Module IV : **Optical Communication**

Contents

- Optical Principles
- Optical Communication Systems
- Fiber-Optic Cables
- Optical Transmitters and Receivers
- Wavelength-Division Multiplexing
- Passive Optical Networks
- 40/100-Gbps Networks and Beyond

Optical Principles

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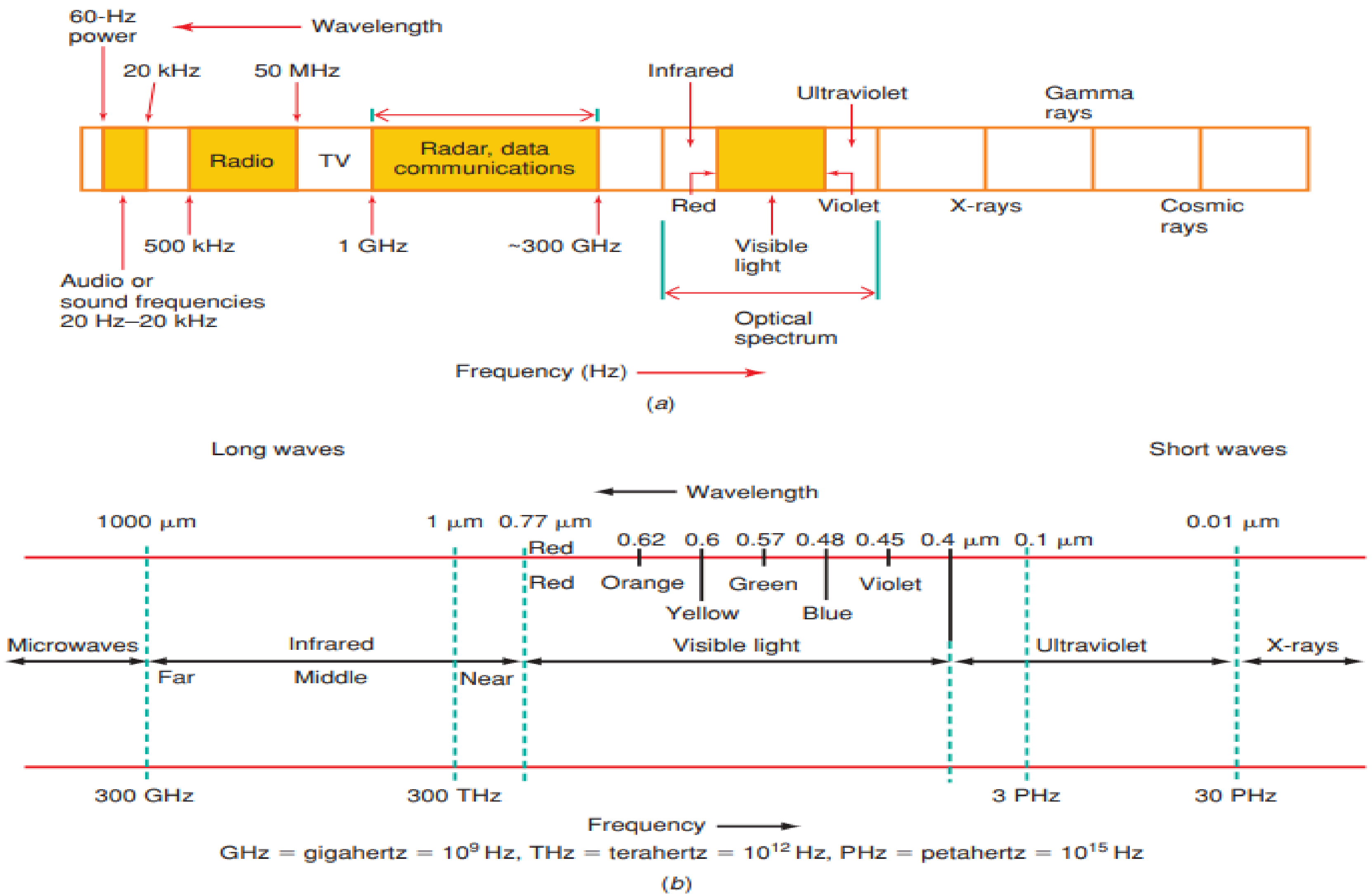
Light

- Light, radio waves, and microwaves are all forms of electromagnetic radiation. Light frequencies fall between those of microwaves and X-rays, as shown in Fig. 19-1(a).
- Radio frequencies range from approximately 10 kHz to 300 GHz.
- Microwaves extend from 1 to 300 GHz. The range of about 30 to 300 GHz is generally defined as millimeter waves.
- Further up the scale is the **optical spectrum**, made up of infrared, visible, and ultraviolet light.
- The frequency of the optical spectrum is in the range of 3×10^{11} to 3×10^{16} Hz. This includes both the **infrared and the ultraviolet bands as well as the visible parts** of the spectrum.
- The visible spectrum is from 4.3×10^{14} to 7.5×10^{14} Hz

Figure 19-1 The optical spectrum. (*a*) Electromagnetic frequency spectrum showing the optical spectrum. (*b*) Optical spectrum details.



- We rarely refer to the "frequency of light." Light is expressed in terms of wavelength. Recall that wavelength is a distance measured in meters between peaks of a wave. It is calculated with the familiar expression
- $$\boldsymbol{\lambda = c/f} = 300{,}000{,}000/f$$
- where λ (lambda) is the wavelength in meters, 300,000,000 is the speed of light in **meters** per second, and f is the frequency in hertz.
- Light waves are very short and usually expressed in nanometers (nm, one-billionth of a meter) or micrometers (μm, one-millionth of a meter)

Speed of Light.

- Light waves travel in a straight line as microwaves do. Light rays emitted by a candle, lightbulb, or other light source move out in a straight line in all directions. Light waves are assumed to have a spherical wave front as do radio waves.
- The speed of light is approximately 300,000,000 m/s, or about 186,000 mi/s, in free space

- These are the values normally used in calculation, but for a more accurate outcome, the actual values are closer to 2.998×10^8 m/s, or 186,280 mi/s.
- The **speed of light depends** upon the **medium** through which the light passes. The figures given above are correct for light traveling in free space, i.e., for light traveling in air or a vacuum.
- When light passes through another material such as glass, water, or plastic, its speed is slower
- Another unit of measure for light wavelength is the angstrom. One angstrom (Å) is equal to 10^{-10} m or 10^{-4} µm. To say it the other way, 1 µm equals 10,000 Å.

Physical Optics:

- Physical optics refers to the ways that light can be processed. Light can be processed or manipulated in many ways.
- For example, lenses are widely used to focus, enlarge, or decrease the size of light waves from **some source**

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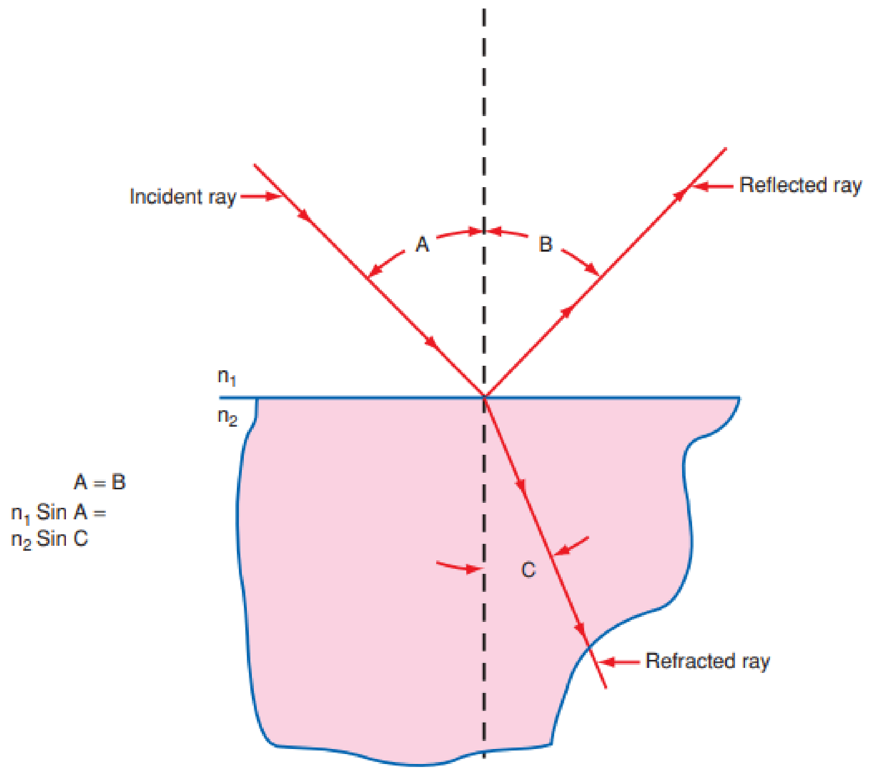
Reflection

- The simplest way of manipulating light is to reflect it. When light rays strike a reflective surface, such as a mirror, the light waves are thrown back or reflected. By using mirrors, the direction of a light beam can be changed.
- Assume an imaginary line that is perpendicular with the flat mirror surface. A perpendicular line, of course, makes a **right angle with the surface**, as shown.
- This imaginary perpendicular line is referred to as **the normal**. The normal is usually drawn at the point where the mirror reflects the light beam. If the light beam follows the normal, the reflection will simply go back along the same path.
- The reflected light ray will exactly coincide with the original light ray. If the light ray strikes the mirror at some angle A from the normal, the reflected light ray will leave the mirror at the same angle B to the normal. This principle is known as the law of reflection. It is usually expressed in the following form: The angle of incidence is **equal** to the angle of reflection. A=B

- The light ray from the light source is usually called the incident ray. It makes an angle A with the normal at the reflecting surface, called the angle of incidence. The reflected ray is the light wave that leaves the mirror surface. Its direction is determined by the angle of reflection B, which is exactly equal to the angle of incidence. A = B

Figure 19-2 Illustrating reflection and refraction at the interface of two optical materials.



$$\text{Refractive Index}(n)=\frac{\text{Speed of light in vacuum}}{\text{Speed of light in medium}}$$

