CHAPTER

2

Fundamentals of Fiber-Optic Components

About This Chapter

Fiber optics started as a branch of optics and evolved into a hybrid field that includes electronics and telecommunications. The basic concept behind a fiber is optical, and some single or bundled optical fibers are used as optical components. However, the most common use of fiber optics is in telecommunications, where many concepts originated in electronics and radio communications. Today, signals are converted back and forth between optical and electronic formats as they pass through the global telecommunications network. Fiber-optic transmitters and receivers are opto-electronic devices, part optical and part electronic. To understand fiber-optic communications, you need to learn about three fields: optics, electronics, and telecommunications.

This chapter introduces optical and electronic concepts to lay the groundwork for understanding fiber-optic components. Chapter 3 covers communications systems. Later chapters explain particular devices and systems in more detail.

Basics of Optics

Optics is the part of physics dealing with light and its interaction with matter. The workings of optical fibers depend on optics, so you need to understand basic optical principles and how light interacts with matter. To prepare you, we will review these principles without going into great detail or length. Some parts of this review may seem unnecessary, but read it anyway because later chapters assume you understand these fundamentals.

From a physical standpoint, you can consider light to be either *electromagnetic waves* or particles called *photons*. This is the famous wave-particle duality of modern physics.

Both viewpoints are valid and valuable. Optical engineers are concerned with the path that light follows, so they often consider light as *rays* that follow straight lines between or within optical elements, bending only at surfaces.

Light can be considered as electromagnetic waves, photons, or rays.

Each of these viewpoints can be useful at different times. The ray model of light propagation represents how light passes through space and optical devices. Rays are easy to visualize; you can think of them as laser beams drawing straight lines in space. Yet light is not really made up of rays; it's made up of electromagnetic waves or photons. You can learn other things about light by considering it to be waves or photons.

Electromagnetic Waves and Photons

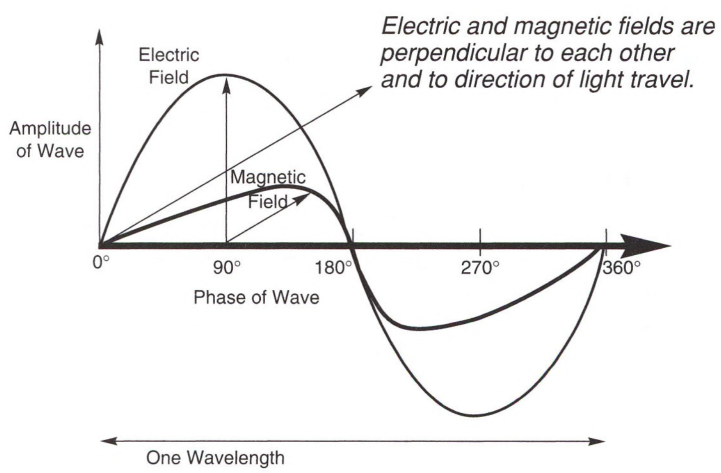
Viewed as an electromagnetic wave, *light* is composed of electric and magnetic fields, which vary in amplitude as they move through space together at the speed of light, denoted *c*. The two fields are perpendicular to each other and to the direction in which the light travels, as shown in Figure 2.1. The amplitude of each field varies *sinusoidally*, like a sine function in trigonometry, rising from zero to a positive peak, going back through zero, hitting a negative peak, then returning to zero. The distance that light travels during that complete cycle is called the *wavelength*. The usual symbol for wavelength is the Greek letter λ (lambda), and that's one symbol you should remember. The number of waves or cycles per second is called the *frequency*, and it's measured in hertz (after Heinrich Hertz, who discovered electromagnetic waves). Frequency usually is denoted by the Greek letter ν (nu). Wavelength decreases as frequency increases, and waves can be measured by either.

Many light sources such as red laser pointers emit *continuous* light waves, which oscillate steadily at the same frequency. You can think of them as sine waves that go on for a very long time. Other sources emit pulses of light, and it's useful to think of pulses of light as groups of photons.

A photon is a quantum of electromagnetic energy.

A photon is a quantum of electromagnetic energy. It's also a *wave packet*, a series of a few waves that build quickly to a peak amplitude, then fade back to nothing, as shown in

FIGURE 2.1
A light wave consists of electric and magnetic fields.



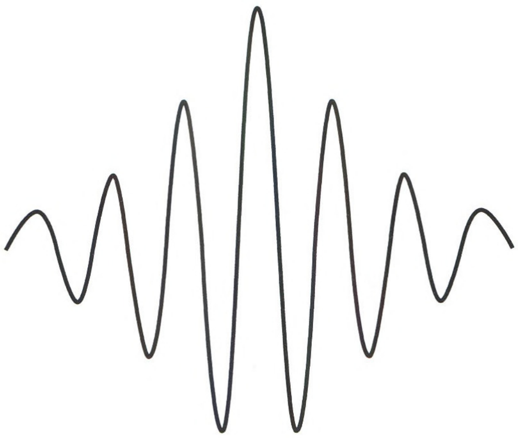


FIGURE 2.2
A single photon is a short packet of waves.

Figure 2.2. Like a continuous wave, a pulse or wave packet has a wavelength and a frequency, but the wavelength and frequency are not as well defined as for a continuous beam. Thanks to the uncertainty principle, the shorter the pulse, the larger the uncertainty in wavelength.

The amount of energy carried by a single photon depends on the oscillation frequency: The faster the wave oscillates, the higher the energy. A continuous wave is a series of photons, emitted one after the other. Each photon has a unit of energy set by the wavelength or frequency, so the total energy is the number of photons times that photon energy. In wave terms, this is proportional to the wave amplitude squared.

The Electromagnetic Spectrum

What we call "light" is only a small part of the spectrum of *electromagnetic radiation.* The fundamental nature of all electromagnetic radiation is the same. It can be viewed as photons or waves and travels at the speed of light (*c*), which is approximately 300,000 kilometers per second (km/s), or 180,000 miles per second (mi/s). The difference between radiation in different parts of the electromagnetic spectrum is a quantity that can be measured in several ways: as the length of a wave, as the energy of a photon, or as the oscillation frequency of an electromagnetic field. Figure 2.3 compares these three views.

The light carried in fiber-optic communications systems can be viewed as either a wave or a particle.

