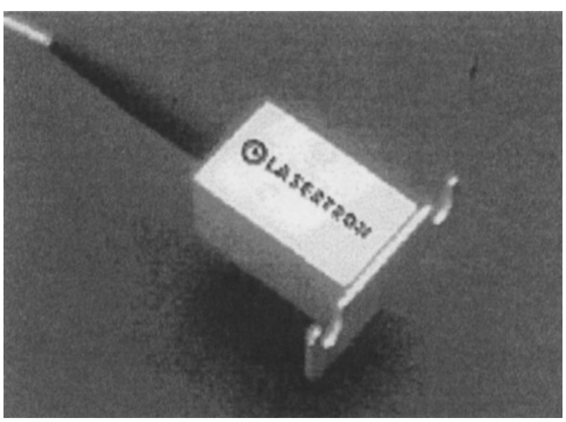


Figure 8-25 *14-pin DIL package* (Courtesy of Lasertron)

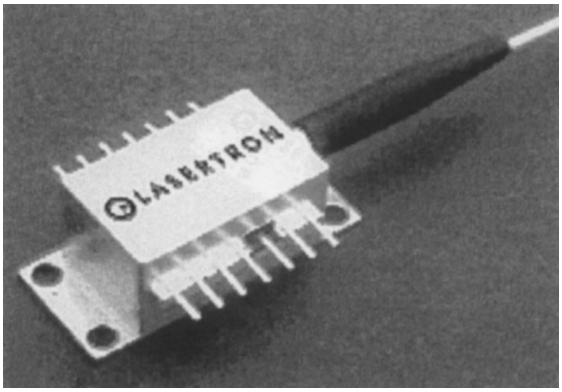


Figure 8-26 *1550-nm DFB laser in butterfly package* (Courtesy of Lasertron)

XIV. DIRECT VERSUS EXTERNAL MODULATION

Lasers and LEDs used in telecommunication applications are modulated using one of two methods: *direct modulation* or *external modulation*.

- In direct modulation (Figure 8-27), the output power of the device varies directly with the input drive current. Both LEDs and lasers can be directly modulated using analog and digital signals. The benefit of direct modulation is that it is simple and cheap. The disadvantage is that it is slower than indirect modulation with limits of less than approximately 3 GHz.

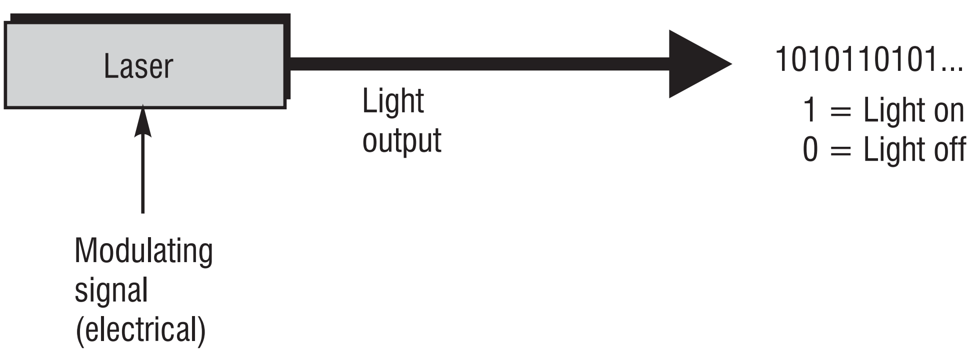


Figure 8-27 *Direct modulation*

- In external modulation (Figure 8-28), an external device is used to modulate the intensity or phase of the light source. The light source remains on while the external modulator acts like a “shutter” controlled by the information being transmitted. External modulation is typically used in high-speed applications such as long-haul telecommunication or cable TV head ends. The benefits of external modulation are that it is much faster and can be used with higher-power laser sources. The disadvantage is that it is more expensive and requires complex circuitry to handle the high frequency RF modulation signal.

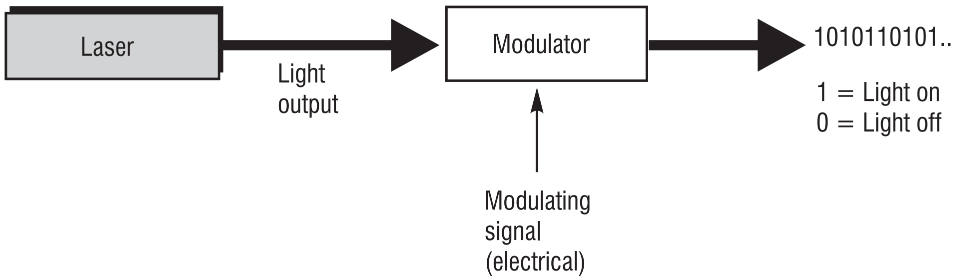


Figure 8-28 *External modulation*

External modulation is typically accomplished using an integrated optical modulator that incorporates a waveguide Mach-Zehnder interferometer fabricated on a slab of lithium niobate ($LiNbO_3$). The waveguide is created using a lithographic process similar to that used in the manufacturing of semiconductors. The waveguide region is slightly doped with impurities to increase the index of refraction so that the light is guided through the device (Figure 8-29).

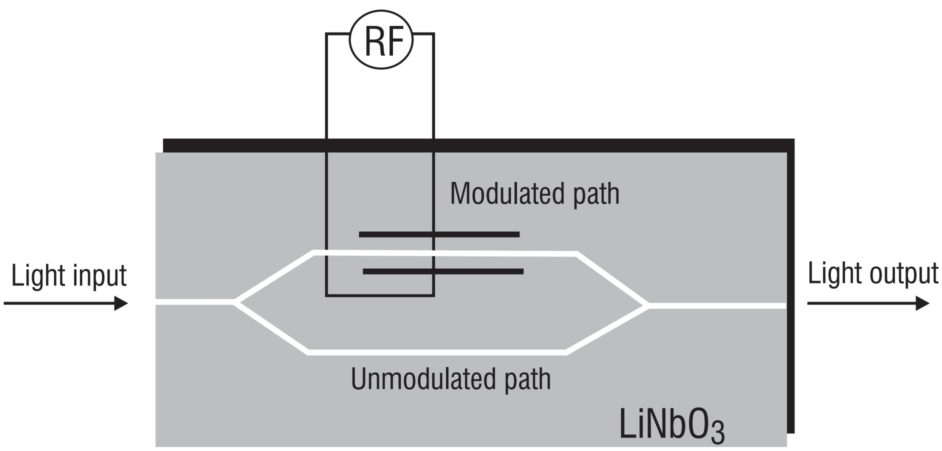


Figure 8-29 *External modulation using Mach-Zehnder waveguide interferometer*

Light entering the modulator (via fiber pigtail) is split into two paths. One path is unchanged or unmodulated. The other path has electrodes placed across it. Because $LiNbO_3$ is an *electro-optic material*, when a voltage is placed across the waveguide its index of refraction is changed, causing a phase delay proportional to the amplitude of the applied voltage. When the light is then recombined, the two waves interfere with one another. If the two waves are in phase, the interference is constructive and the output is on. If the two waves are out of phase, the interference is destructive and the waves cancel each other. The input voltage associated with a 180° phase shift is known as V_π . The induced phase shift can be calculated using:

$$\boxed{\text{Phase shift} = \Delta\theta = 180° \times V_{\text{in}}/V_\pi} \qquad (8\text{-}18)$$

where V_{in} is the voltage applied to the modulator. Lithium niobate modulators are well developed and used extensively in both CATV and telecommunication applications. Devices are available at both the 1310-nm and 1550-nm wavelengths.