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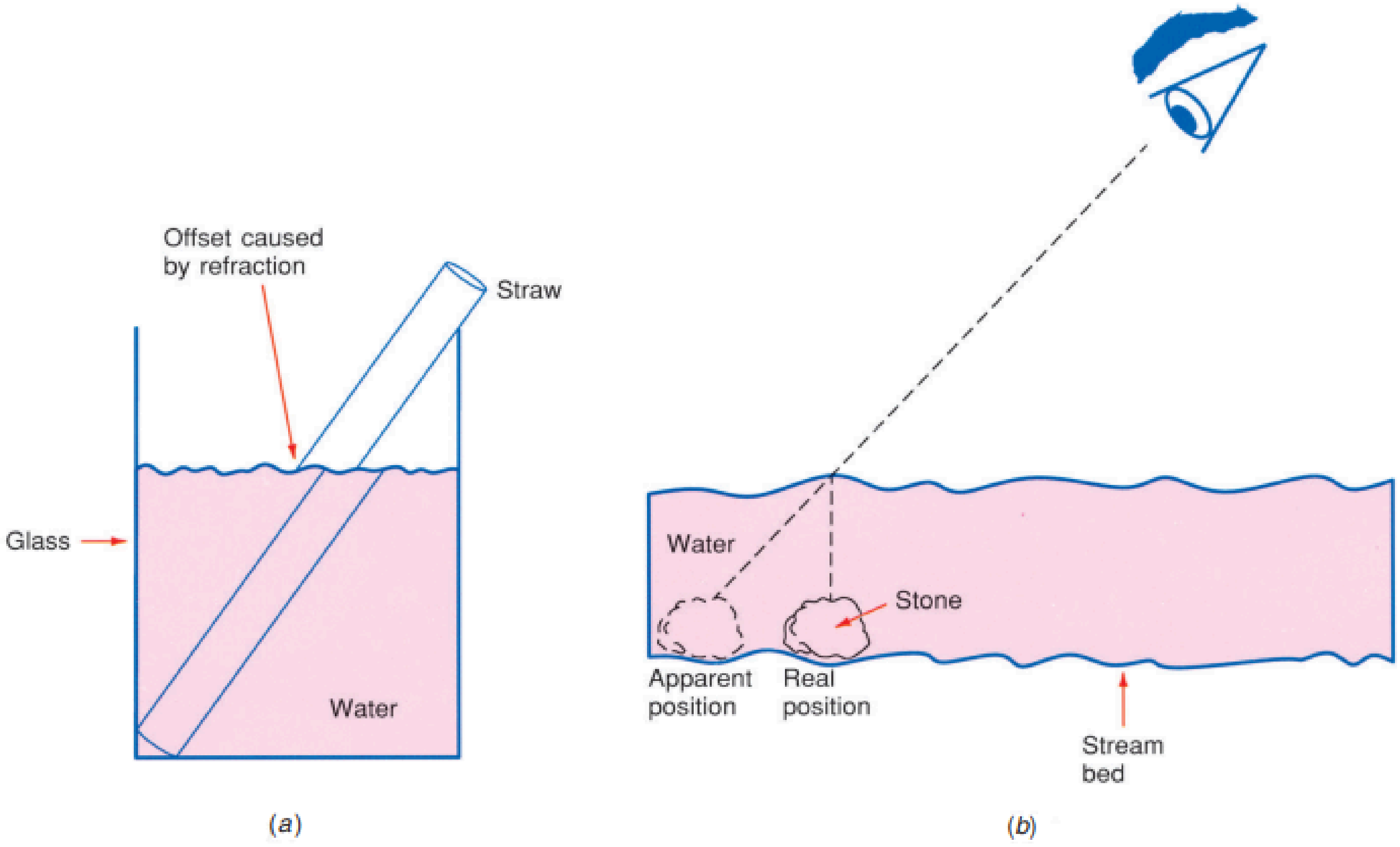
Refraction

- The direction of the light ray can also be changed by refraction, which is the bending of a light ray that occurs when the light rays pass from one medium to another.
- In reflection, the light ray bounces away from the reflecting surface rather than being absorbed by or passing through the mirror.
- Refraction occurs only when light passes through transparent material such as air, water, and glass. Refraction takes place at the point where two different substances come together.
- For example, where air and water come together, refraction will occur. The dividing line between the two different substances or media is known as the boundary, or interface. The refraction occurs because light travels at different speeds in different materials.
- The speed of light in free space is typically much higher than the speed of light in water, glass, or other materials. The **amount of refraction of the light of a material** is usually expressed in terms of the **index of refraction n.** This is the ratio of the speed of light in air to the speed of light in the substance. It is also a function of the light wavelength. Naturally, the index of refraction of air is 1, The refractive index of water is approximately 1.33, and that of glass is 1.5 and **2.42** for **diamond**

Figure 19-3 Examples of the effect of refraction.



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- When a light ray passes from one medium to another, the light wave is bent according to the index of refraction.
- In Fig. 19-2, the incident ray strikes the surface at angle A to the normal but is refracted at an angle C. The relationship between the angles and indices of refractions are n1 sin A = n2 sin C

Figure 19-4 How light rays are bent when passing from one medium to another.

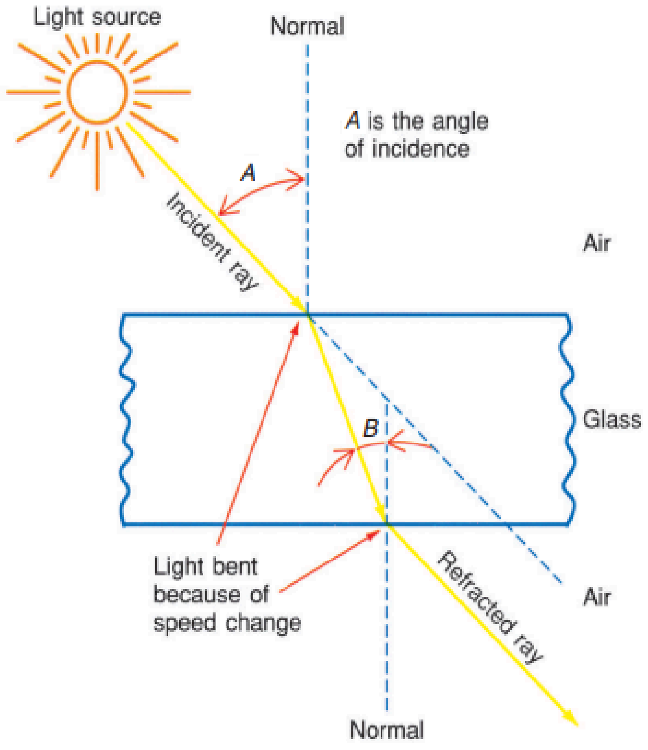
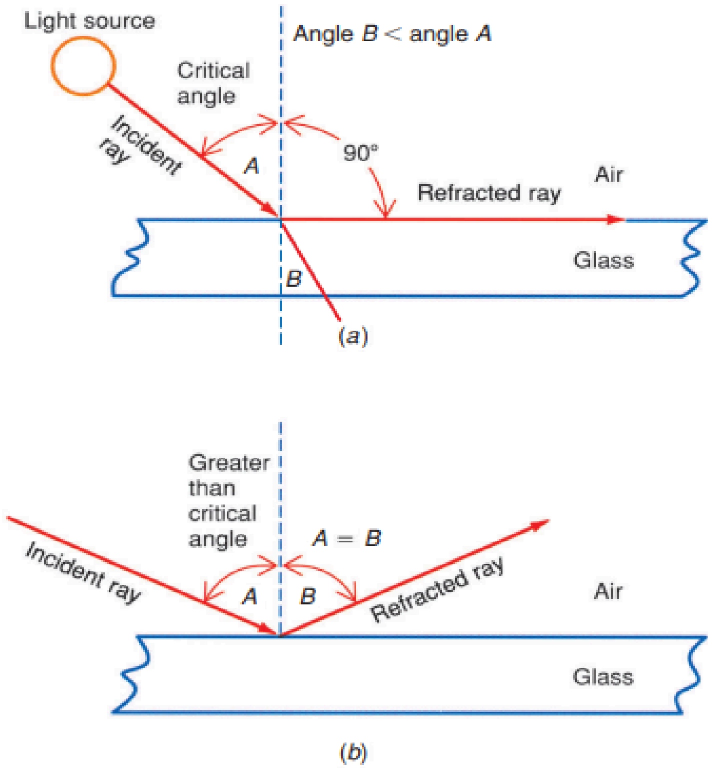


Figure 19-5 Special cases of refraction. (*a*) Along the surface. (*b*) Reflection.



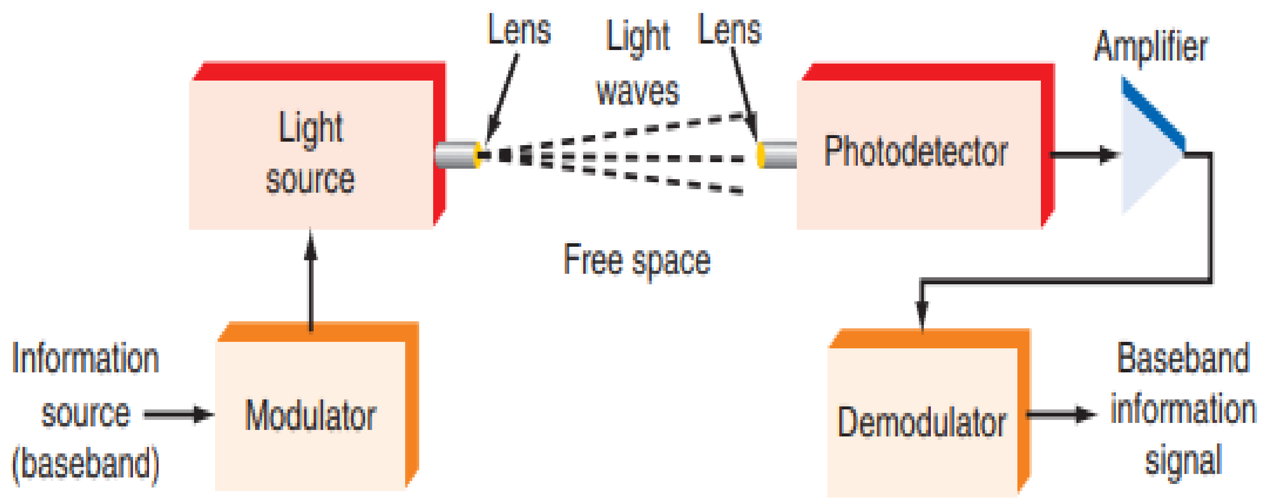
- If the light ray passes from the glass back into air, it will again change direction, as Fig. 19-4 shows.
- The important point to note is that the angle of the refracted ray B is not equal to the angle of incidence A. If the angle of incidence is increased, at some point the angle of refraction will equal 90° to the normal, as shown in Fig. 19-5(a). when the **angle of refraction** is **90°** and the **refracted ray emerges parallel** to the **interface** between the dielectrics, the angle of incidence must be less than 90°.
- When this happens, the refracted light ray in red travels along the interface between the air and glass. In this case, the angle of incidence A is said to be the critical angle. The critical angle value depends upon the index of refraction of the glass.
- If you make the angle of incidence greater than the critical angle, the light ray will be reflected from the interface [see Fig. 19-5(b)]. When the light ray strikes the interface at an angle greater than the critical angle, the light ray does not pass through the interface into the glass. The effect is as if a mirror existed at the interface.
- When this occurs, the angle of reflection B is equal to the angle of incidence A as if a real mirror were used. This action is known as total internal reflection, which occurs only in materials in which the velocity of light is slower than that in air. This is the basic principle that allows a fiber-optic cable to work

Optical Communication Systems

- Optical communication systems use light as the carrier of the information to be transmitted.
- As indicated earlier, the medium may be free space as with radio waves or a special light “pipe” or waveguide known as fiber-optic cable.
- Both media are used, although the fiber-optic cable is far more practical and more widely used.