Each measurement—wavelength, energy, or frequency—has its own characteristic unit. The preferred unit depends on the part of the spectrum. The optics world usually talks in wavelength, which is measured in meters, *micrometers* (μm or 10^{-6} m), *nanometers* (nm or 10^{-9} m), or sometimes in angstroms (1Å = 10^{-10} m). Don't even think of wavelength in inches. (If you absolutely have to know, 1 μm is 0.00003937 in.) Frequency is measured in cycles per second (cps) or hertz (Hz), with megahertz (MHz) meaning a million hertz and gigahertz (GHz) meaning a billion hertz. (The metric system uses the standard prefixes listed in Appendix A to provide different units of length, weight, frequency, and other quantities. The prefix makes a unit a multiple of a standard unit. For example, a millimeter is a thousandth [10^{-3}] of a meter, and a kilometer is a thousand [10^{3}] meters.)

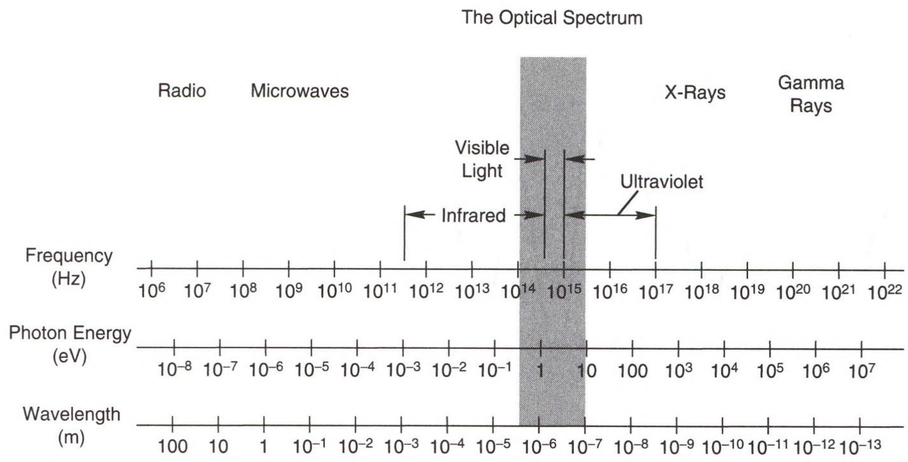


FIGURE 2.3
Electromagnetic spectrum.

Photon energy can be measured in many ways, but the most convenient here is in electron volts (eV)—the energy that an electron gains in moving through a 1-volt (V) electric field.

All the measurement units shown on the spectrum chart are actually different rulers that measure the same thing. There are simple ways to convert between them. Wavelength is inversely proportional to frequency, according to the formula:

$$\text{wavelength} = \frac{c}{\text{frequency}}$$

or

$$\lambda = \frac{c}{\nu}$$

where c is the speed of light, λ is wavelength, and ν is frequency. To get the right answer, all terms must be measured in the same units. Thus c must be in meters per second (m/s), λ must be in meters, and frequency must be in hertz (or cycles per second). Plugging in the approximate value of c, we have a more useful formula for wavelength:

$$\lambda = \frac{3 \times 10^8 \text{ m/s}}{\nu}$$

You can also turn this around to get the frequency if you know the wavelength:

$$\nu = \frac{3 \times 10^8 \text{ m/s}}{\lambda}$$

Not many people talk about photon energy (E) in fiber optics, but a value can be gotten from Planck's law, which states:

$$E = h\nu$$

where h is Planck's constant (6.63×10^{-34} J-s, or 4.14×10^{-15} eV-s) and ν is the frequency. Because most interest in photon energy is in the part of the spectrum measured in wavelength, a more useful formula is

$$E(eV) = \frac{1.2399}{\lambda\ (\mu m)}$$

which gives energy in electron volts when wavelength is measured in micrometers (μm).

We are mainly interested in a small part of the spectrum shown in Figure 2.3—the optical region, where optical fibers and other optical devices work. That region includes light visible to the human eye at wavelengths of 400 to 700 nm and nearby parts of the infrared and ultraviolet, which have similar properties. Roughly speaking, this means wavelengths of 200 to 20,000 nm (0.2 to 20 μm).

The wavelengths normally used for communications through silica glass optical fibers are 750 to 1700 nm (0.75 to 1.7 μm) in the near infrared, where silica is the most transparent. Glass and silica fibers can transmit visible light over shorter distances, and special grades of silica (often called *fused quartz*) can transmit near-ultraviolet light over short distances. Plastic fibers transmit best at visible wavelengths.

Fiber-optic communications systems transmit near-infrared light invisible to the human eye.

Wave Phase and Interference

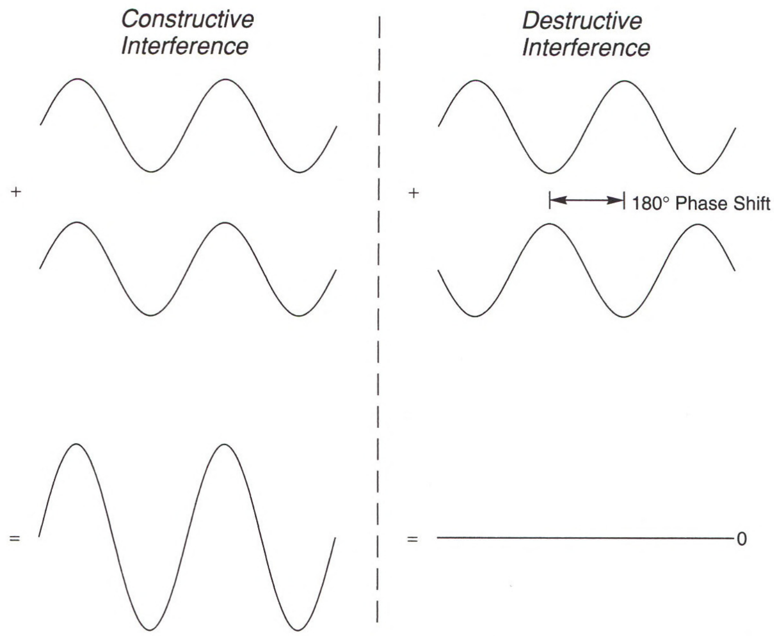
One important consequence of the wave nature of light is that light waves have a property called *phase*, which measures the progress of the wave in its cyclical variation in amplitude. Figure 2.1 showed one complete cycle, in which the amplitude of the electric and magnetic fields rises, falls, and returns to the starting point. Light waves from a continuous source repeat this cycle endlessly. Repeating this cycle is like going around a circle, and the phase is measured as an angle between 0° and 360°. The electric and magnetic fields depend on each other, so normally the phase is measured only for the electric field.