XV. FIBER OPTIC DETECTORS

The purpose of a fiber optic detector is to convert light emanating from the optical fiber back into an electrical signal. The choice of a fiber optic detector depends on several factors including wavelength, responsivity, and speed or rise time. Figure 8-30 depicts the various types of detectors and their spectral responses.

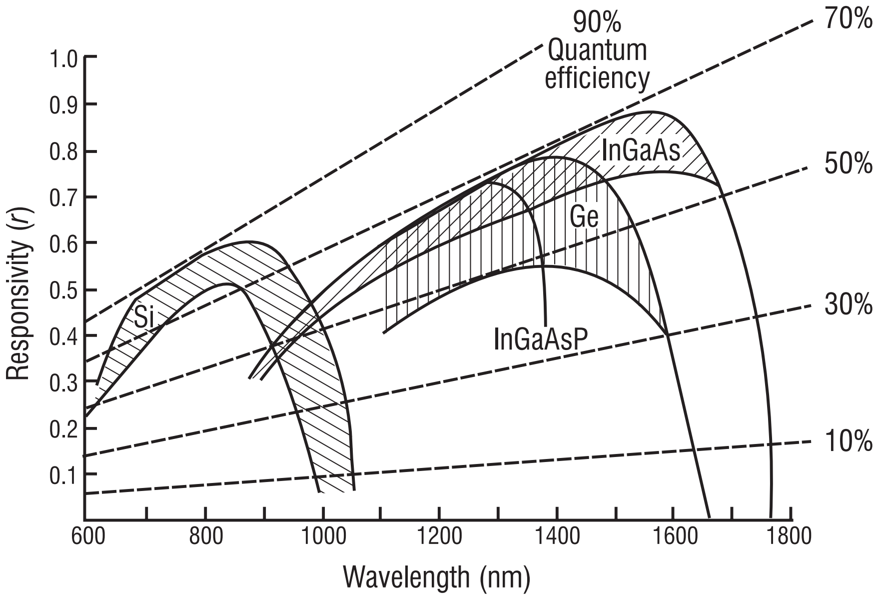


Figure 8-30 *Detector spectral response*

The process by which light is converted into an electrical signal is the opposite of the process that produces the light. Light striking the detector generates a small electrical current that is amplified by an external circuit. Absorbed photons excite electrons from the valence band to the conduction band, resulting in the creation of an electron-hole pair. Under the influence of a bias voltage these carriers move through the material and induce a current in the external circuit. For each electron-hole pair created, the result is an electron flowing in the circuit. Typical current levels are small and require some amplification as shown in Figure 8-31.

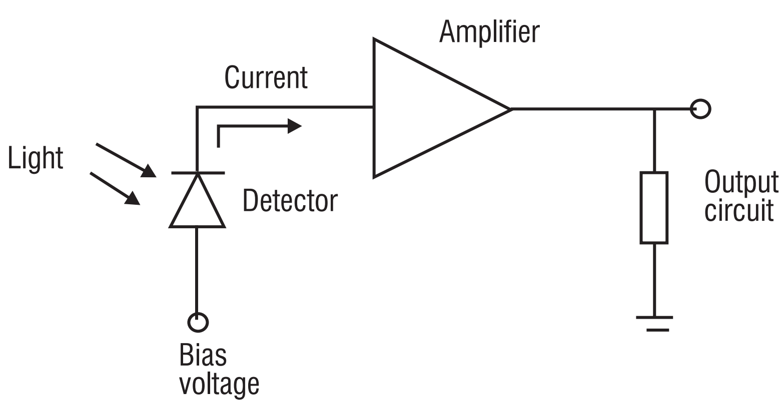


Figure 8-31 *Typical detector amplifier circuit*

The most commonly used photodetectors are the PIN and avalanche photodiodes (APD). The material composition of the device determines the wavelength sensitivity. In general, silicon devices are used for detection in the visible portion of the spectrum; InGaAs crystal are used in the near-infrared portion of the spectrum between 1000 nm and 1700 nm, and germanium PIN and APDs are used between 800 nm and 1500 nm. Table 8-5 gives some typical photodetector characteristics:

Table 8-5 Typical Photodetector Characteristics

Photodetector	Wavelength (nm)	Responsivity (A/W)	Dark Current (nA)	Rise Time (ns)
Silicon PN	550–850	0.4–0.7	1–5	5–10
Silicon PIN	850–950	0.6–0.8	10	0.070
InGaAs PIN	1310–1550	0.85	0.5–1.0	0.005–5
InGaAs APD	1310–1550	0.80	30	0.100
Germanium	1000–1500	0.70	1000	12

Some of the more important detector parameters listed below are defined and described in Module 1-6, *Optical Detectors and Human Vision.*

Responsivity—the ratio of the electrical power to the detector's output optical power

Quantum efficiency—the ratio of the number of electrons generated by the detector to the number of photons incident on the detector

Quantum efficiency = (Number of electrons)/Photon

Dark current—the amount of current generated by the detector with no light applied. Dark current increases about 10% for each temperature increase of 1°C and is much more prominent in Ge and InGaAs at longer wavelengths than in silicon at shorter wavelengths.

Noise floor—minimum detectable power that a detector can handle. The noise floor is related to the dark current since the dark current will set the lower limit.

Noise floor = Noise (A)/Responsivity (A/W)

Response time—the time required for the detector to respond to an optical input. The response time is related to the bandwidth of the detector by

$$BW = 0.35/t_r$$

where t_r is the rise time of the device. The rise time is the time required for the detector to rise to a value equal to 63.2% of its final steady-state reading.

Noise equivalent power (NEP)—at a given modulation frequency, wavelength, and noise bandwidth, the incident radiant power that produces a signal-to-noise ratio of *one* at the output of the detector (Source: Electronic Industry Association—EIA)

XVI. FIBER OPTIC SYSTEM DESIGN CONSIDERATIONS

When designing a fiber optic communication system some of the following factors must be taken into consideration:

- Which modulation and multiplexing technique is best suited for the particular application?
- Is enough power available at the receiver (power budget)?
- Rise-time and bandwidth characteristics
- Noise effects on system bandwidth, data rate, and bit error rate
- Are erbium-doped fiber amplifiers required?
- What type of fiber is best suited for the application?
- Cost

A. Power Budget

The power arriving at the detector must be sufficient to allow clean detection with few errors. Clearly, the signal at the receiver must be larger than the noise. The power at the detector, P_r, must be above the threshold level or *receiver sensitivity* P_s.

$$\boxed{P_r \geq P_s} \qquad (8\text{-}19)$$

The receiver sensitivity P_s is the signal power, in dBm, at the receiver that results in a particular bit error rate (BER). Typically the BER is chosen to be one error in 10^9 bits or 10^{-9}.

Example 7

A receiver has sensitivity P_s of –45 dBm and a BER of 10^{-9}. What is the minimum power that must be incident on the detector?

Solution: Use Equation 8-3 to find the source power in milliwatts, given the power sensitivity in dBm. Thus,

$$-45 \text{ dBm} = 10 \log\left(\frac{P}{1 \text{ mW}}\right)$$

so that $$P = (1 \text{ mW}) \times 10^{-4.5} = 3.16 \times 10^{-5} \text{ mW} = 31.6 \text{ nanowatts}$$

for a probability of error of 1 in 10^9.