- The main limitation of communication systems is their restricted information-carrying capabilities.
- This information-handling ability is directly proportional to the bandwidth of the communication channel.
- Using light as the transmission medium provides vastly increased bandwidths.
- Instead of using an electric signal traveling over a cable or electromagnetic waves traveling through space, the information is put on a light beam and transmitted through space or through a special fiber optic waveguide.

Figure 19-6 Free-space optical communication system.



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Light Wave Communication in Free Space:

- Fig. 19-6 shows the elements of an optical communication system using free space.
- It consists of a light source modulated by the signal to be transmitted, a photodetector to pick up the light and convert it back into an electric signal, an amplifier, and a demodulator to recover the original information signal.

Light Sources

- A transmitter is a light source.
- Other common light sources are light emitting diodes (LEDs) and lasers. These sources can follow electric signal changes as fast as 100 GHz or more.
- Lasers generate monochromatic, or single-frequency, light that is fully coherent; i.e., all the light waves are lined up in sync with one another and as a result produce a very narrow and intense light beam

Modulator

- A modulator is used to vary the intensity of the light beam in accordance with the modulating baseband signal.
- Amplitude modulation, also referred to as intensity modulation, is used where the information or intelligence signal controls the brightness of the light. Analog signals vary the brightness continuously over a specified range.
- This technique is used in some cable TV systems.
- Digital signals simply turn the light beam off and on at the data rate. Digital modulation is usually NRZ-formatted binary data that turns a laser on or off to produce off-on keying (OOK) or amplitude-shift keying (ASK)
- A modulator for analog signals can be a **power transistor** in series with the light source and its dc power supply (see Fig. 19-7). The voice, video, or other information signal is applied to an amplifier that drives the class A modulator transistor

- Amplitude modulation is used with analog signals, but otherwise most light wave communication is accomplished by pulse modulation.
- Pulse modulation refers to turning the light source on and off in accordance with some serial binary signal.
- The most common type of pulse modulation is pulse-code modulation (PCM), which is serial binary data organized into bytes or longer words. NRZ, RZ, and Manchester formats are common.

Receiver

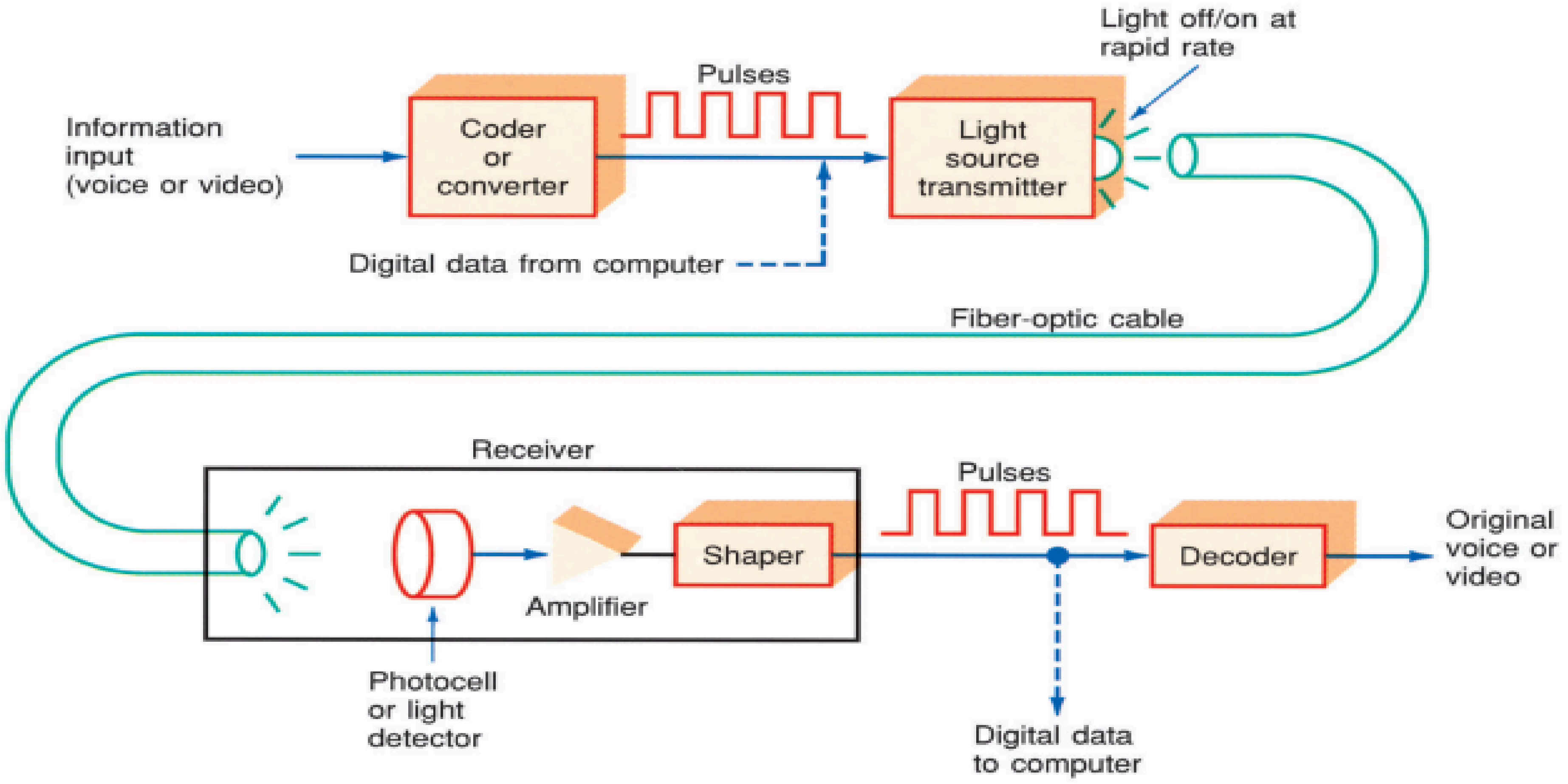
- The modulated light wave is picked up by a photodetector. This is usually photodiode or transistor whose conduction is varied by the light.
- The small signal is amplified and then demodulated to recover the originally transmitted signal. Digital processing may be necessary.
- For example, if the original signal is voice that was digitized by an A/D converter before being transmitted as a PCM signal, then a D/A converter will be needed at the receiver to recover the voice signal.

Fiber-Optic Communication System

- Instead of free space, some type of light-carrying cable can be used. Today, fiberoptic cables have been highly refined.
- Cables many miles long can be constructed and then interconnected for the purpose of transmitting information; a new transmission medium(fiber-optic cables) is now available. Its great advantage is its immense information carrying capacity (wide bandwidth).
- Whereas hundreds of telephone conversations may be transmitted simultaneously at microwave frequencies, many thousands of signals can be carried on a light beam through a fiber-optic cable. fiber-optic communication systems have an almost limitless capacity for information transfer
- The components of a typical fiber-optic communication system are shown in Fig. 19-8. The information signal to be transmitted may be voice, video, or computer data. The first step is to convert the information to a form compatible with the communication medium, usually by converting continuous analog signals such as voice and video (TV) signals to a series of digital pulses. An A/D converter is used for this purpose.

Fiber-Optic Communication System

Figure 19-8 Basic elements of a fiber-optic communication system.



Fiber-Optic Communication System

These digital pulses are then used to flash a powerful light source off and on very rapidly. In simple low-cost systems that transmit over short distances, the light source is usually a light-emitting diode that emits a low-intensity infrared light beam.

Infrared beams such as those used in TV remote controls are also used in transmission. The light beam pulses are then fed into a fiber-optic cable, which can transmit them over long distances.

At the receiving end, a light-sensitive device known as a photocell, or light detector, is used to detect the light pulses. It converts the light pulses to an electric signal.

The electrical pulses are amplified and reshaped back into digital form. They are fed to a decoder, such as a D/A converter, where the original voice or video is recovered.

Figure 19-9 Applications of fiber-optic cables.

1. TV studio to transmitter interconnection eliminating a microwave radio link.
2. Closed-circuit TV systems used in buildings for security.
3. Secure communication systems at military bases.
4. Computer networks, wide area, metro, and local area.
5. Shipboard communication.
6. Aircraft communication/controls.
7. Interconnection of measuring and monitoring instruments in plants and laboratories.
8. Data acquisition and control signal communication in industrial process control systems.
9. Nuclear plant instrumentation.
10. College campus communication.
11. Utilities (electric, gas, and so on) station communication.
12. Cable TV systems replacing coaxial cable.
13. The Internet.
14. Backhaul for cellular basestations.
15. Distributed antenna systems (DAS).
16. Connections between servers, routers and switches in data centers.
17. Connection between the cellular basestation and the remote radio head mounted at the antenna.

Benefits of fiber-optic cables over conventional electrical cables

Figure 19-10 Benefits of fiber-optic cables over conventional electrical cables.

1. *Wider bandwidth.* Fiber-optic cables have high information-carrying capability.

2. *Low loss.* Fiber-optic cables have less signal attenuation over a given distance than an equivalent length of coaxial cable.

3. *Lightweight.* Glass or plastic cables are much lighter than copper cables and offer benefits when low weight is critical (e.g., aircraft).

4. *Small size.* Practical fiber-optic cables are much smaller in diameter than electrical cables and thus can be contained in a relatively small space.

5. *Security.* Fiber-optic cables cannot be as easily "tapped" as electrical cables, and they do not radiate signals that can be picked up for eavesdropping purposes. There is less need for complex and expensive encryption techniques.

6. *Interference immunity.* Fiber-optic cables do not radiate signals, as some electrical cables do, and cause interference to other cables. They are immune to the picking up of interference from other sources.

7. *Greater safety.* Fiber-optic cables do not carry electricity. Therefore, there is no shock hazard. They are also insulators and thus not susceptible to lightning strikes as electrical cables are. They can be used in corrosive and/or explosive environments without danger of sparks.