Electromagnetic waves combine by adding their amplitudes. If you start with a pair of waves with the same wavelength and amplitude, and the peaks and valleys line up perfectly, their amplitudes add, producing an effect called *constructive interference* (shown in Figure 2.4). However, if the peaks of one wave line up with the valleys of the other wave, the sum of the two intensities at any instant is zero, because one has a positive value and the other has a negative value of the same amount. This case, also shown in Figure 2.4, is known as *destructive interference*. Destructive interference occurs when the two waves are 180° out of phase. With intermediate phase shifts, the combined amplitude is between the peak of constructive interference and the null of destructive interference. (Because the wave repeats indefinitely, we only measure phase shifts within one cycle, between 0° and 360°.)

Light waves add or subtract in amplitude depending on their relative phase.

We normally don't see this interference effect because most light sources radiate light in all directions at a wide range of wavelengths. Turn on two light bulbs in a dark room, and the total intensity is the sum of the two intensities. To see interference you need to combine two identical light waves so their amplitudes add or subtract. You can do this by passing light through a pair of closely spaced slits. Light spreads out from each of the slits,

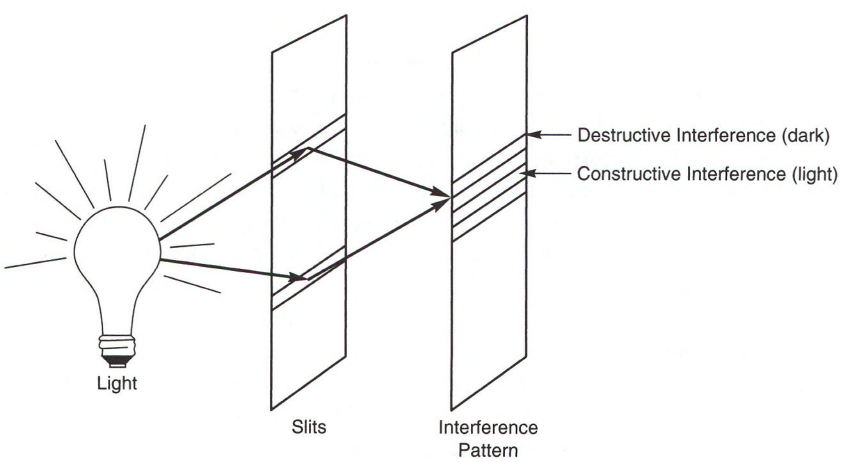
FIGURE 2.4
Constructive and destructive interference.



producing a pattern of light and dark regions where the waves interfere constructively and destructively, as shown in Figure 2.5. (The pattern arises because the waves travel slightly different distances from the two slits.)

If you're familiar with the law of conservation of energy, you may wonder where the energy goes when the light waves interfere destructively. The energy doesn't disappear; it's just rearranged in space, appearing where the waves interfere constructively. The total

FIGURE 2.5
Interference of light waves traveling slightly different paths produces bright and dark stripes.



amount of light in the interference pattern is the total passing through the two slits, but it's not spread evenly.

Refractive Index

The speed of light in a vacuum (*c*) is considered the universal speed limit. Normally nothing travels faster, although sometimes light can go a bit over the speed limit if it carries no information.

Refractive index is the speed of light in a vacuum divided by the speed of light in a material.

Light always travels more slowly through transparent materials than through a vacuum. The speed difference for a material is measured by a number called the *refractive index*, denoted by the letter n in optics, which equals the speed of light in a vacuum divided by the speed of light in the material:

$$n = \frac{c_{\text{vacuum}}}{c_{\text{material}}}$$

The refractive index of a vacuum equals 1.0 by definition. For normal optical materials, the refractive index is greater than 1.0 in the optical part of the spectrum. (There are some peculiar exceptions you don't need to worry about.) In practice, the refractive index is measured by comparing the speed of light in a material to the speed of light in air rather than in a vacuum. This makes little practical difference because the refractive index of air at normal pressure and temperature is 1.000293.

Refraction occurs when light changes speed as it goes between two materials.

Light changes speed as it goes from one material into another, such as from air into glass. This causes an effect we call *refraction.* To understand refraction, consider what happens to the peaks of light waves as they enter glass from air, as shown in Figure 2.6. The peaks of the waves line up in air, but when the waves hit the glass at an angle, some of the light enters the glass while the rest remains in the air. The frequency of the wave does not change as the waves slow down in the glass, so the wave takes the same time to complete a cycle, but it doesn't travel as far between peaks in glass as it did in the air. The waves in air continue at the same speed until they reach the surface of the glass, where they also slow down. This process of slowing down bends the path of the light, as you can see in Figure 2.6. The same thing would happen if you braked the wheels on only one side of your car; its path would turn toward the side where the wheels slowed.

Figure 2.6 shows the wave view of light, with a broad *wavefront* passing through the glass. In practice, it's more useful to consider refraction from the ray viewpoint. The bold line in the figure represents the light ray, which bends at the surface of the glass. That ray shows how the path of the light bends as light passes between the two media.

The bending of light at a surface depends on the refractive indexes of the two materials and the *angle of incidence* at the surface. Both the angle of incidence and the *angle of refraction* of the transmitted light are measured from a line perpendicular to the surface called the *normal.* Snell's law describes this bending:

$$n_i \sin I = n_r \sin R$$

where n_i and n_r are the refractive indexes of the initial medium and the medium into which the light is refracted, and I and R are the angles of incidence and refraction, respectively, as shown in Figure 2.6.

FIGURE 2.6
Refraction of light entering glass.