The received power at the detector is a function of:

1. Power emanating from the light source (laser diode or LED)—(P_L)
2. Source to fiber loss (L_{sf})
3. Fiber loss per km (F_L) for a length of fiber (L)
4. Connector or splice losses (L_{conn})
5. Fiber to detector loss (L_{fd})

The allocation of power loss among system components is the *power budget*. The *power margin* is the difference between the received power P_r and the receiver sensitivity P_s by some margin L_m.

$$\boxed{L_m = P_r - P_s} \tag{8-20}$$

where L_m is the loss margin in dB

P_r is the received power

P_s is the receiver sensitivity in dBm

If all of the loss mechanisms in the system are taken into consideration, the loss margin can be expressed as Equation 8-21.

$$\boxed{L_m = P_L - L_{sf} - (F_L \times L) - L_{conn} - L_{fd} - P_s} \tag{8-21}$$

All units are dB and dBm.

Example 8

A system has the following characteristics:

LED power (P_L) = 2 mW (3 dBm)

LED to fiber loss (L_{sf}) = 3 dB

Fiber loss per km (F_L) = 0.5 dB/km

Fiber length (L) = 40 km

Connector loss (L_{conn}) = 1 dB (one connector between two 20-m fiber lengths)

Fiber to detector loss (L_{fd}) = 3 dB

Receiver sensitivity (P_s) = –36 dBm

Find the loss margin.

Solution:

L_m = 3 dBm – 3 dB – (40 km × 0.5 dB/km) – 1 dB – 3 dB – (–36 dBm) = 12 dB

This particular fiber optic loss budget is illustrated in Figure 8-32, with each loss graphically depicted.

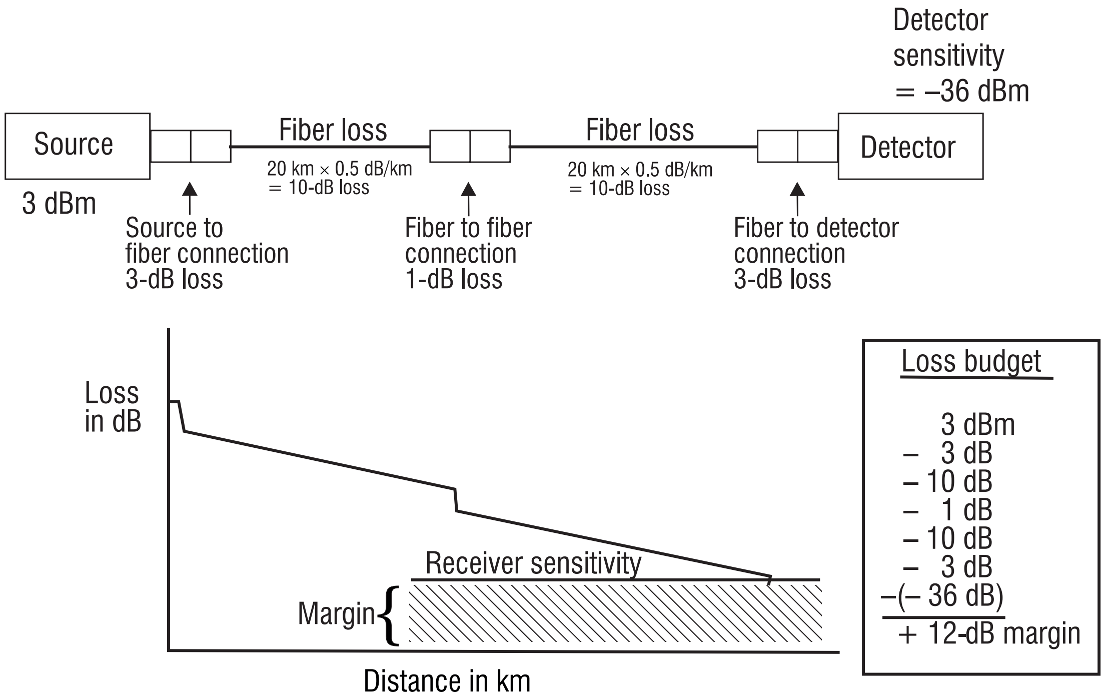


Figure 8-32 *Fiber optic loss budget*

B. Bandwidth and Rise Time Budgets

The transmission data rate of a digital fiber optic communication system is limited by the rise time of the various components, such as amplifiers and LEDs, and the dispersion of the fiber. The cumulative effect of all the components should not limit the bandwidth of the system. The rise time t_r and bandwidth BW are related by

$$\boxed{\mathrm{BW} = 0.35/t_r} \qquad (8\text{-}22)$$

This equation is used to determine the required system rise time. The appropriate components are then selected to meet the system rise time requirements. The relationship between total system rise time and component rise time is given by Equation 8-23

$$\boxed{t_s = (t_{r1}^2 + t_{r2}^2 + t_{r3}^2 + \cdots)^{1/2}} \qquad (8\text{-}23)$$

where t_s is the total system rise time and t_{r1}, t_{r2}, ... are the rise times associated with the various components.

To simplify matters, divide the system into five groups:

1. Transmitting circuits (t_{tc})
2. LED or laser (t_L)
3. Fiber dispersion (t_f)
4. Photodiode (t_{ph})
5. Receiver circuits (t_{rc})

The system rise time can then be expressed as

$$\boxed{t_s = (t_{tc}^{\ 2} + t_L^{\ 2} + t_f^{\ 2} + t_{ph}^{\ 2} + t_{rc}^{\ 2})^{1/2}} \tag{8-24}$$

The system bandwidth can then be calculated using Equation 8-25 from the total rise time t_s as given in Equation 8-24.

$$\boxed{BW = 0.35/t_s} \tag{8-25}$$

Electrical and Optical Bandwidth

- *Electrical bandwidth* (BW_{el}) is defined as the frequency at which the ratio *current out/current in* (I_{out}/I_{in}) drops to 0.707. (Analog systems are usually specified in terms of electrical bandwidth.)
- *Optical bandwidth* (BW_{opt}) is the frequency at which the ratio *power out/power in* (P_{out}/P_{in}) drops to 0.5.

Because P_{in} and P_{out} are directly proportional to I_{in} and I_{out} (not I^2_{in} and I^2_{out}), the half-power point is equivalent to the half-current point. This results in a BW_{opt} that is larger than the BW_{el} as given in Equation 8-26.

$$\boxed{BW_{el} = 0.707 \times BW_{opt}} \tag{8-26}$$

Example 9

A 10-km fiber with a BW × length product of 1000 MHz × km (optical bandwidth) is used in a communication system. The rise times of the other components are t_{tc} = 10 ns, t_L = 2 ns, t_{ph} = 3 ns, and t_{rc} = 12 ns. Calculate the *electrical* BW for the system.