Fiber-Optic Cables

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- A fiber-optic cable is thin **glass** or **plastic cable** that acts as a **light "pipe."**
- It is not really a hollow tube carrying light, but a long, thin strand of glass or plastic fiber. Fiber cables have a **circular cross section** with a diameter of only a fraction of an inch.
- Some **fiber optic cables** are the size of **a human hair**. A light source is placed at the one end of the fiber, and light passes through it and exits at the other end of the cable.
- How the light propagates through the fiber depends upon the laws of optics

Principles of Fiber-Optic Cable:

Fiber-optic cables operate on the **optical principles of total internal reflection** as described earlier in this chapter. Fig. 19-11(a) shows a thin fiber-optic cable. A beam of light is focused on the end of the cable. It can be positioned in a number of different ways so that the light enters the fiber at different angles. For example, light ray A enters the cable perpendicular to the end surface. Therefore, the light beam travels straight down the fiber and exits at the other end. This is the most desirable condition

Fiber-Optic Cables

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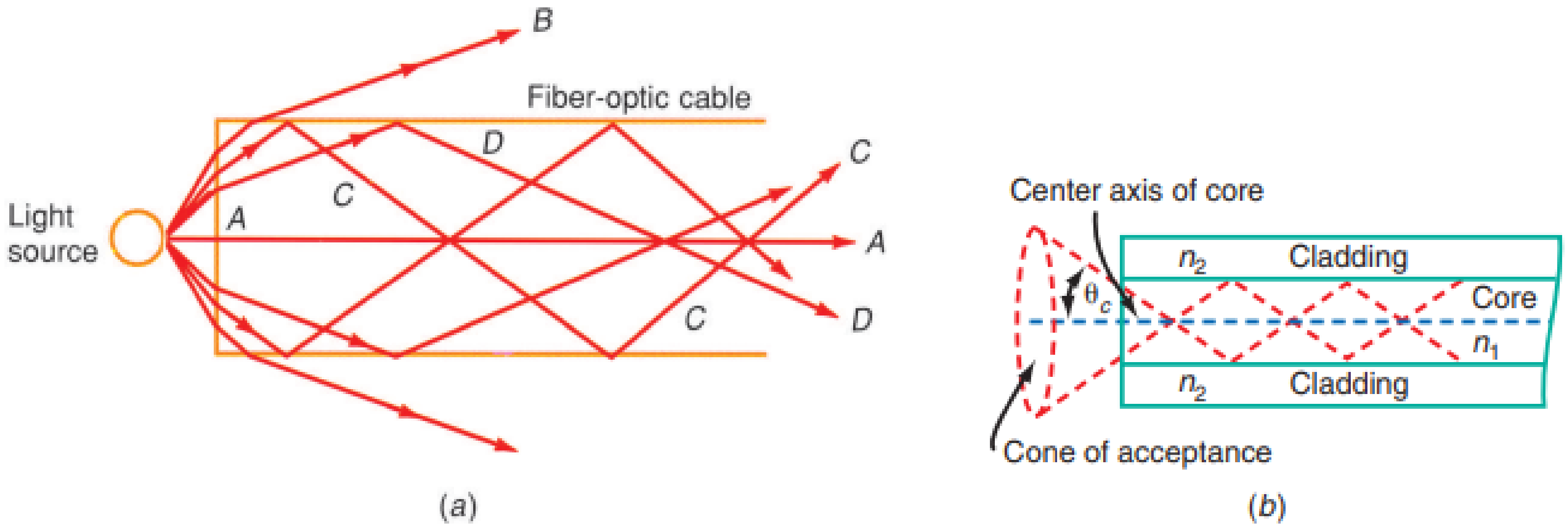
- **Critical Angle.** The angle of light beam **B** is such that its angle of incidence is less than the critical angle, and therefore refraction takes place. The light wave passes through the fiber and exits the edge into the air at a different angle.
- The angle of incidence of light beams C and D is greater than the critical angle.
- Therefore, total internal reflection takes place, and the light beams are reflected off the surface of the fiber cable. The light beam bounces back and forth between the surfaces until it exits at the other end of the cable

Figure 19-11 (*a*) Light rays in a fiber-optic cable. (*b*) Critical angle and cone of acceptance.



Fiber-Optic Cables

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- The core of the fiber has a higher index of refraction than the **cladding** surrounding the core as shown in Fig. 19-11(b). The light enters the core at an infinite number of angles but only those rays entering the core at an angle greater than the critical angle actually pass down the core. These light rays are reflected off the interface between core and cladding as they pass down the cable.
- Fig. 19-11(b) shows the critical angle of the cable θc, sometimes referred to as the acceptance angle θA. This angle is formed between the center axis line of the core and the line that defines the maximum point where light entering the cable will undergo total internal reflection.
- If the light beam entering the end of the cable has an angle greater than the critical angle, it will be internally reflected and propagated down the cable
- **Numerical Aperture**. Refer to the angles in Fig. 19-11(b). External to the end of the cable is what is **called a cone of acceptance**; it is defined by the critical angle.

Fiber-Optic Cables

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- Any light beam outside the cone will not be internally reflected and transmitted down the cable.
- The cone of acceptance defines the numerical aperture (NA) of the cable. This is a number less than 1 that gives some indication of the range of angles over which a particular cable will work. The NA can be calculated with the expression

$$\mathrm{NA} = \sin \theta_c$$

For example, if the critical angle is 20°, the NA is

$$\mathrm{NA} = \sin 20^\circ = 0.342$$

The NA can also be determined from the indices of refraction of the core and cladding:

$$\mathrm{NA} = \sqrt{n_1^2 - n_2^2}$$

If $n_1 = 1.5$ and $n_2 = 1.4$, the numerical aperture is

$$\mathrm{NA} = \sqrt{(1.5)^2 - (1.4)^2} = \sqrt{2.25 - 1.96} = \sqrt{0.29} = 0.5385$$

Typical numerical apertures for common cables are 0.275 and 0.29.

The numerical aperture of a fi ber-optic cable is 0.29. What is the critical angle?

Fiber-Optic Cables

Fiber-Optic Cable Construction

- Fiber-optic cables come in a variety of sizes, shapes, and types. The simplest cable contains a single strand of fiber; a complex cable is made up of multiple fibers with different layers and other elements.
- The portion of a fiber-optic cable that carries the light is made from either glass or plastic. Another name for glass is silica.
- The optical characteristics of glass are superior to those of plastic. However, glass is far more expensive and more fragile than plastic.
- Although plastic is less expensive and more flexible, its attenuation of light is greater. For a given intensity, light will travel a farther distance in glass than in plastic
- The construction of a fiber-optic cable is shown in Fig. 19-11(b). The glass or plastic optical fiber is contained within an outer cladding.

Fiber-Optic Cables

Fiber-Optic Cable Construction

- The index of refraction of the outer cladding N2 is slightly less than the index of refraction N1 of the core. Typical values for N1 and N2 are 1.5 and 1.4, respectively. Over the cladding is a plastic jacket similar to the outer insulation on an electrical cable
- The fiber, which is called the core, is usually surrounded by a protective cladding (see Fig. 19-12). The cladding is also made of glass or plastic but has a lower index of refraction.
- To protecting the fiber core from nicks and scratches, the cladding gives strength.
- Some fiber-optic cable has a 1)glass core with a glass cladding. Other cables have a 2)plastic core with a plastic cladding. Another arrangement, plastic-clad silica (PCS) cable, is a 3)glass core with a plastic cladding

Figure 19-12 Basic construction of a fiber-optic cable.

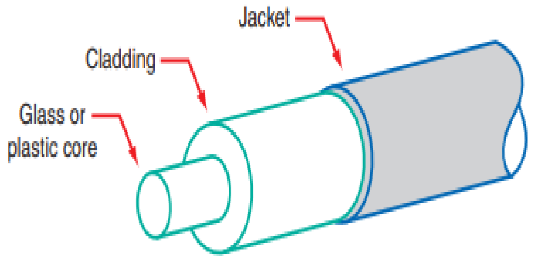
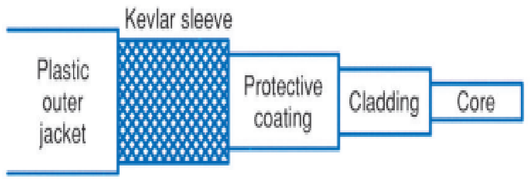


Figure 19-13 Typical layers in a fiber-optic cable.



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Fiber-Optic Cable Construction

- Most claddings are covered with a clear protective coating for added strength and resistance to moisture and damage (see Fig. 19-13)

Types of Fiber-Optic Cables

- There are two basic ways of classifying fiber-optic cables: The first method is by the index of refraction, which varies across the cross section of the cable.
- The second method of classification is by mode, which refers to the various paths the light rays can take in passing through the fiber.
- **Step Index Cable**. The two ways to define the index of refraction variation across a cable are the step index and the graded index. Step index refers to the fact that there is a sharply defined step in the index of refraction where the fiber core and the cladding interface. It means that the core has one constant index of refraction N1 and the cladding has another constant index of refraction N2. When the two come together, there is a distinct step (see Fig. 19-15).

Fiber-Optic Cables

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Figure 19-15 A step index cable cross section.