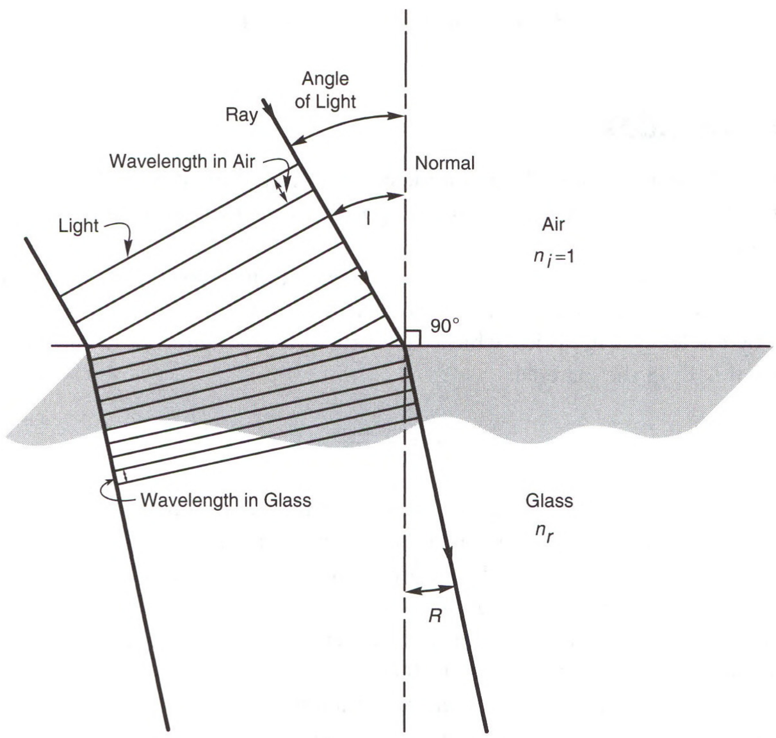


Figure 2.6 shows the standard example of light going from air into glass. The same thing happens in reverse when light emerges into air on the other side of the glass. If the front and rear surfaces of the glass are flat, light emerges at the same angle at which it entered, and the net refraction is zero, as when you look through a flat window. (The light is displaced a little bit, but we usually don't notice that shift.) If one or both surfaces are curved, the light rays emerge at a different angle than when they entered the glass, and you see a net refraction or bending of the light rays, as if you were looking through a lens. Figure 2.7 shows the overall refractive effect.

Total internal reflection occurs when light in a high-index material hits a boundary with a material of lower refractive index at a glancing angle.

What does this have to do with fiber optics? Stop and consider what happens when light in a medium with a high refractive index (such as glass) comes to an interface with a medium having a lower refractive index (such as air). If the glass has a refractive index of 1.5 and the air an index of 1.0, the equation becomes

$$1.5 \sin I = 1 \sin R$$

Instead of being bent closer to the normal, as in Figure 2.6, the light is bent farther from it, as in Figure 2.8. This isn't a problem if the angle of incidence is small. For $I = 30°$, $\sin I = 0.5$, and $\sin R = 0.75$. But a problem does occur when the angle of incidence becomes too steep. For $I = 60°$, $\sin I = 0.866$, so Snell's law says that

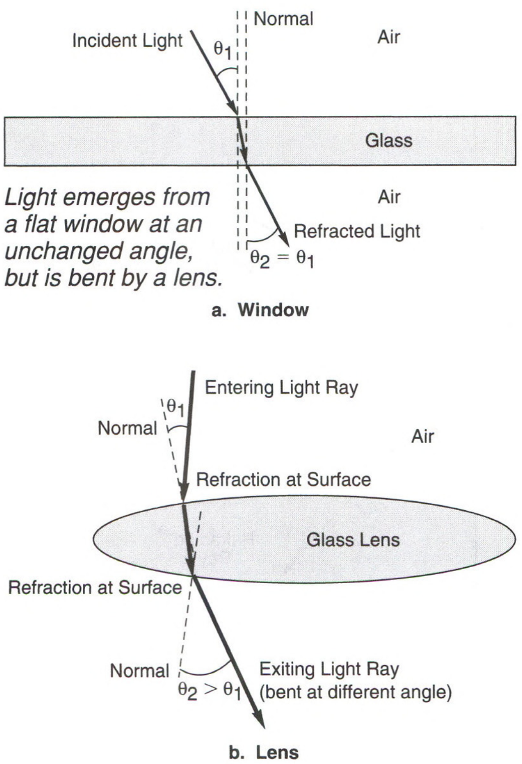


FIGURE 2.7
Refraction through a window and a lens.

sin $R = 1.299$. Your pocket calculator will tell you this is an error. That angle can't exist because the sine can't be greater than 1.0.

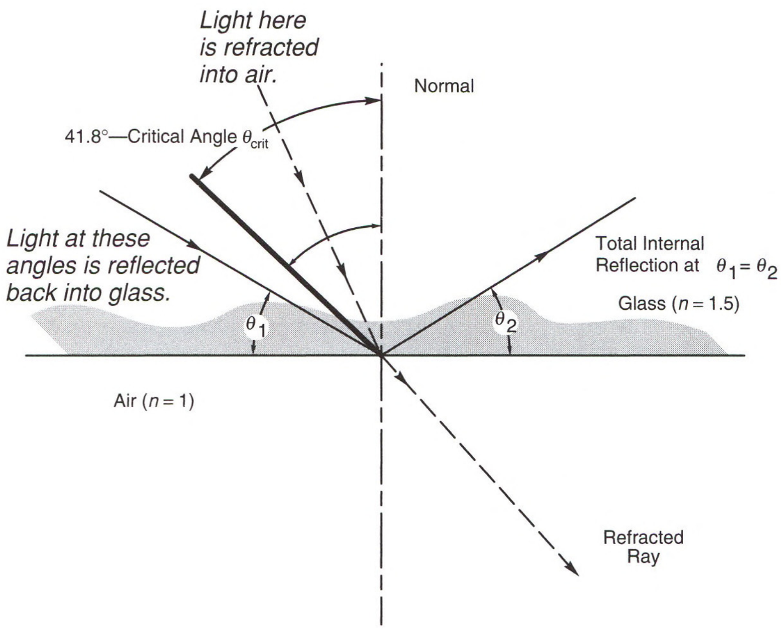
Snell's law indicates that refraction can't take place when the angle of incidence is too large, and that's true. Light cannot get out of the glass if the angle of incidence exceeds a value called the critical angle, where the sine of the angle of refraction would equal 1.0. (Recall from trigonometry that the maximum value of the sine is 1.0 at 90°, where the light would be going along the surface.) Instead, total internal reflection bounces the light back into the glass, obeying the law that the angle of incidence equals the angle of reflection, as shown in Figure 2.8. It is this total internal reflection that confines light in optical fibers, at least to a first approximation. As you will see in Chapter 4, the mechanism of light guiding is more complex in modern communication fibers.

The *critical angle* above which total internal reflection takes place, θ_{crit}, can be deduced by turning Snell's law around, to give

$$\theta_{crit} = \arcsin (n_r/n_i)$$

For the example given, with light trying to emerge from glass with $n = 1.5$ into air, the critical angle is arcsin (1/1.5), or 41.8°.

FIGURE 2.8
Refraction and total internal reflection.



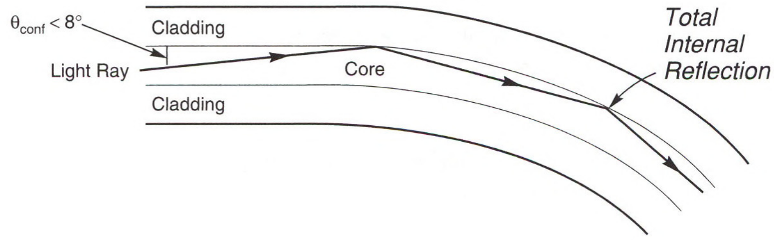
Light Guiding

Light is guided in the core of an optical fiber by total internal reflection at the boundary.