Solution:

Because we are looking for the electrical BW, first calculate the electrical BW of the 2-km fiber from the optical BW and then calculate the rise time $t_r = t_f$.

$$BW_{opt} = (1000 \text{ MHz} \times \text{km})/10 \text{ km} = 100 \text{ MHz}$$

$$BW_{el} = 0.707 \times 100 \text{ MHz} = 70.7 \text{ MHz}$$

The fiber rise time is

$$t_r = t_f = 0.35/(70.7 \text{ MHz}) = 4.95 \text{ ns}$$

The system rise time is

$$t_s = (10^2 + 2^2 + 4.95^2 + 3^2 + 12^2)^{1/2} = 16.8 \text{ ns}$$

System BW_{el} is

$$BW_{el} = 0.35/(16.8 \times 10^{-9}) = 20.8 \text{ Mhz}$$

C. Connectors

Many types of connectors are available for fiber optics, depending on the application. The most popular are:

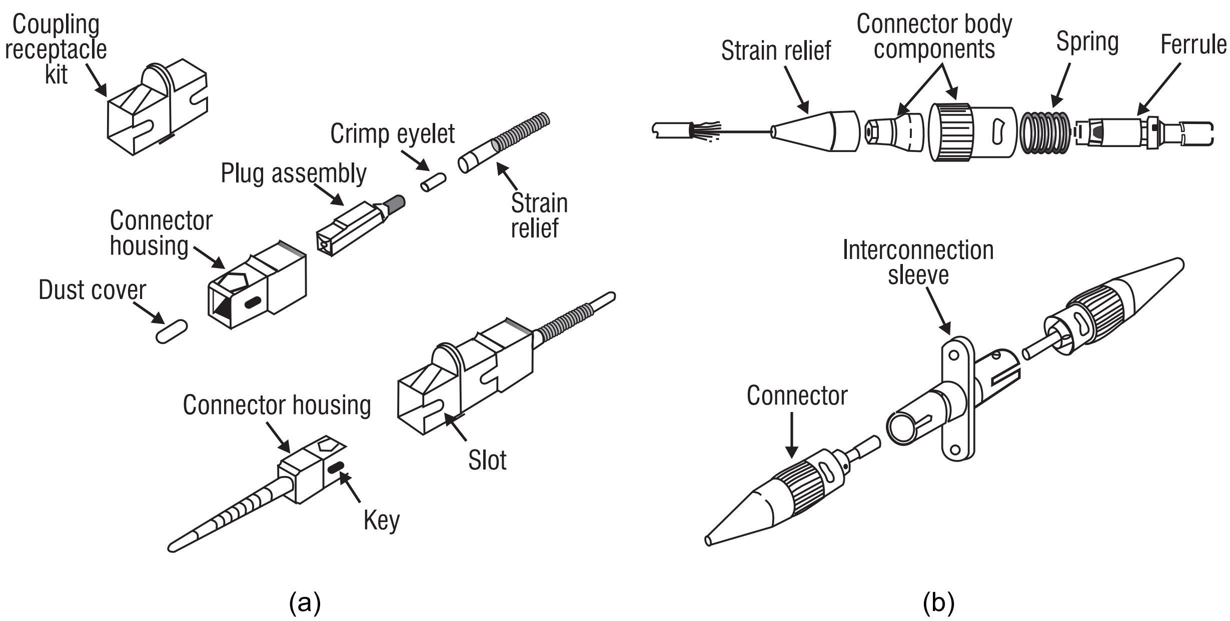
SC—snap-in single-fiber connector

ST and FC—twist-on single-fiber connector

FDDI—fiber distributed data interface connector

In the 1980s, there were many different types and manufacturers of connectors. Today, the industry has shifted to standardized connector types, with details specified by organizations such as the Telecommunications Industry Association, the International Electrotechnical Commission, and the Electronic Industry Association.

Snap-in connector (SC)—developed by Nippon Telegraph and Telephone of Japan. Like most fiber connectors, it is built around a cylindrical ferrule that holds the fiber, and it mates with an interconnection adapter or coupling receptacle. A push on the connector latches it into place, with no need to turn it in a tight space, so a simple tug will not unplug it. It has a square cross section that allows high packing density on patch panels and makes it easy to package in a polarized duplex form that ensures the fibers are matched to the proper fibers in the mated connector (Figure 8-33a).



Courtesy of Siecor, Inc.

Figure 8-33 (a) *SC connector* (b) *ST connector*

Twist-on single-fiber connectors (ST and FC)—long used in data communication; one of several fiber connectors that evolved from designs originally used for copper coaxial cables (see Figure 8-33b)

Duplex connectors—A duplex connector includes a pair of fibers and generally has an internal key so it can be mated in only one orientation. Polarizing the connector in this way is important because most systems use separate fibers to carry signals in each direction, so it matters which fibers are connected. One simple type of duplex connector is a pair of SC connectors, mounted side by side in a single case. This takes advantage of their plug-in-lock design.

Other duplex connectors have been developed for specific types of networks, as part of comprehensive standards. One example is the fixed-shroud duplex (FSD) connector specified by the fiber distributed data interface (FDDI) standard (see Figure 8-34).

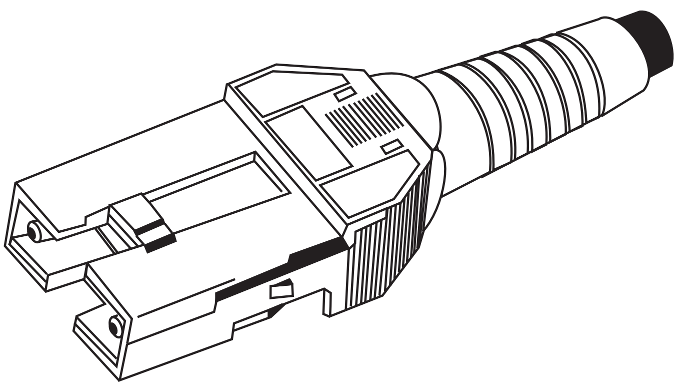


Figure 8-34 *FDDI connector*

D. Fiber Optic Couplers

A fiber optic coupler is a device used to connect a single (or multiple) fiber to many other separate fibers. There are two general categories of couplers:

- Star couplers (Figure 8-35a)
- T-couplers (Figure 8-35b)

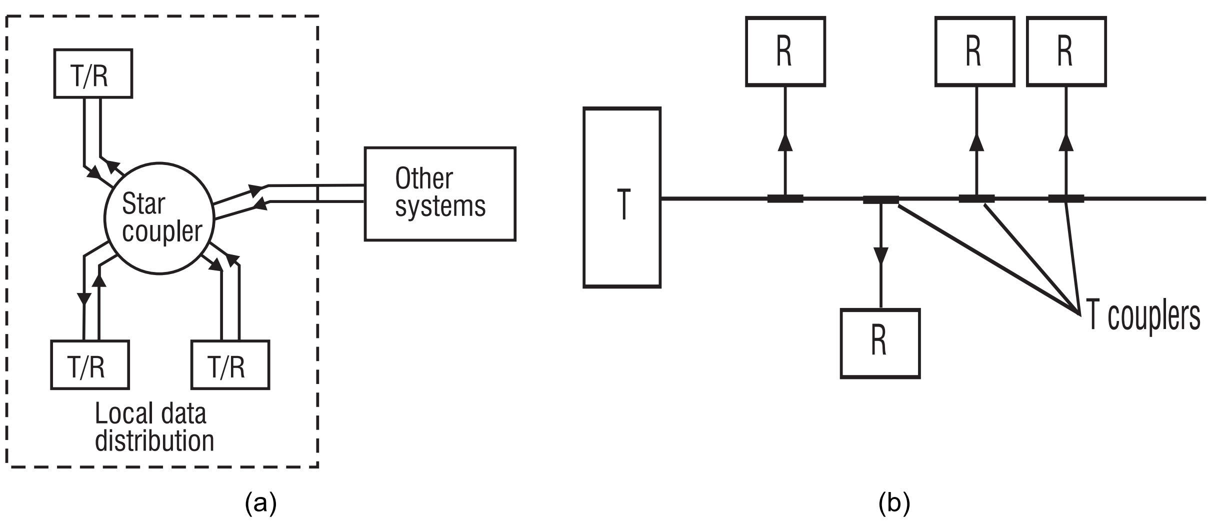


Figure 8-35 (a) *Star coupler* (b) *T-coupler*

Transmissive type

Optical signals sent into a mixing block are available at all output fibers (Figure 8-36). Power is distributed evenly. For an $n \times n$ star coupler (n-inputs and n-outputs), the power available at each output fiber is $1/n$ the power of any input fiber.