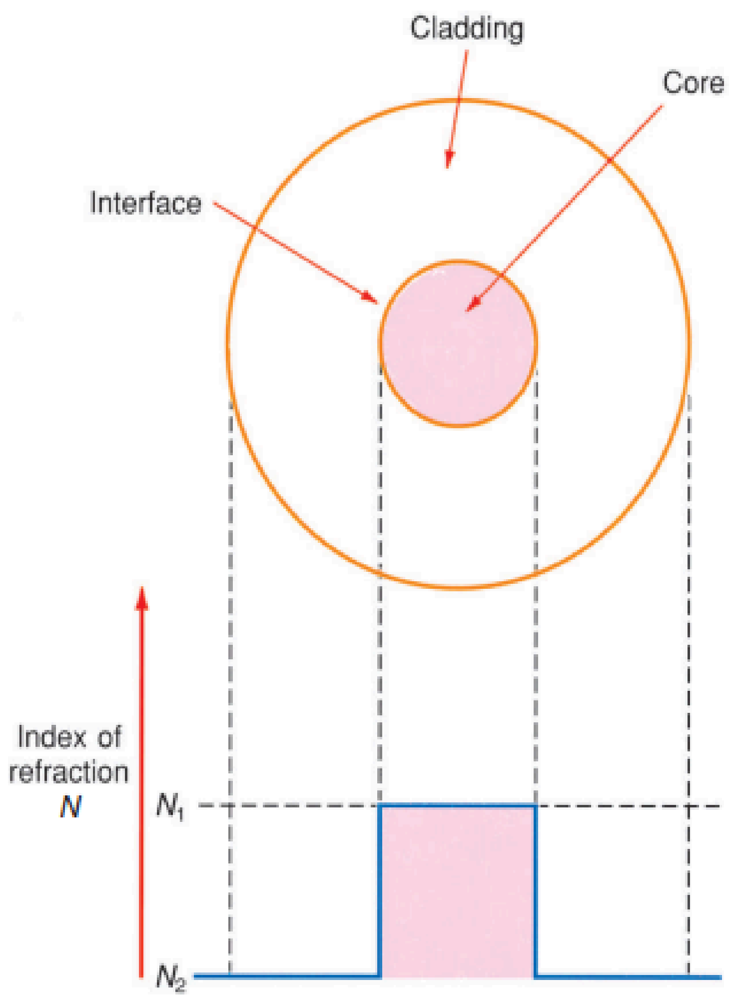
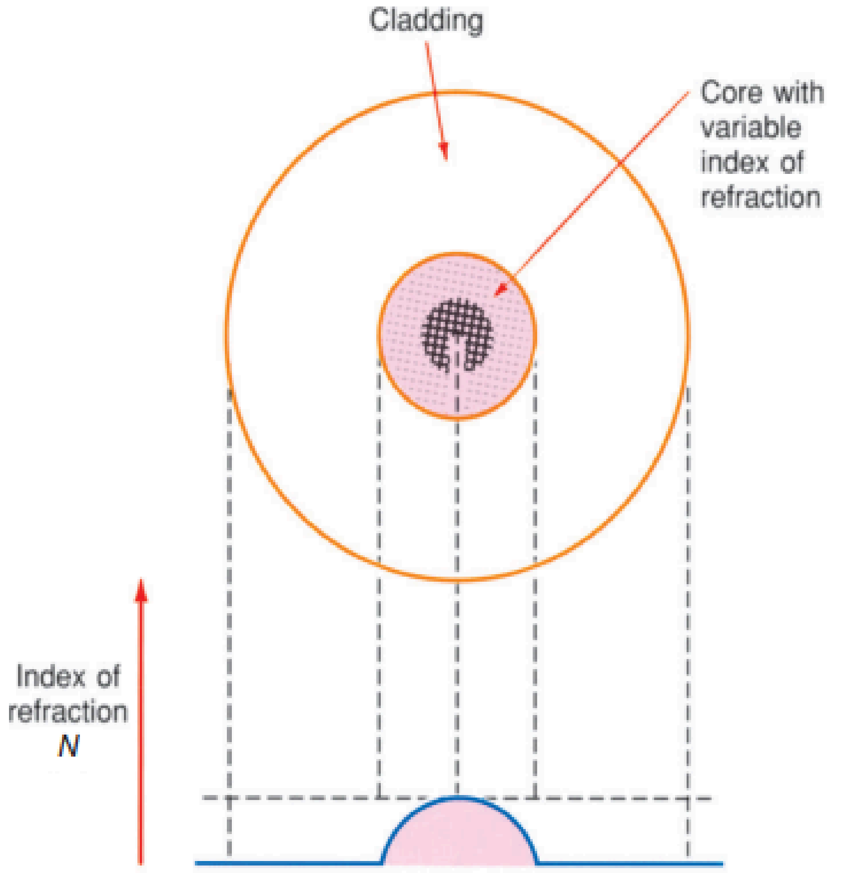


Figure 19-16 Graded index cable cross section.



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- **Graded Index Cable.** The other type of cable has a graded index. Here, the index of refraction of the core is not constant. Instead, it varies smoothly and continuously over the diameter of the core (see Fig. 19-16).
- **Cable Mode.** Mode refers to the number of paths for the light rays in the cable. There are two classifications: single mode and multimode.
- In single mode, light follows a single path through the core;
- In multimode, the light takes many paths. Each type of fiber-optic cable uses one of these methods of rating the **index** or **mode**. In practice, there are three commonly used types of fiber-optic cable: multimode step index , single-mode step index and multimode graded index
- **Multimode Step Index Cable**. The multimode step index fiber cable is probably the most common and widely used type. It is also the easiest to make and therefore the least expensive. It is widely used for short to medium distances at relatively low pulse frequencies. The main advantage of a multimode stepped index fiber is its **large size**. Typical core diameters are in the 50- to 1000-μm range. Such large-diameter cores are excellent at gathering light and transmitting it efficiently. This means that an inexpensive light source such as an LED can be used to produce the light pulses.

Fiber-Optic Cables

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- **Dispersion.** Dispersion is the distortion of the optical signal due to the characteristics of the cable. For example, in Fig. 19-17, a short light pulse is applied to the end of the cable by the source. Light rays from the source travel in multiple paths.
- At the end of the cable, the rays that travel the shortest distance reach the end first. Other rays begin to reach the end of the cable later, until the light ray with the longest path finally reaches the end, concluding the pulse. In Fig. 19-17, ray A reaches the end first, then B, and then C. The result is a pulse at the other end of the cable that is lower in amplitude because of the attenuation of the light in the cable and increased in duration because of the different arrival times of the various light rays. This stretching of the pulse is referred to as modal dispersion

Figure 19-17 A multimode step index cable.

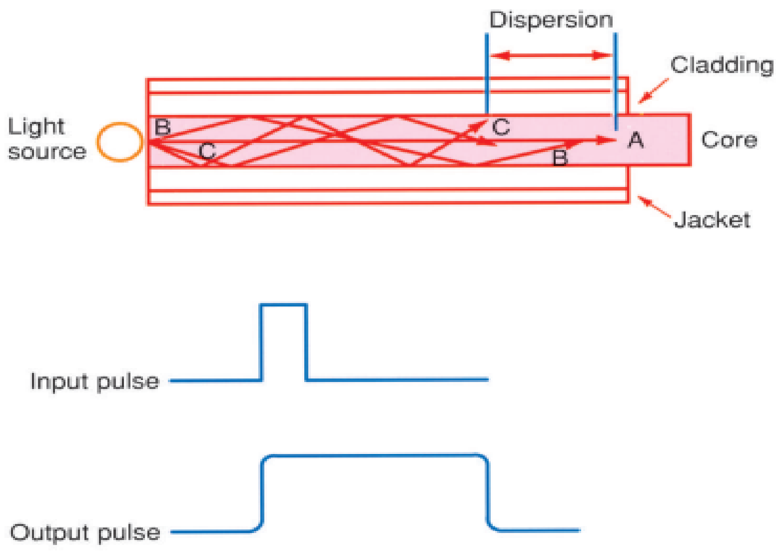
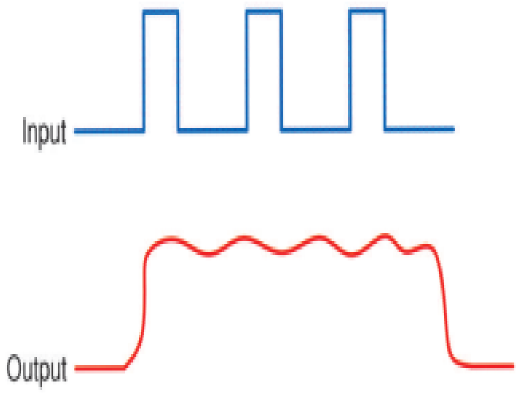


Figure 19-18 The effect of modal dispersion on pulses occurring too rapidly in a multimode step index cable.



Fiber-Optic Cables

- **Dispersion.**

Chromatic dispersion occurs when multiple wavelengths of light are used, as in dense wavelength-division multiplexing (DWDM) systems. This type of dispersion is the most troubling at data rates above 10 Gbps.

Polarization mode dispersion (PMD). This is a phenomenon that occurs in single-mode fiber (SMF). One of the newer and better ways to deal with dispersion is to use electronic dispersion compensation (EDC)

Fiber-Optic Cables

- **Single-Mode Step Index Cable.** A single-mode or monomode step index fiber cable essentially eliminates modal dispersion by making the core so small that the total number of modes or paths through the core is minimized (see Fig. 19-19). Typical core sizes are 2 to 15 μm.
- The only path through the core is down the center. With minimum refraction, little pulse stretching occurs. The output pulse has essentially the same duration as the input pulse.
- Single-mode step index fibers are by far the best because the pulse repetition rate can be high and the maximum amount of information can be carried.
- For very long distance transmission and maximum information content, single-mode step index fiber cables should be used. The main problem with this type of cable is that it is extremely small, difficult to make, and therefore very expensive.
- It is also more difficult to handle. Splicing and making interconnections are more difficult. Finally, for proper operation, an expensive, superintense light source such as a laser must be used. For long distances, however, this is the type of cable preferred

Fiber-Optic Cables

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Figure 19-19 Single-mode step index cable.

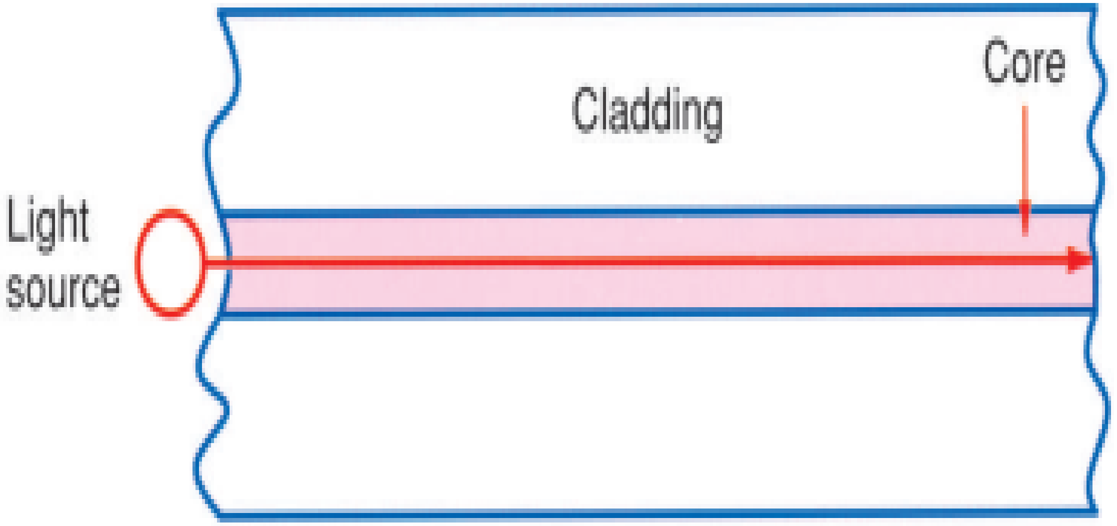
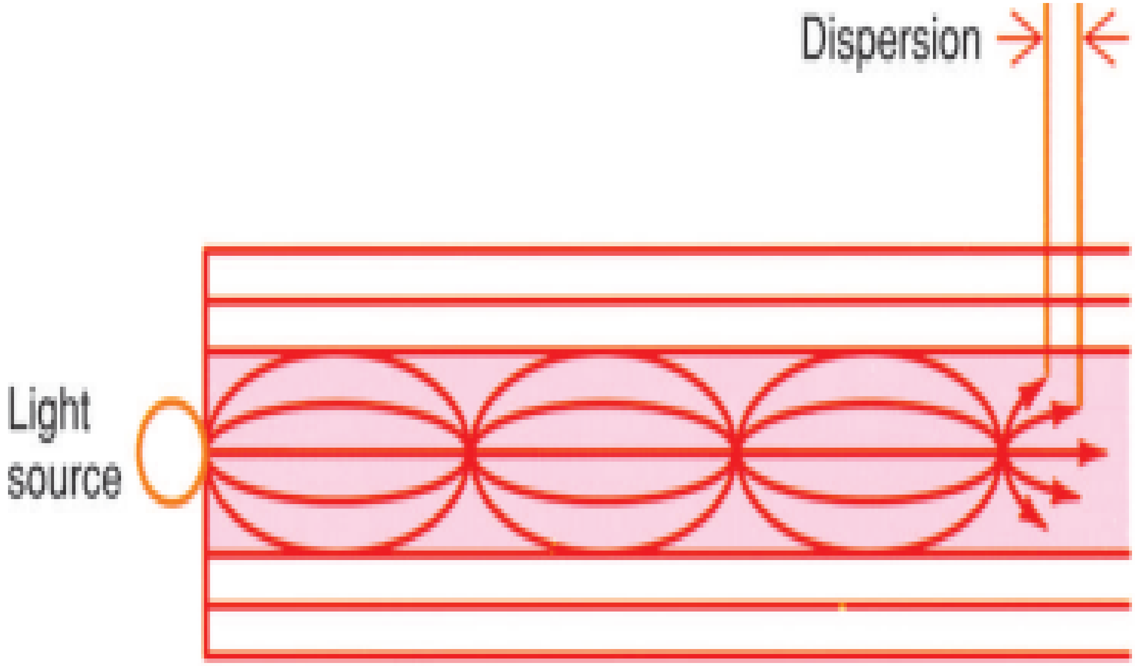


Figure 19-20 A multimode graded index cable.