The two key elements of an optical fiber—from an optical standpoint—are its *core* and *cladding*. The core is the inner part of the fiber, which guides light. The cladding surrounds it completely. The refractive index of the core is higher than that of the cladding, so light in the core that strikes the boundary with the cladding at a glancing angle is confined in the core by total internal reflection, as shown in Figure 2.9.

The difference in refractive index between core and cladding need not be large, and is less than 1% in most telecommunications fibers. For a 1% difference, corresponding to $n_r/n_i = 0.99$, the critical angle, θ_{crit}, measured from the normal is about 82°. That means light is confined in the core if it strikes the cladding interface at an angle of 8° or less, as shown in Figure 2.9. The upper limit measured from the interface is called the *confinement angle*, θ_{conf}, of the fiber.

FIGURE 2.9
Light guiding in an optical fiber.



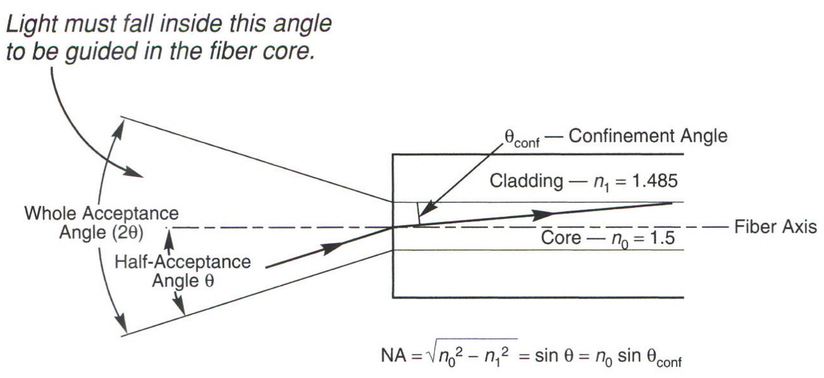


FIGURE 2.10 *Measuring the acceptance angle.*

Another way to look at light guiding in a fiber is to measure the fiber's *acceptance angle*—the angle over which light rays entering the fiber will be guided along its core, shown in Figure 2.10. Because the acceptance angle is measured in air outside the fiber, it differs from the confinement angle in the glass. The acceptance angle normally is measured as *numerical aperture* (NA), which for light entering a fiber from air is approximately

$$\mathrm{NA} = \sqrt{(n_0^2 - n_1^2)}$$

where n_0 is the refractive index of the core and n_1 is the index of the cladding. For a fiber with core index of 1.50 and cladding index of 1.485 (a 1% difference), NA = 0.21. An alternative but equivalent definition is the sine of the half-angle over which the fiber can accept light rays, 12° in this example (θ in Figure 2.10). Another alternative definition is $\mathrm{NA} = n_0 \sin \theta_{conf}$, where θ_{conf} is the confinement angle in the fiber core (8° in this example). These angles are measured from a line drawn through the center of the core, called the *fiber axis.*

The angle over which a fiber accepts light depends on the refractive indexes of the core and cladding.

Note that the half-acceptance angle is larger than the largest glancing angle at which light rays must strike the cladding interface to be reflected, which I said earlier was 8°. What does this mean? Look at Snell's law of refraction again. The difference is the factor n_0, which is the refractive index of the core glass, or 1.5. As you can see in Figure 2.10, refraction bends a light ray entering the fiber so that it is at a smaller angle to the fiber axis than it was in the air. The sine of the angle inside the glass equals that of the angle outside the glass, divided by the refractive index of the core (n_0).

Light Collection Efficiency

An optical fiber will pick up some light from any light source. You can see this if you point a single large-core fiber at a lightbulb. Look into the other end of the fiber, taking care not to get your eye too close. You should see an illuminated spot in the fiber. That light comes from the bulb, but it's only a tiny fraction of the total the bulb emits. Appendix E describes eye-safety precautions, which are important if you are using a laser source.

Light source size and alignment are critical in collecting light in a fiber core.

Developing ways for small-core fibers to collect light efficiently was an important step in developing practical fiber-optic communications. This includes both collecting light from external sources and transferring light from one fiber to another. *Coupling* light efficiently into the fiber requires both focusing it onto the core and aligning it so it falls within the fiber's acceptance angle. The combination imposes demanding requirements.

Simple optics can focus the light from an ordinary bulb so it forms a narrow beam. You can see the results in a flashlight beam or a searchlight. A careful look reveals that the focusing is not perfect, but the beams are strongly directional. However, focusing a large light source into a narrow beam leaves a large spot that spreads far beyond the fiber core. Large light sources can be focused onto small spots with strong magnifying lenses. You've probably used that trick to burn a hole in paper with focused sunlight. However, that normally leaves the light spreading at too large an angle for the fiber to collect it efficiently.

For communication systems, it's generally more efficient to find a light source that is close to the fiber core in size. Generally these are semiconductor lasers, which emit light from a small spot, or optical-fiber amplifiers, which emit light from a doped core, as described later. Light-emitting diodes (LEDs) can be used with some larger core fibers because they are less expensive and the larger cores can collect more of their light. Larger light sources generally are easier to align with fibers, but their lower intensity delivers less light. Chapter 9 describes light sources in more detail.

Joining the ends of optical fibers requires careful alignment and fight tolerances.

Transferring light between fibers requires careful alignment and tight tolerances. Light transfer is most efficient when the ends of two fibers are permanently joined in a splice (described in Chapter 13). Temporary junctions between two fiber ends, made by connectors (also described in Chapter 13) typically have slightly higher losses but allow much greater flexibility in reconfiguring a fiber-optic network. Special devices called *couplers* (described in Chapter 14) are needed to join three or more fiber ends. One of the most important functional differences between fiber-optic and wire communications is that fiber couplers are much harder to make than their metal-wire counterparts.

Transfer losses must be considered in fiber-optic communications systems.

Losses in transferring signals between wires are so small that they can normally be neglected. This is not so for fiber optics. As you will see in Chapter 21, system designers should account for coupling losses at each connector, coupler, splice, and light source.

Fiber Transmission

Attenuation, dispersion, and crosstalk can degrade signals transmitted by optical fibers.