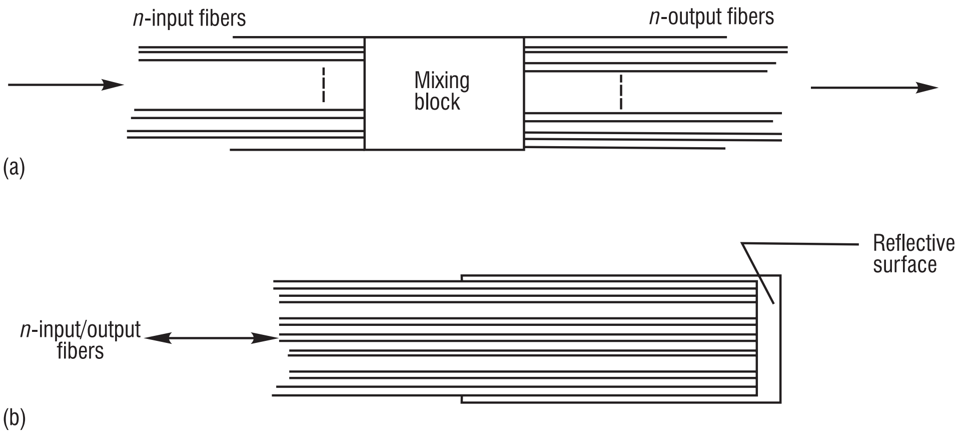


Figure 8-36 *Star couplers* (a) *Transmissive* (b) *Reflective*

The output power from a star coupler is simply

$$\boxed{P_o = P_{in}/n} \tag{8-27}$$

where n = number of output fibers.

The **power division** (power splitting ratio) in decibels is given by Equation 8-28.

$$\boxed{PD_{st}(\text{dB}) = -10 \log(1/n)} \tag{8-28}$$

The power division in decibels gives the number of decibels apparently lost in the coupler from single input fiber to single fiber output. **Excess power loss** (Loss_{ex}) is the power lost from input to *total* output, as given in Equation 8-29 or 8-30.

$$\boxed{\text{Loss}_{ex} = \frac{P_{out}(\text{total})}{\text{P}_{in}}} \tag{8-29}$$

$$\boxed{\text{Loss}_{ex/dB} = -10 \log \frac{P_{out}(\text{total})}{P_{in}}} \tag{8-30}$$

Example 10

An 8×8 star coupler is used in a fiber optic system to connect the signal from one computer to eight terminals. If the power at an input fiber to the star coupler is 0.5 mW, find (1) the power at each output fiber and (2) the power division in decibels.

Solution:

1. The 0.5-mW input is distributed to eight fibers. Each has (0.50 mW)/8 = 0.0625 mW.
2. The power division, in decibels, from Equation 8-28 is

$$PD_{ST} = -10 \times \log(1/8) = 9.03 \text{ dB}$$

Example 11

A 10 × 10 star coupler is used to distribute the 3-dBm power of a laser diode to 10 fibers. The excess loss ($Loss_{ex}$) of the coupler is 2 dB. Find the power at each output fiber in dBm and μW.

Solution:

The power division in dB from Equation 8.28 is

$$PD_{st} = -10 \times \log(1/10) = 10 \text{ dB}$$

To find P_{out} for each fiber, subtract PD_{st} and $Loss_{ex}$ from P_{in} in dBm:

$$3 \text{ dBm} - 10 \text{ dB} — 2 \text{ dB} = -9 \text{ dBm}$$

To find P_{out} in watts we use Equation 8-3:

$$-9 = 10 \times \log(P_{out}/1 \text{ mW})$$

$$P_{out} = (1 \text{ mW})(10^{-0.9})$$

Solving, we get

$$P_{out} = 126 \text{ μW}$$

An important characteristic of transmissive star couplers is *cross talk* or the amount of input information coupled into another input. Cross coupling is given in decibels and is typically greater than 40 dB.

The **reflective star coupler** has the same power division as the transmissive type, but cross talk is not an issue because power from any fiber is distributed to all others.

T-couplers

In Figure 8-37, power is launched into port 1 and is split between ports 2 and 3. The power split does not have to be equal. The power division is given in decibels or in percent. For example, and 80/20 split means 80% to port 2, 20% to port 3. In decibels, this corresponds to 0.97 dB for port 2 and 6.9 dB for port 3.

Figure 8-37 *T-coupler*

$$10 \log (P_2/P_1) = -0.97 \text{ dB}$$

$$10 \log (P_3/P_1) = -6.96 \text{ dB}$$

Directivity describes the transmission between the ports. For example, if $P_3/P_1 = 0.5$, P_3/P_2 does not necessarily equal 0.5. For a highly directive T-coupler, P_3/P_2 is very small. Typically, no power is expected to be transferred between any two ports on the same side of the coupler.

Another type of T-coupler uses a graded-index (GRIN) lens and a partially reflective surface to accomplish the coupling. The power division is a function of the reflecting mirror. This coupler is often used to monitor optical power in a fiber optic line.

E. Wavelength-Division Multiplexers

The couplers used for wavelength-division multiplexing (WDM) are designed specifically to make the coupling between ports a function of wavelength. The purpose of these couplers is to separate (or combine) signals transmitted at different wavelengths. Essentially, the transmitting coupler is a mixer and the receiving coupler is a wavelength filter. Wavelength-division multiplexers use several methods to separate different wavelengths depending on the spacing between the wavelengths. Separation of 1310 nm and 1550 nm is a simple operation and can be achieved with WDMs using bulk optical diffraction gratings. Wavelengths in the 1550-nm range that are spaced at greater than 1 to 2 nm can be resolved using WDMs that incorporate interference filters. An example of an 8-channel WDM using interference filters is given in Figure 8-38. Fiber Bragg gratings are typically used to separate very closely spaced wavelengths in a DWDM system (< 0.8 nm).

(Courtesy of DiCon, Inc.)

Figure 8-38 *8-channel WDM*

Erbium-doped fiber amplifiers (EDFA)—The EDFA is an optical amplifier used to boost the signal level in the 1530-nm to 1570-nm region of the spectrum. When it is pumped by an external laser source of either 980 nm or 1480 nm, signal gain can be as high as 30 dB (1000 times). Because EDFAs allow signals to be regenerated without having to be converted back to electrical signals, systems are faster and more reliable. When used in conjunction with wavelength-division multiplexing, fiber optic systems can transmit enormous amounts of information over long distances with very high reliability.