Fiber-Optic Cables

- **Multimode Graded Index Cable.** Multimode graded index fiber cables have several modes, or paths, of transmission through the cable, but they are much more orderly and predictable. Fig. 19-20 shows the typical paths of the light beams.
- Because of the continuously varying index of refraction across the core, the light rays are bent smoothly and repeatedly converge at points along the cable.
- The light rays near the edge of the core take a longer path but travel faster because the index of refraction is lower. All the modes or light paths tend to arrive at one point simultaneously. The result is less modal dispersion.
- As a result, this cable can be used at very high pulse rates, and therefore a considerable amount of information can be carried.
- This type of cable is also much wider in diameter, with core sizes in the 50- to 100- μm range. Therefore, it is easier to splice and interconnect, and cheaper, less intense light sources can be used

Fiber-Optic Cables

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Fiber-Optic Cable Specifications:

The most important specifications of a fiber-optic cable are size, attenuation, and bandwidth.

- **Cable Size.** Fiber-optic cable comes in a variety of sizes and configurations as previously indicated. Size is normally specified as the diameter of the core, and cladding is given in micrometers (μm)
- Cables come in two common varieties, simplex and duplex. Simplex cable, as the name implies, is just a single-fiber core cable, as shown in Fig. 19-21. In a common duplex cable, as shown in Fig. 19-22, two cables are combined within a single outer cladding. Cables are available with 4, 10, and 12 parallel fibers

Figure 19-21 Fiber-optic cable dimensions.

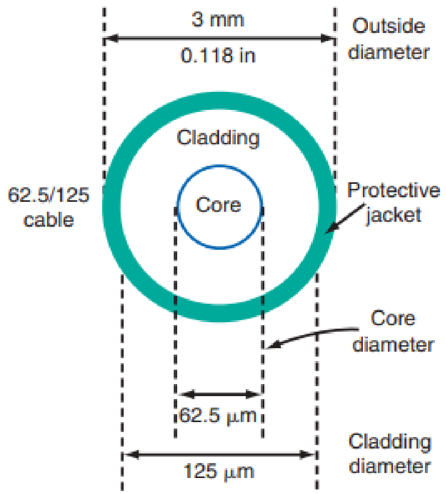
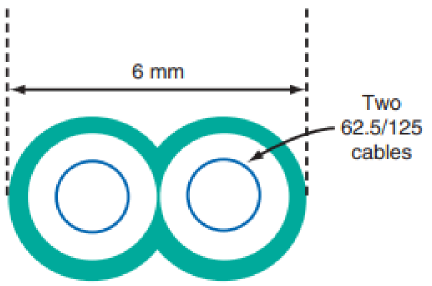


Figure 19-22 Cross section of a duplex cable.



Fiber-Optic Cables

Fiber-Optic Cable Specifications:

- **Attenuation.** The most important specification of a fiber-optic cable is its attenuation.
- Attenuation refers to the loss of light energy as the light pulse travels from one end of the cable to the other. The light pulse of a specific amplitude or brilliance is applied to one end of the cable, but the light pulse output at the other end of the cable will be much lower in amplitude.
- The intensity of the light at the output is lower because of various losses in the cable. The main reason for the loss in light intensity over the length of the cable is light absorption, scattering, and dispersion
- **Absorption** refers to how light energy is converted to heat in the core material because of the impurity of the glass or plastic. **Scattering** refers to the light lost due to light waves entering at the wrong angle and being lost in the cladding because of refraction. **Dispersion**, as mentioned, refers to the pulse stretching caused by the many different paths through the cable.

Fiber-Optic Cables

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Fiber-Optic Cable Specifications:

The attenuation of a fiber-optic cable is expressed in decibels (dB) per unit of length. The standard is decibels per kilometer.

The standard decibel formula is used dB = 10 log Pout/ Pin

where Pout is the power out and Pin is the power in. Because light intensity is a type of electromagnetic radiation, it is normally expressed and measured in power units, watts.

Bandwidth. The bandwidth of a fiber-optic cable determines the maximum speed of the data pulses the cable can handle. The bandwidth is normally stated in terms of megahertz-kilometers (MHz·km). A common 62.5/125-μm cable has a bandwidth in the 100- to 300-MHz·km range. Cables with 500 and 600 MHz·km are also common. Even higher-bandwidth cables up to 5000 MHz-km are available to carry gigahertz-range signals.

As the length of the cable is increased, the bandwidth decreases in proportion. If a 160-MHz·km cable length is doubled from 1 to 2 km, its bandwidth is halved to 80 MHz·km

Fiber-Optic Cables

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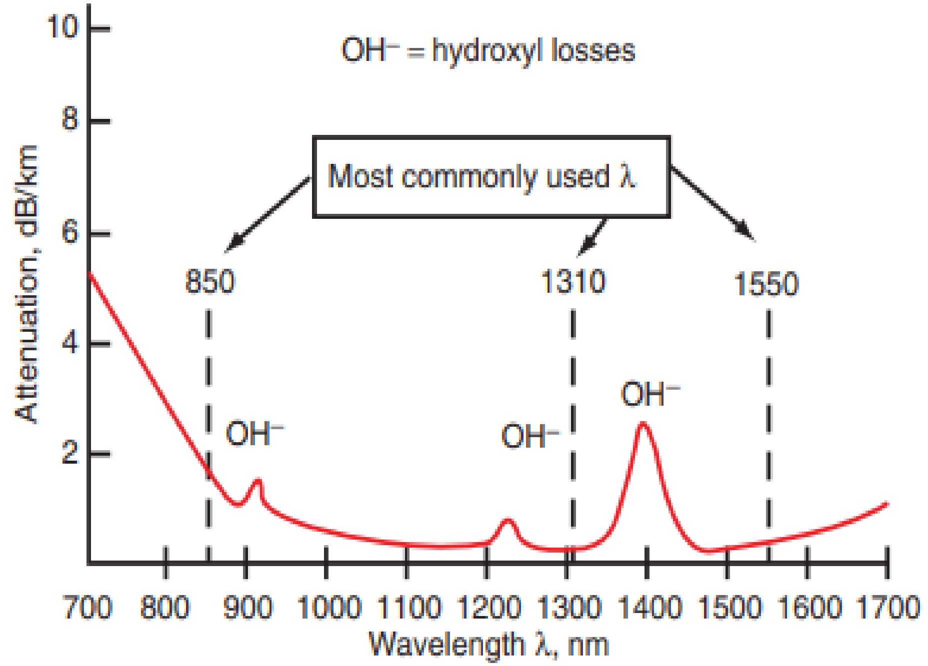
Fiber-Optic Cable Specifications:

- **Frequency Range.** Most fiber-optic cable operates over a relatively wide light frequency range, although it is normally optimized for a narrow range of light frequencies.
- The most commonly used light frequencies(wavelengths) are 850, 1310, and 1550 nm (or 0.85, 1.31, and 1.55 μm). The cable has minimum attenuation to these frequencies. Fig. 19-24 shows attenuation versus wavelength for a typical cable

Figure 19-24 Attenuation versus wavelength of a typical fiber-optic cable.



- **Connectors and Splicing**
- When long fiber-optic cables are needed, two or more cables can be spliced together

Fiber-Optic Cables

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Connectors and Splicing

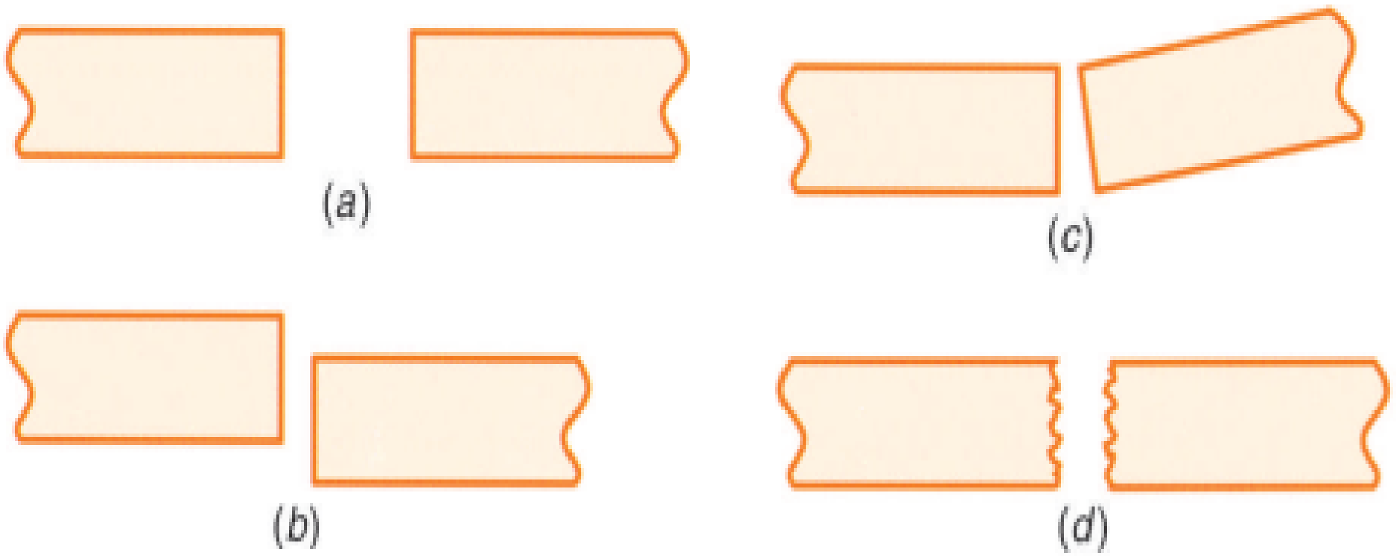
- When long fiber-optic cables are needed, two or more cables can be spliced together
- **Connectors**. Connectors are special mechanical assemblies that allow fiber-optic cables to be connected to one another.
- Fiber-optic connectors are the optical equivalent of electrical plugs and sockets. They are mechanical assemblies that hold the ends of a cable and cause them to be accurately aligned with the ends of another cable.
- Most fiber-optic connectors either snap or twist together or have threads that allow the two pieces to be screwed together. Connectors ensure precise alignment of the cables. The ends of the cables must be aligned with precision so that maximum light from one cable is transferred to another
- A typical fiber-optic connector is shown in Fig. 19-26(a). One end of the connector, called the ferrule, holds the fiber securely in place. A matching fitting holds the other fiber securely in place. When the two are screwed together, the ends of the fibers touch, thereby establishing a low-loss coupling. Fig. 19-26(b) shows in greater detail how the connector aligns the fibers