Optical fibers inevitably affect light transmitted through them. The same is true for any material transmitting any kind of signals. You notice these effects most for poor transmitters, like dirty windows or crackling telephone lines. However, they are present even for the tenuous gas dispersed in intergalactic space, which astronomers can spot because it absorbs a tiny fraction of the light passing through it. Generally these effects degrade signals, and if they become large enough, they can make it impossible to receive the signals.

The three principal effects that degrade signals in optical fibers are *attenuation, dispersion,* and *crosstalk.* You can see analogous effects when electronic signals go through copper wires or are broadcast as radio or television signals. These effects are critical to the performance of fiber-optic systems, so I will introduce the concepts here before exploring them in more detail in later chapters.

Fiber Attenuation

Attenuation makes signal strength fade with distance. In some cases, such as broadcast radio, distance alone can cause attenuation because signals spread out through space as they travel. As the signal spreads over a larger volume, the intensity drops.

Absorption, scattering, and light leakage are the components of fiber attenuation.

This is not the case in optical fibers, which are *waveguides* that confine light within the core along their entire length. This prevents signals from spreading over a larger volume, but other effects cause different types of attenuation. The three primary effects are *absorption*, *scattering*, and *leakage* of light from the fiber core. You will learn more about these later, but a basic understanding of the concepts will help you now.

Although optical fibers are made of extremely pure glass, they absorb a tiny fraction of the light passing through them. The amount depends on the wavelength and the presence of impurities. Certain impurities cause strong absorption, but even pure silica has some absorption. Every transparent object absorbs a little light but transmits most of the light that enters it; opaque materials transmit a little light a little way inside them, but they absorb (or reflect) most of the incident light.

Atoms within the fiber scatter light out of the core.

Atoms within the glass also scatter light. The physics are complex, but the atoms act as if they were tiny reflective particles, like droplets in a fog bank. Scattering reflects light in other directions, so it escapes from the fiber core and is lost from the signal. Like absorption, scattering is inherent in all fiber materials, but generally is small. The amount of scattering increases at shorter wavelengths, so it's higher at visible wavelengths than in the infrared. The physics are the same as for light scattering in the atmosphere, which spreads short-wavelength blue light all over the sky, while allowing longer red wavelengths to reach us as the sun rises and sets.

Light leakage occurs when light escapes from the fiber core into the cladding. It's normally very low unless the fiber is bent sharply, when light can escape by hitting the core-cladding boundary at a steep enough angle to avoid total internal reflection. As you will learn later, fiber installation and the environment can bend fibers in ways that allow light to leak out, but normally this loss is the smallest of the three types. Like leaky plumbing, it's a rare event that indicates something has gone wrong.

Although absorption and scattering are extremely small in optical fibers, total attenuation accumulates when light travels through many kilometers of fiber. Attenuation normally is measured by comparing the strength of the input signal to the output. For example, if 99% of the input light emerges from the other end, a fiber has 1% attenuation.

Attenuation of a fiber is the product of the length times the characteristic loss in decibels per kilometer.

Attenuation is cumulative, and normally uniform through the entire length of a fiber. Thus every meter of fiber should have the same attenuation as the previous meter. If 99% of the light emerges from the first meter, 99% of that light should emerge from the second meter, and so on. For a 10-meter fiber, the light emerging should be

$$\begin{aligned}\text{Output} &= \text{Input} \times 0.99 \times 0.99 \times 0.99 \times 0.99 \times 0.99 \\ &\quad \times 0.99 \times 0.99 \times 0.99 \times 0.99 \times 0.99 = 0.904 \times \text{Input}\end{aligned}$$

More generally, the output is

$$\text{Output} = \text{Input} \times (\text{transmission/unit length})^{\text{Total length}} = \text{Input} \times (0.99)^{10}$$

These sorts of calculations get messy, so generally attenuation is measured in *decibels* (dB), which are very useful units, although peculiar ones. The decibel is a logarithmic unit measuring the ratio of output to input power. (It is actually a tenth of a unit called a *bel* after Alexander Graham Bell, but that base unit is virtually never used.) Loss in decibels is defined as

$$\text{dB loss} = -10 \times \log_{10}\left(\frac{\text{power out}}{\text{power in}}\right)$$

Thus, if output power is 0.001 of input power, the signal has experienced a 30-dB loss.

The minus sign is added to avoid negative numbers in attenuation measurements. It is not used in systems where the signal level might increase, where the sign of the logarithm indicates if the signal has decreased (minus) or increased (plus).

Each optical fiber has a characteristic attenuation that is measured in decibels per unit length, normally decibels per kilometer. The total attenuation (in decibels) in the fiber equals the characteristic attenuation times the length. To understand why, consider a simple example with a fiber having the relatively high attenuation of 10 dB/km. That is, only 10% of the light that enters the fiber emerges from a 1-km length. If that output light was sent through another kilometer of the same fiber, only 10% of it would emerge (or 1% of the original signal), for a total loss of 20 dB.

Decibel losses are easy to underestimate; every 10 dB decreases signal strength by a factor of 10.

As you can see, the decibel scale simplifies calculations of attenuation. It's widely used in electronics and acoustics as well as optics. You'll learn more about decibels later, but you should realize that they are easy to underestimate. Decibels are really exponents, not ordinary numbers. Every additional 10-dB loss reduces the output a factor of 10. A 20-dB loss is a factor of 100 ($10^{2.0}$), a 30-dB loss is a factor of 1000 ($10^{3.0}$), and a 40-dB loss is a factor of 10,000 ($10^{4.0}$). These numbers can get very big very fast. Appendix B gives some comparisons for decibel units, which you may find surprising.

Bandwidth and Dispersion

Optical fibers are unique in transmitting high-speed signals with low attenuation.

Low attenuation alone is not enough to make fibers invaluable for telecommunications. The thick wires that transmit electrical power also have very low loss, but they cannot transmit information at high speeds. Optical fibers are attractive because they combine low loss with high bandwidth to allow high-speed signals to travel over long distances. In a communication system, this becomes high bandwidth, the ability to carry billions of bits per second over many kilometers.

Concepts such as *bandwidth* and *information capacity* are crucial in communications, and the next chapter will tell you more about them. They measure the flow of information through a communication system. For example, television signals have more bandwidth than audio signals. In general, the more bandwidth or information, the better.

Attenuation of copper wires increases with signal frequency.

The more information you want to transmit, the faster the signal has to vary, and it's the need for rapidly varying signals that can cause problems in transmitting high-bandwidth signals. Different effects limit different types of communications. The number of dots and dashes an old-fashioned electrical telegraph could transmit was limited by how fast one operator could hit the transmitting key and how fast another could write down or relay the incoming signals.