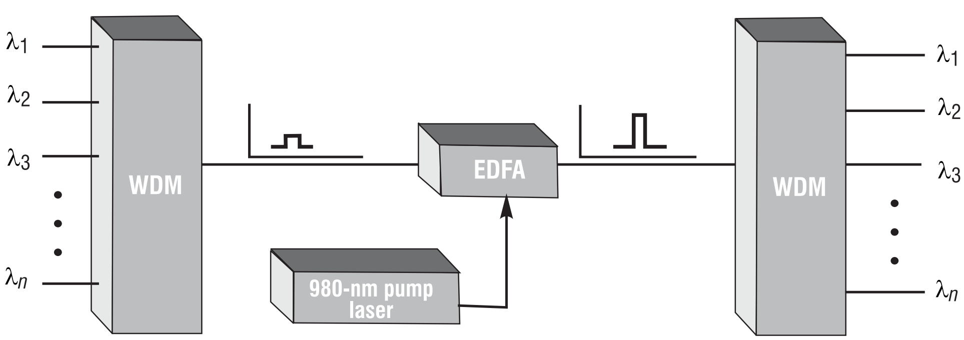


Figure 8-39 *Wavelength-division multiplexing system using EDFAs*

Fiber Bragg gratings—Fiber Bragg gratings are devices that are used for separating wavelengths through diffraction, similar to a diffraction grating (see Figure 8-40). They are of critical importance in DWDM systems in which multiple closely spaced wavelengths require separation. Light entering the fiber Bragg grating is diffracted by the induced period variations in the index of refraction. By spacing the periodic variations at multiples of the half-wavelength of the desired signal, each variation reflects light with a 360° phase shift causing a constructive interference of a very specific wavelength while allowing others to pass. Fiber Bragg gratings

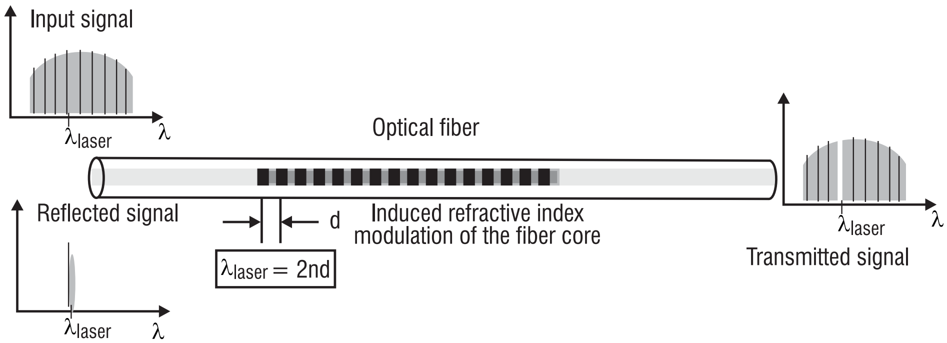
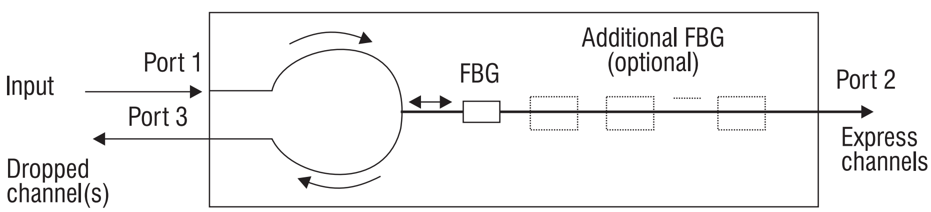


Figure 8-40 *Fiber Bragg grating*

are available with bandwidths ranging from 0.05 nm to >20 nm. Fiber Bragg grating are typically used in conjunction with *circulators*, which are used to drop single or multiple narrow-band WDM channels and to pass other "express" channels (see Figure 8-41). Fiber Bragg gratings have emerged as a major factor, along with EDFAs, in increasing the capacity of next-generation high-bandwidth fiber optic systems.



Courtesy of JDS-Uniphase

Figure 8-41 *Fiber optic circulator*

Figure 8-42 depicts a typical scenario in which DWDM and EDFA technology is used to transmit a number of different channels of high-bandwidth information over a single fiber. As shown, *n*-individual wavelengths of light operating in accordance with the ITU grid are multiplexed together using a multichannel coupler/splitter or wavelength-division multiplexer. An *optical isolator* is used with each optical source to minimize troublesome back reflections. A tap coupler then removes 3% of the transmitted signal for wavelength and power monitoring. Upon traveling through a substantial length of fiber (50-100 Km), an EDFA is used to boost the signal strength. After a couple of stages of amplifications, an add/drop channel consisting of a fiber Bragg grating and circulator is introduced to extract and then reinject the signal operating at the λ_3 wavelength. After another stage of amplification via EDFA, a *broadband* WDM is used to combine a 1310-nm signal with the 1550-nm window signals. At the receiver end, another broadband WDM extracts the 1310-nm signal, leaving the 1550-nm window signals. The 1550-nm window signals are finally separated using a DWDM that employs an array of fiber Bragg gratings, each tuned to the specific transmission wavelength. This system represents the current state of the art in high-bandwidth fiber optic data transmission.

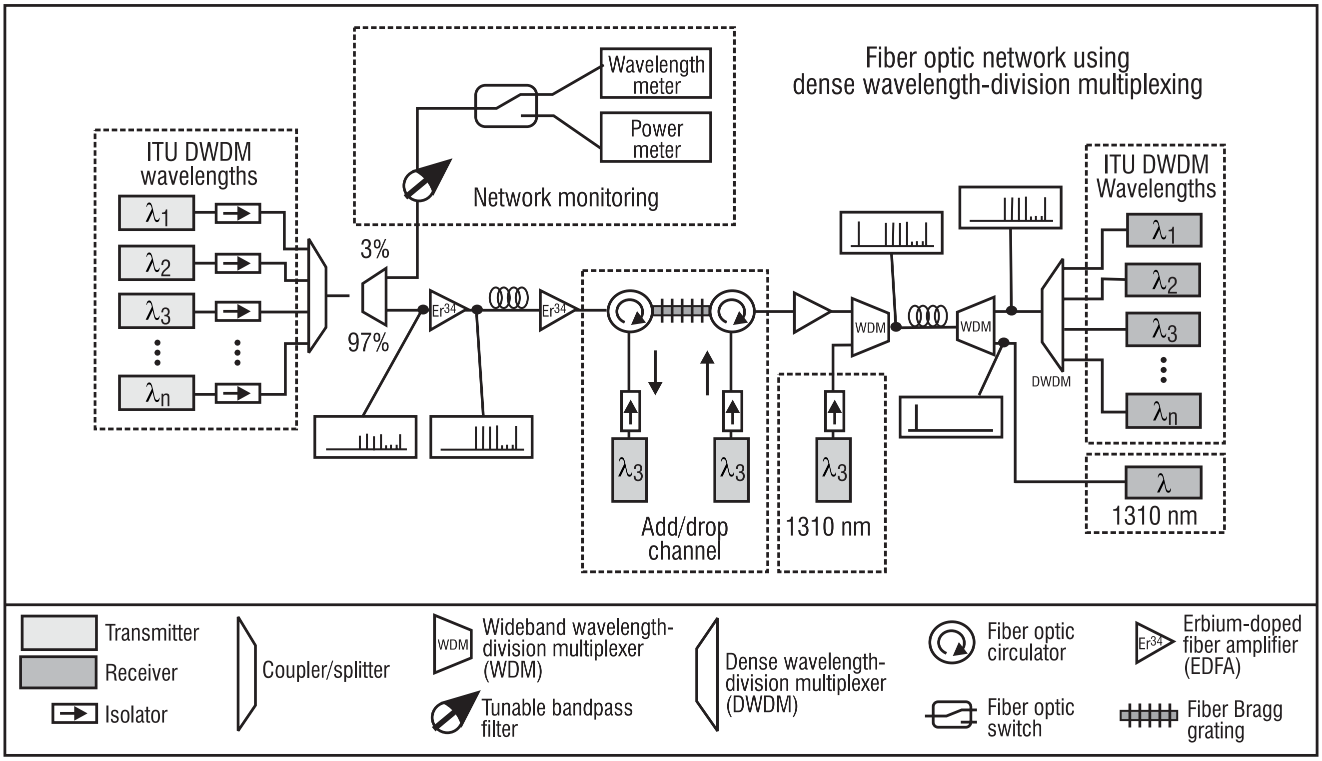


Figure 8-42 *Typical DWDM transmission system* (Courtesy of Newport Corporation)

What's ahead?