Fiber-Optic Cables

Connectors and Splicing

- **Connectors**. Connectors are normally used at the end of the cable applied to the light source or the end of the cable connected to the photodetector

Figure 19-25 Misalignment and rough end surfaces cause loss of light and high attenuation. (*a*) Too much end separation. (*b*) Axial misalignment. (*c*) Angular misalignment. (*d*) Rough, uneven surfaces.



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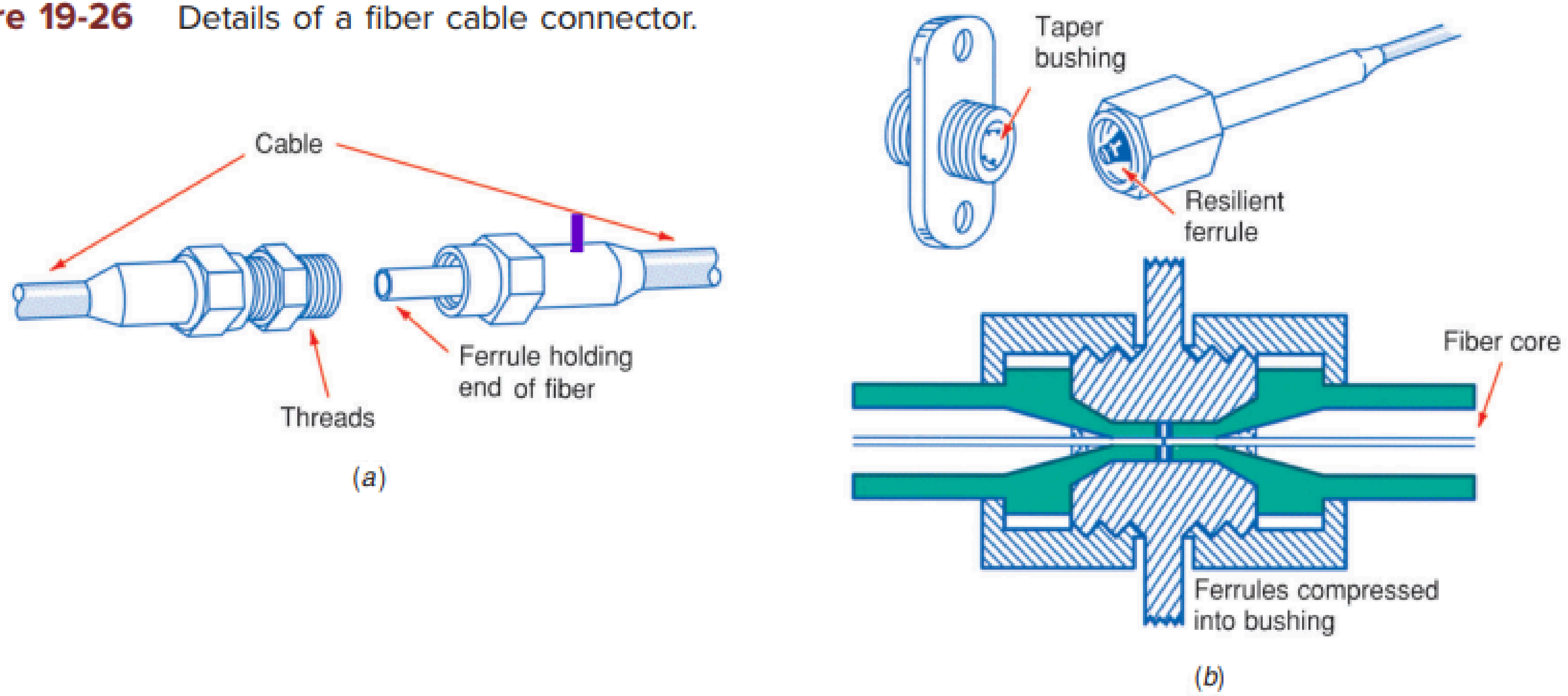
Connectors and Splicing

- **Connectors**. Connectors are also used at the repeater units where the light is picked up, converted to an electrical pulse, amplified and reshaped, and then used to create a new pulse to continue the transmission over a long line.
- Connectors are used on the back of interface adapters that plug into computers

Figure 19-26 Details of a fiber cable connector.



Fiber-Optic Cables

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Connectors and Splicing

- **Splicing.** Splicing fiber-optic cable means permanently attaching the end of one cable to another. This is usually done without a connector.
- The first step is to cut the cable, called cleaving the cable, so that it is perfectly square on the end. Cleaving is so important to minimizing light loss that special tools have been developed to ensure perfect cuts.
- The two cables to be spliced are then permanently bonded together by heating them instantaneously to high temperatures so that they fuse or melt together.
- Special tools and splicing machines must be used to ensure perfect alignment. Installing a connector begins with cleaving the fiber so that it is perfectly square. Polishing usually follows.
- Again, the special cleaving and polishing machines devised for this purpose must always be used. Poorly spliced cable or poorly installed connectors create an enormous loss

Optical Transmitters and Receivers

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- **Transmitter:** In an optical communication system, transmission begins with the transmitter, which consists of a carrier generator and a modulator.
- The carrier is a light beam that is usually modulated by turning it on and off with digital pulses. The basic transmitter is essentially a light source.
- **The receiver** is a light or photodetector that converts the received light back to an electric signal. In this section, we can discuss the types of light sources used in fiber-optic systems and the transmitter circuitry, as well as the various light detectors and the related receiver circuits.

Light Sources:

- Conventional light sources such as incandescent lamps cannot be used in fiber-optic systems because they are too slow. To transmit high-speed digital pulses, a very fast light source must be used.
- The two most commonly used light sources are light-emitting diodes (LEDs) and semiconductor lasers

Optical Transmitters and Receivers

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Light Sources:

- **Light-Emitting Diodes**. A light-emitting diode (LED) is a PN-junction semiconductor device that emits light when forward-biased. When a free electron encounters a hole in the semiconductor structure, the two combine, and in the process they give up energy in the form of light.
- Semiconductors such as gallium arsenide (GaAs) are superior to silicon in light emission. Most LEDs are GaAs devices optimized for producing red light.
- LEDs are widely used for displays indicating whether a circuit is off or on, or for displaying decimal and binary data. However, because an LED is a fast semiconductor device, it can be turned off and on very quickly and can transmit the narrow light pulses required in a digital fiber-optics system.
- LEDs can be designed to emit virtually any color light desired. The LEDs used for fiber-optic transmission are usually in the red and near-infrared ranges.
- Typical wavelengths of LED light commonly used are 0.85, 1.31, and 1.55 µm, more commonly designated 850, 1310, and 1550 nm

Optical Transmitters and Receivers

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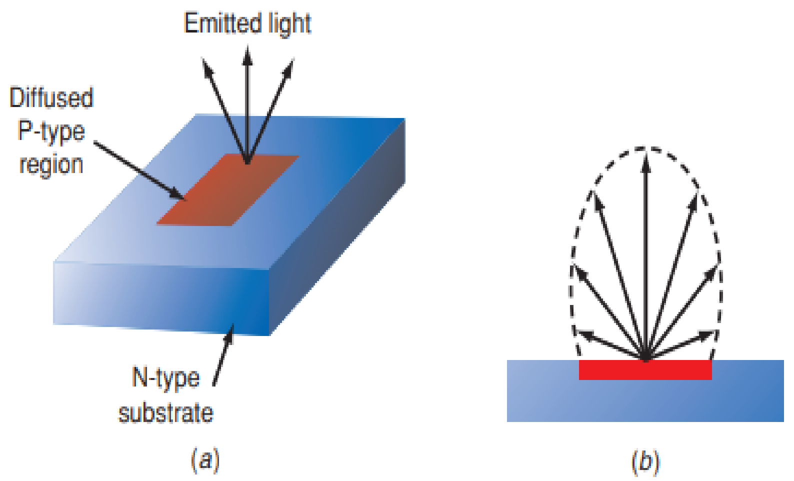
Light Sources:

- One physical arrangement of the LED is shown in Fig. 19-27(a). A P-type material is diffused into the N-type substrate, creating a diode.
- Radiation occurs from the P-type material and around the junction. Fig. 19-27(b) shows a common light radiation pattern.
- The light output from an LED is expressed in terms of power. Typical light output levels are in the 10- to 50-µW range. Sometimes the light output is expressed in dBm or dB referenced of 1 mW (milliwatt). Common levels are 215 to 230 dBm.

Figure 19-27 (*a*) Typical LED construction. (*b*) Light radiation pattern.