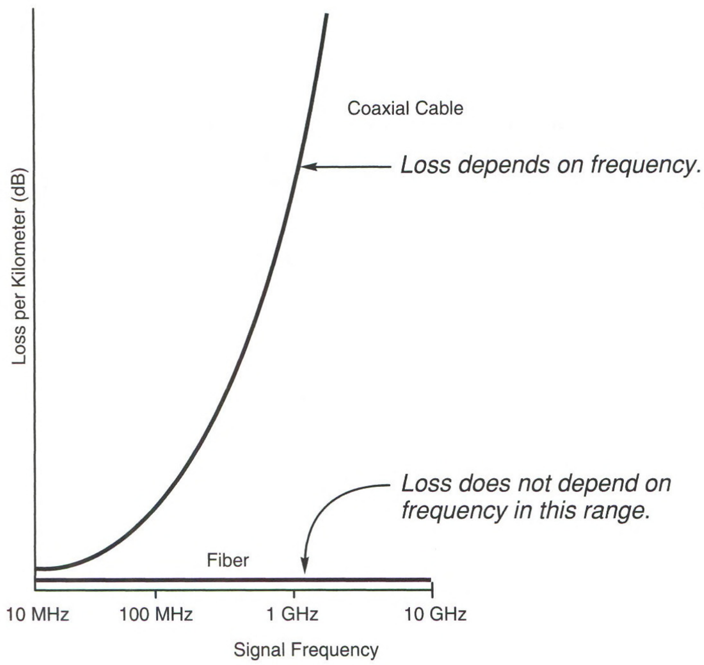


FIGURE 2.11
Loss as a function of frequency.

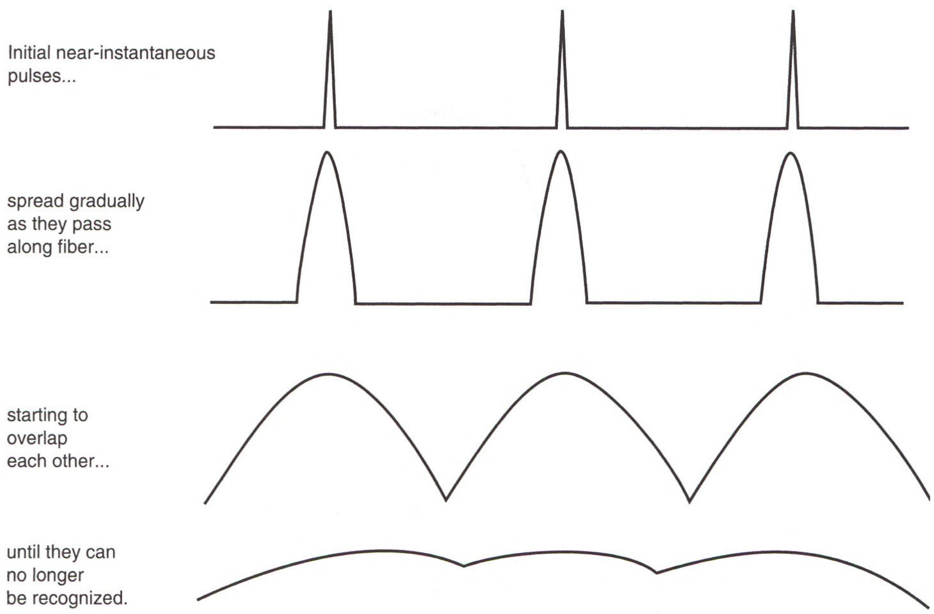
The speed limit on electrical wires comes from the nature of electrical currents. Moving electrons induce currents in the copper around them, so the impedance of a wire increases with the speed at which the signal varies. In practice, that means the higher the frequency, the higher the attenuation. Pairs of copper wires have very low attenuation at the extremely low frequencies used for electrical power transmission, 60 Hz in North America and 50 Hz in Europe, and they can carry audio frequencies over reasonable distances, but not television signals. Coaxial cables can transmit higher frequencies, but their attenuation increases sharply with frequency, as shown in Figure 2.11. In contrast, optical fibers have essentially the same attenuation across a wide range of operating frequencies, although dispersion does attenuate high signal frequencies, as described below.

Dispersion limits fiber transmission bandwidth.

The main limitation on fiber-optic bandwidth is an effect called *dispersion.* It is easiest to visualize if you consider a signal as made up of an instantaneous pulse containing many photons. The photons are not perfectly identical, so they spread out a little as they travel, like a group of race cars on a track. Some spreading occurs because the wavelengths differ slightly, and the refractive index of the glass varies with wavelength. Other spreading comes because the photons may travel slightly different paths through some types of fiber. The effects are small, but like attenuation they accumulate with distance. The farther the pulses travel, the more the photons spread out. If the light travels far enough, the first photons in one pulse catch up with the last photons in the previous pulse, and eventually it's no longer possible to tell the pulses apart, as shown in Figure 2.12. You'll learn more about dispersion in Chapter 5.

Figure 2.12 is an oversimplification in one important aspect: In real fiber-optic systems, digital signals start as boxy square-wave pulses, created by switching a light source on and

FIGURE 2.12
Pulse dispersion.



off very quickly. Gradually the edges round off as some photons get ahead and others fall behind. From a signal-processing standpoint, the sharp edges of a square wave are really signals at frequencies many times higher than the rate at which the pulses are being switched off and on. As the pulse of photons blurs out along the fiber, those high-frequency components are lost. Thus the blurring of sharp square-wave pulses into rounded lumps is really high-frequency attenuation, and optical fibers do have limited transmission bandwidth. But what's important is that the limit for optical fibers is at much higher frequencies than for copper wires.

Crosstalk and Nonlinear Effects

Crosstalk is the leakage of signals between nominally independent channels.

Crosstalk occurs when signals cross the barriers that are supposed to separate them from each other. You have crosstalk on the phone if you hear a radio station or another conversation in the background. The different communication channels—phone lines and radio broadcasts—are supposed to be separate from each other. However, a little bit of one can leak into another channel. There are many reasons for electrical crosstalk. Phone wires can act as antennas to pick up strong radio signals. Currents in one pair of wires can induce signals in another pair running beside them. Sometimes other equipment may transmit signals through the air at the same frequency, so you might hear static on your AM radio when a motor operates nearby.

Fibers are immune to the usual electronic crosstalk. They don't carry electrical currents, and the light inside them is unaffected by nearby currents. You can run fibers along power lines and never hear a thing, although the 60-cycle hum would overwhelm telephone wires.