Over the past five years, major breakthroughs in technology have been the impetus for tremendous growth experienced by the fiber optic industry. The development of EDFAs, fiber Bragg gratings and DWDM, as well as advances in optical sources and detectors that operate in the 1550-nm range, have all contributed to advancing the fiber optics industry to one of the fastest growing and most important industries in telecommunication today. As the industry continues to grow, frustrating bottlenecks in the "information superhighway" will lessen, which will in turn usher in the next generation of services, such as telemedicine, Internet telephony, distance education, e-commerce, and high-speed data and video. More recent advances in EDFAs that operate at 1310-nm and 1590-nm technology will allow further enhancement in fiber optic systems. The future is bright. Just remember, the information superhighway is paved with glass!

Problem Exercises/Questions

1. A fiber of 1-km length has P_{in} = 1 mW and P_{out} = 0.125 mW. Find the loss in dB/km.

2. A communication system uses 8 km of fiber that has a 0.8-dB/km loss characteristic. Find the output power if the input power is 20 mW.

3. A 5-km fiber optic system has an input power of 1 mW and a loss characteristic of 1.5 dB/km. Determine the output power.

4. What is the maximum core diameter for a fiber to operate in single mode at a wavelength of 1310 nm if the N.A. is 0.12?

5. A 1-km-length multimode fiber has a modal dispersion of 0.50 ns/km and a chromatic dispersion of 50 ps/km·nm. If it is used with an LED with a linewidth of 30 nm, (a) what is the total dispersion? (b) Calculate the bandwidth (BW) of the fiber.

6. A digital MUX operates with 16 sources. The rate of data in each source is 8000 bytes/second (assume 8 bits per byte). Data are transmitted byte by byte.
   (a) What is the data rate of the MUX output?
   (b) What is the channel switching rate?

7. A receiver has a sensitivity P_s of −40 dBm for a BER of 10^{-9}. What is the minimum power (in watts) that must be incident on the detector?

8. A system has the following characteristics:
   - LED power (P_L) = 1 mW (0 dBm)
   - LED to fiber loss (L_{sf}) = 3 dB
   - Fiber loss per km (F_L) = 0.2 dB/km
   - Fiber length (L) = 100 km
   - Connector loss (L_{conn}) = 3 dB (3 connectors spaced 25 km apart with 1 dB of loss each)
   - Fiber to detector loss (L_{fd}) = 1 dB
   - Receiver sensitivity (P_s) = −40 dBm

   Find the loss margin and sketch the power budget curve.

9. A 5-km fiber with a BW × length product of 1200 MHz × km (optical bandwidth) is used in a communication system. The rise times of the other components are t_{tc} = 5 ns, t_L = 1 ns, t_{ph} = 1.5 ns, and t_{rc} = 5 ns. Calculate the electrical BW for the system.

10. A 4 × 4 star coupler is used in a fiber optic system to connect the signal from one computer to four terminals. If the power at an input fiber to the star coupler is 1 mW, find (a) the power at each output fiber and (b) the power division in decibels.

11. An 8 × 8 star coupler is used to distribute the +3-dBm power of a laser diode to 8 fibers. The excess loss (Loss_{ex}) of the coupler is 1 dB. Find the power at each output fiber in dBm and μW.

Laboratory: Making a Fiber Optic Coupler

In this lab you will fabricate a 2 × 2 fiber optic coupler using 1-mm-diameter plastic fiber. The coupler can be used for a variety of applications including wavelength-division multiplexing and power splitting, which will be outlined in this lab.

Equipment List

The following equipment is needed to complete this laboratory.

2 1-foot sections of 1-mm-diameter plastic-jacketed fiber (Part #2705FIBOPT)[1]

1 razor blade

1 heat gun

1 4" piece of heat-shrink tubing

2 high-brightness LEDs (1 green and 1 red)

2 plastic fiber connectors (Part #2400228087-1)[1]

2 plastic fiber LED mounts (Part #2400228040-1)[1]

4 multimode ST-connectors for 1-mm fiber (Part #F1-0065)[2]

1 electronic breadboard with +5-volt supply

1 850-nm fiber optic source with ST adapter (Part #9050-0000)[2]

1 850-nm fiber optic detector with ST adapter (Part #F1-8513HH)[2]

1 low-cost diffraction grating (Part #J01-307)[3]

1 1-meter patch cord (terminated with ST connectors)

1 fiber optic termination kit (includes scissors, alcohol wipes, crimp tool, fiber-inspection microscope, razor blades, etc.)[1]

(Notations 1, 2, 3: See sources in APPENDIX.)

Procedure

PART I: Making a Fiber Optic Coupler

1. With the razor blade, carefully strip off approximately 3" of the fiber jacket in the middle of the fiber (see Figure 8-43).

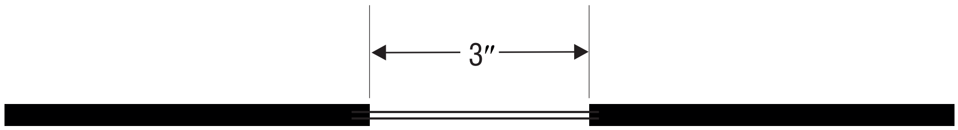


Figure 8-43

2. Where the fiber has been stripped, twist the two fibers together.

3. On each end of the stripped area, place a small weight (i.e., paperweight, book) to hold the fiber in place (see Figure 8-44).

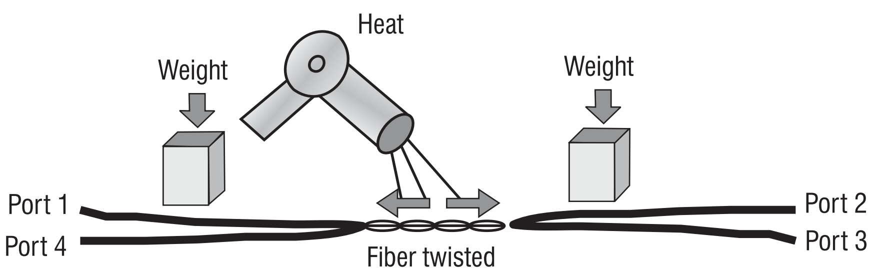


Figure 8-44

4. Using the heat gun on the low setting, apply heat to the twisted area. Move the heat gun gently back and forth to uniformly melt the fiber. CAUTION: Do not hold the heat gun stationary because the fiber will melt quickly!

5. As the fiber is heated, you will notice that it will contract a bit. This is normal. When the contraction subsides, remove the heat gun and let the fiber cool for a minute.

6. With a laser pointer or fiber optic source, shine light into port 1 of the coupler. You should observe a fair amount of coupling (~20–30%) into port 3 of the coupler. If more coupling is needed, repeat the heating process until the desired coupling is obtained.