Optical Transmitters and Receivers

Light Sources:

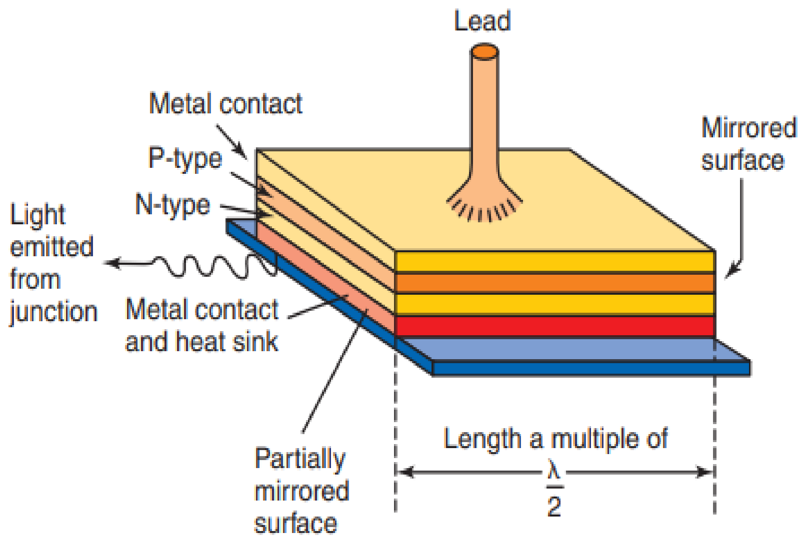
- Forward bias current levels to achieve this power level are in the 50- to 200-mA range. High output LEDs with output ratings in the 600- to 2500-µW range are also available.
- A typical LED used for lighting is relatively slow to turn on and off. A typical turn on/turn-off time is about 150 ns. This is too slow for most data communication applications by fiber optics.
- Faster LEDs capable of data rates up to 50 MHz are available. For faster data rates, a laser diode must be used. Special LEDs are made just for fiber-optic applications.
- These units are made of gallium arsenide or indium phosphide (GaAs or InP) and emit light at 1.3 µm. Other LEDs

Optical Transmitters and Receivers

Light Sources:

- **Laser Diodes.** The other commonly used light transmitter is a laser, which is a light source that emits coherent monochromatic light. Monochromatic light is a pure single frequency light.
- Although an LED emits red light, that light covers a narrow spectrum around the red frequencies. Coherent refers to the fact that all the light waves emitted are in phase with one another.
- Coherence produces a focusing effect on a beam so that it is narrow and, as a result, extremely intense.

Figure 19-29 A Fabry-Perot injection laser diode.



Optical Transmitters and Receivers

Light Sources:

- The most widely used light source in fiber-optic systems is the injection laser diode (ILD), also known as a Fabry-Perot (FP) laser. Like the LED, it is a PN junction diode usually made of GaAs. See Fig. 19-29.
- At some current level, it emits a brilliant light. The physical structure of the ILD is such that the semiconductor structure is cut squarely at the ends to form internal reflecting surfaces. One of the surfaces is usually coated with a reflecting material such as gold.
- The other surface is only partially reflective. When the diode is properly biased, the light is emitted and bounces back and forth internally between the reflecting surfaces.
- The distance between the reflecting surfaces has been carefully measured so that it is some multiple of a half wave at the light frequency. The bouncing back and forth of the light waves causes their intensity to reinforce and build up.
- The structure is like a cavity resonator for light. The result is an incredibly high-brilliance, single-frequency light beam that is emitted from the partially reflecting surface

Optical Transmitters and Receivers

Light Detectors: The receiver part of the optical communication system is relatively simple. It consists of a detector that senses the light pulses and converts them to an electric signal. This signal is amplif ed and shaped into the original serial digital data. The most critical component is the light sensor.

- **Photodiode.** The most widely used light sensor is a photodiode. It is a silicon PN-junction diode that is sensitive to light. This diode is normally reverse-biased, as shown in Fig. 19-35.
- The only current that fl ows through it is an extremely small reverse leakage current. When light strikes the diode, this leakage current increases significantly.
- This current flows through a resistor and develops a voltage drop across it. The result is an output voltage pulse.
- **Phototransistor.** The reverse current in a diode is extremely small even when exposed to light. The resulting voltage pulse is very small and so must be amplified. The base collector junction is exposed to light.
- The base leakage current produced causes a larger emitter-to-collector current to flow.

Optical Transmitters and Receivers

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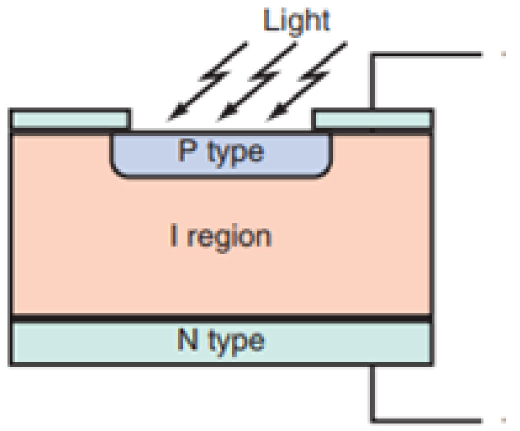
- Thus the transistor amplifies the small leakage current into a larger, more useful output (see Fig. 19-36).
- Phototransistor circuits are far more sensitive to small light levels, but they are relatively slow. Thus further amplification and pulse shaping are normally used.
- **PIN Diode.** The sensitivity of a standard PN-junction photodiode can be increased and the response time decreased by creating a new device that adds an undoped or intrinsic (I) layer between the P and N semiconductors. The result is a PIN diode (Fig. 19-37).
- The thin P layer is exposed to the light, which penetrates to the junction, causing electron flow proportional to the amount of light.
- PIN diodes are significantly faster in response to rapid light pulses of high frequency.
- And their light sensitivity is far greater than that of an ordinary photodiode

Figure 19-37 Structure of a PIN photodiode.



Optical Transmitters and Receivers

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- **Avalanche Diode.** The avalanche photodiode (APD) is a more widely used photo sensor. It is the fastest and most sensitive photodiode available, but it is expensive and its circuitry is complex.
- Like the standard photodiode, the APD is reverse-biased. However, the operation is different. The APD uses the reverse breakdown mode of operation that is commonly found in zener and IMPATT microwave diodes.
- When a sufficient amount of reverse voltage is applied, an extremely high current flows because of the avalanche effect. Normally, several hundred volts of reverse bias, just below the avalanche threshold, are applied.
- When light strikes the junction, breakdown occurs and a large current flows. This high reverse current requires less amplification than the small current in a standard photodiode.
- Germanium APDs are also significantly faster than the other photodiodes and are capable of handling the very high gigabit-per-second data rates possible in some systems

Wavelength-Division Multiplexing

- Wavelength-division multiplexing, another name for frequency-division multiplexing, has been widely used in radio, TV, and telephone systems.
- The best example today is the multiplexing of dozens of TV signals on a common coaxial cable coming into the home.
- In WDM, different frequencies or “colors’’ of infrared light are employed to carry individual data streams.
- These are combined and carried on a single fiber.
- Although frequency as a parameter is more widely used to distinguish the location of wireless signals below 300 GHz, at light frequencies the wavelength parameter is the preferred measure.

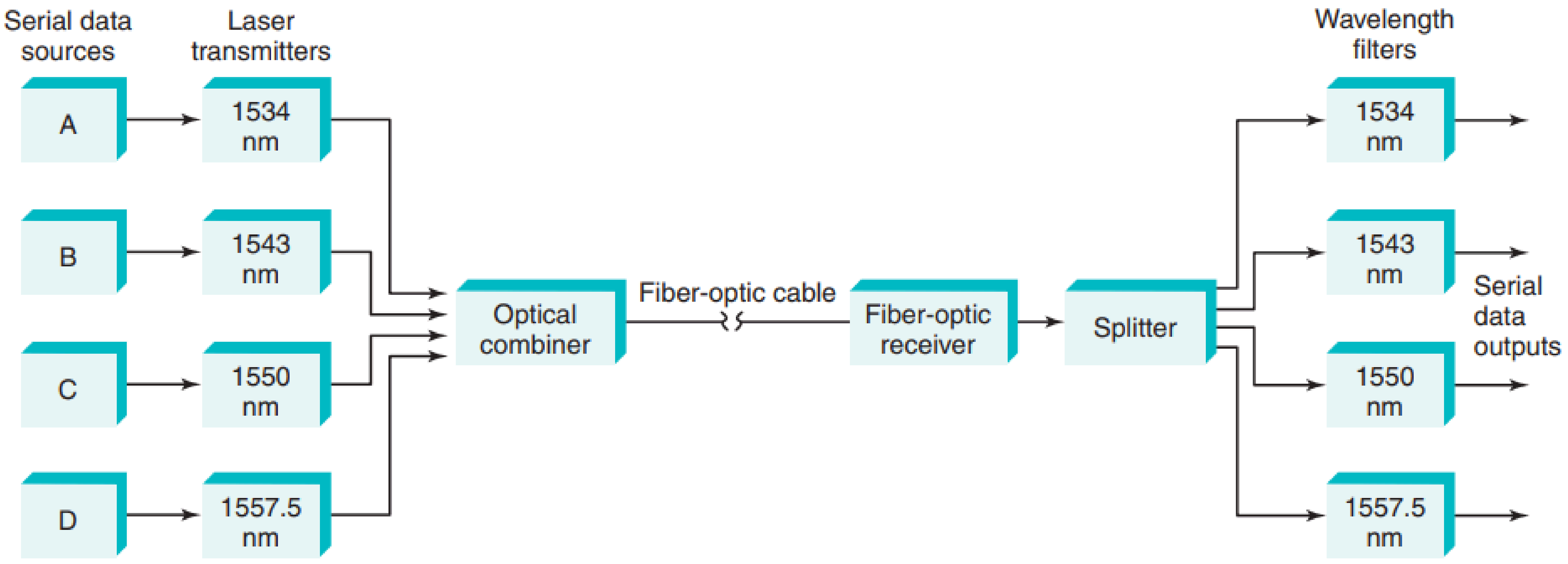
Cont…

- Data to be transmitted in a fiber-optic network is used to modulate (by OOK or ASK) a laser-generated infrared light.
- Infrared signals best match the light-carrying characteristics of fiber-optic cable, which has an attenuation response to infrared light such that the lowest attenuation (about 0.2 dB/km) occurs in two narrow bands of frequencies, one centered at 1310 nm and the other at 1550 nm.

Coarse Wavelength-Division Multiplexing

- The first coarse WDM (CWDM) systems used two channels operating on 1310 and 1550 nm.
- Later, four channels of data were multiplexed.
- Fig. 19-42 illustrates a CWDM system.
- A separate serial data source controls each laser.
- The data source may be a single data source or a multiple TDM source.
- Current systems use light in the 1550-nm range.
- A typical four channel system uses laser wavelengths of 1534, 1543, 1550, and 1557.4 nm.
- Each laser is switched off and on by the input data.
- The laser beams are then optically combined and transmitted over a single-fiber cable.
- At the receiving end of the cable, special optical filters are used to separate the light beams into individual channels.
- Each light beam is detected with an optical sensor and then filtered into the four data streams.

Figure 19-42 A CWDM fiber-optic system.



Dense Wavelength-Division Multiplexing

- Dense wavelength-division multiplexing (DWDM) refers to the use of 8, 16, 32, 64, or more data channels on a single fiber.
- Standard channel wavelengths have been defined by the International Telecommunications Union (ITU) as between 1525 and 1565 nm with a 100-GHz (approximately 0.8-nm) channel spacing.
- The block of channels between about 1525 and 1565 nm is called the C or conventional band.
- Most DWDM activity currently occurs in the C band.
- Another block of wavelengths from 1570 to 1610 nm is referred to as the long-wavelength band, or L band.
- Wavelengths in the 1525- to 1538-nm range make up the S band.

THANK YOU