PART II: Wavelength-Division Multiplexing Demonstration

1. Apply the AMP plastic fiber connectors to the two input fibers (ports 1 and 4) according to manufacturer's specifications. Polish the ends if necessary. Also polish the ends of the unterminated fibers if necessary.

2. On the electronic breadboard, set up the circuit shown in Figure 8-45. Depending on the type of LED, you may have to use epoxy to secure the LED in the mount.

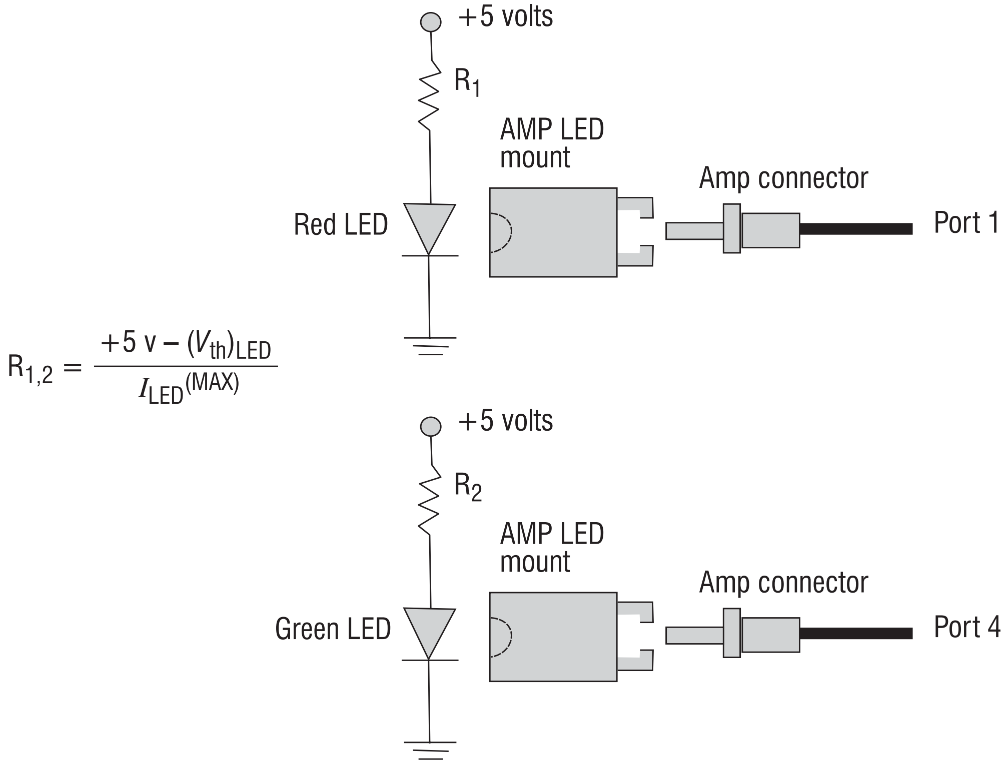


Figure 8-45

3. When the circuit is complete, connect the fibers to the LEDs and observe the output of port 2. The red and green colors will be mixed.

4. To separate the colors, observe the output of port 2 through the diffraction grating. You should observe a central bright spot (coming from the fiber) and two identical diffraction patterns—one on either side—with the red and the green separated (see Figure 8-46). To ensure that the two signals are indeed independent, turn off the LEDs one at a time and observe the output of port 2 through the diffraction grating.

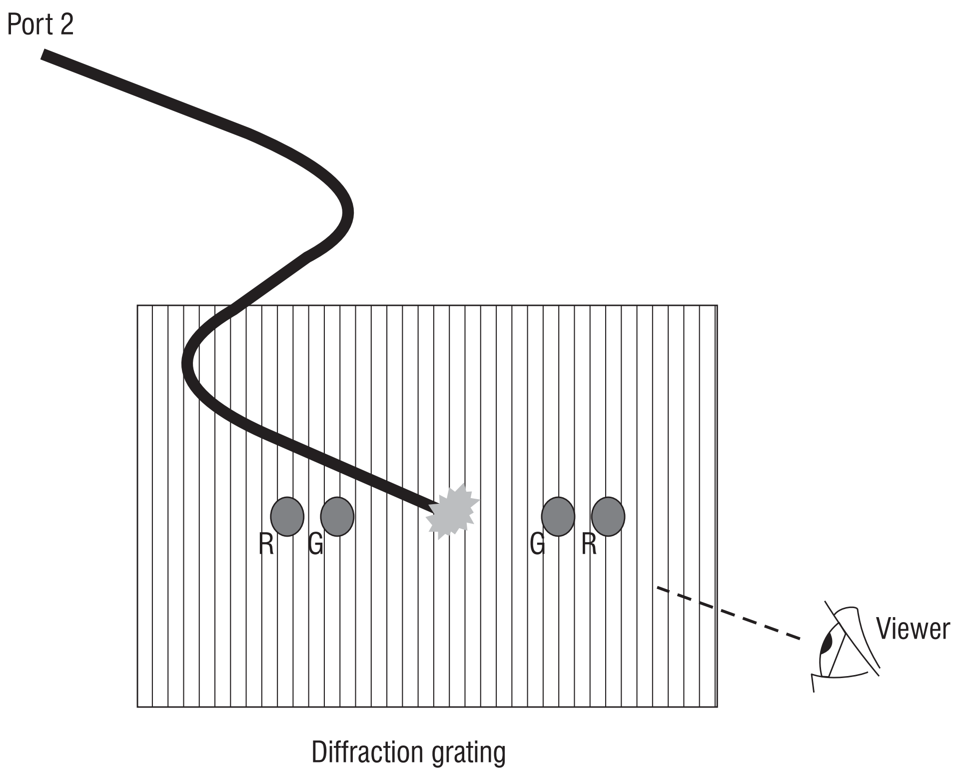


Figure 8-46

Part III: Measuring Coupler Loss

1. Repeat steps 1–6 (Part I) for fabrication of a 2 × 2 coupler.

2. "Connectorize" each port of the coupler using ST-multimode connectors and polish if necessary. (Instructions for termination are supplied with the connectors when purchased.)

3. Measure the output of your fiber optic source at the output of the patch cord. This will be the input power to the coupler. Record the power in Table 8.6.

4. Measure the output power at each of the ports and record in Table 8.6.

5. Calculate the throughput loss using the following equation:

$$L_{th} = -10 \log (P_2/P_1)$$

6. Calculate the tap loss using the following equation:

$$L_{tap} = -10 \log (P_3/P_1)$$

7. Calculate the directionality loss using the following equation:

$$L_{dir} = -10 \log (P_4/P_1)$$

8. Calculate the excess loss using the following equation:

$$L_{ex} = -10 \log (P_2 + P_3)/P_1$$

9. Repeat Part III – steps 3–9 using each port as the input. Record the results in Table 8.6.

Table 8.6

Input Port	Input Power (mW)	Throughput Loss (dB)	Directionality Loss (dB)	Tap Loss (dB)	Excess Loss (dB)
1					
2					
3					
4					

APPENDIX

1. Items may be obtained through
   Electronix Express
   365 Blair Road
   Avenel, NJ 07001
   1-800-972-2225

2. Items may be obtained through
   Fiber Instrument Sales (FIS)
   161 Clear Road
   Oriskany, NY 13424
   1-800-500-0347

3. Items may be obtained through
   Edmund Scientific, Inc.
   101 East Gloucester Pike
   Barrington, NJ 08007
   856-573-6250