However, fibers carrying multiple signals or *optical channels* at different wavelengths—an important technique called *wavelength-division multiplexing*—are vulnerable to crosstalk. Nominally, light signals at different wavelengths passing through the same fiber do not interact because no current flows between them. However, like electrical phone signals passing through parallel wires, there can be secondary interactions called *nonlinear effects* because they aren't directly proportional to the strength of a single signal. These nonlinear effects are complex, and are the prime cause of crosstalk. You'll learn more about them in Chapter 5.

Nonlinear interactions between optical channels in the same fiber can cause crosstalk.

Electro-Optics and Other Components

Electronics play important roles in fiber-optic systems. Because this book is about fiber optics, it doesn't cover electronics in general, but it will cover the electronics used in fiber systems. It assumes only a very general knowledge of electronics.

Electronics play important roles in fiber-optic equipment.

Many components have both optical and electronic elements, which often are called *electro-optics* or *opto-electronics* to emphasize the connection. Sometimes these components are lumped with optical devices and called *photonics*, a term that originated from the idea of manipulating photons just as electronics manipulate electrons.

These components fall into two very broad categories. One includes devices that convert signals between optical and electronic formats, such as transmitters and receivers. These provide vital connections between fiber-optic systems and other equipment, such as telephones and computers. The second includes devices that manipulate light but are powered or controlled by electronic circuits, such as optical amplifiers that raise the strength of optical signals, and modulators that control the intensity of light passing through them. We'll introduce both types of components briefly here and cover them in more detail later.

Transmitters and Light Sources

Optical *transmitters* convert electronic input signals into the optical signals carried by fiber systems. Electronic circuits take the input electronic signal and process it to modulate light generated by a light source. Typically the light source is a semiconductor laser—often called a *laser diode*—or a *light-emitting diode* (LED). You'll learn more about light sources in Chapter 9 and about transmitters in Chapter 10.

Different types of light sources are used for different applications. Lasers generate higher power and can be modulated at higher speeds, so they transmit faster signals farther than LEDs. The wavelength is chosen to meet requirements for transmission distance and bandwidth. Most transmission is in a band called the *near-infrared*, which is invisible to the human eye. High-speed, long-distance systems use a range of wavelengths from 1530 to 1625 nanometers, where optical fibers have low attenuation and optical amplifiers are readily available. Short high-speed systems use 1310 nanometers, a wavelength at which attenuation is somewhat higher but dispersion is lower. Wavelengths of 750 to 900 nanometers are used for systems spanning no more than a few kilometers. Low-cost systems spanning much shorter distances typically use red LEDs and plastic fibers, which have high attenuation.

Transmitter wavelength depends on the application requirements.

Some transmitters include stages that combine or *multiplex* different signals to generate a composite signal containing the information in multiple signals.

THINGS TO THINK ABOUT

Photonics

Newcomers to the world of fiber optics are likely to be confused by the term *photonics*, which is widely used in some circles but ignored in others. The use of this term reflects a confusing and controversial history.

I first heard the term "photonics" about 30 years ago. But it didn't come into popular use until it was adopted some years later by Bell Labs and one of the industry's leading trade magazines (formerly called *Optical Spectra*, now *Photonics Spectra*). The idea was for "photonics" to describe devices that manipulate light in the same way that electronics describes things that manipulate electrons. Because I wrote regularly for a competing magazine, I tended to avoid the word.

Other optical engineers and scientists also showed little enthusiasm, because "photonics" sounded like another word for "optics," which they felt was a perfectly adequate description of their field. Matters came to a head when a group of leaders attempted to change the name of the Optical Society of America to the Optics and Photonics Society. The members soundly rejected the proposal, and the community remains divided on "photonics." Some like its modern sound, but others find it unnecessary or obscure and think "optics" is a better description of the field.

Receivers and Detectors

A receiver converts an optical signal into electronic form.

A *receiver* converts an optical signal into an electrical signal usable by other equipment. The input light signal is directed into a *detector*, which produces a current or voltage proportional to the amount of light illuminating it. Electronic circuits in the receiver amplify that signal and convert it into the format required by electronic equipment at the receiver end of the system. Like transmitters, receivers are designed to operate at specific wavelengths; the usable wavelengths depend on the detector chosen.

The receiver also *demultiplexes* input signals combined at the transmitter, producing separate output signals corresponding to each of the input signals.

Fiber-Optic Applications

The bulk of this book is about fiber-optic applications in communications, but it's important to remember that there are other uses for fiber optics. Chapter 29 describes the wide variety of fiber-optic sensors, from gyroscopes that sense rotation to acoustic sensors that pick up faint undersea sounds. Chapter 30 shows how bundles of optical fibers are used for imaging and illumination.

What Have You Learned?

1. Light is one type of electromagnetic radiation. It is a part of the electromagnetic spectrum with a distinct range of wavelengths, frequencies, and photon energies. Optical wavelengths include the near-ultraviolet, visible, and near-infrared.
2. Light can be viewed as electromagnetic waves, photons, or rays, depending on the situation. Each view has its advantages.

3. A photon is a quantum of electromagnetic energy.
4. Wavelength equals the speed of light divided by the frequency of the wave.
5. Light waves add or subtract in amplitude depending on their relative phase, an effect called *interference.*
6. Refractive index (n) is the speed of light in a vacuum divided by the speed of light in the material. It is always less than 1.0 for materials at optical wavelengths.
7. Refraction is the bending of light as it changes speed when entering a new material. It depends on the refractive index of the material and the angle of incidence.
8. Total internal reflection can trap light inside a material that has a higher refractive index than its surroundings. The critical angle for total internal reflection depends on the difference between the two indexes.
9. Total internal reflection guides light along the core of an optical fiber, which has a higher refractive index than the surrounding cladding.
10. Light that falls within the acceptance angle of a fiber is guided in the core. The numerical aperture is the sine of the acceptance angle.
11. Fiber collection efficiency depends on light source size and alignment to the fiber core.
12. Attenuation reduces the amount of light transmitted, reducing transmission distance. It depends on wavelength and occurs because the glass scatters and absorbs light. It is measured in decibels.
13. Dispersion is the spreading out of signal pulses, which limits fiber transmission bandwidth. Optical fibers have much higher bandwidth than copper wires.
14. Both attenuation and dispersion increase with transmission distance.
15. Electronics play important roles in fiber-optic equipment. Opto-electronic or electro-optic devices have both electronic and optical functions.
16. Transmitters convert electronic input signals to optical format by modulating light from an LED or laser.
17. A receiver converts an optical signal into electronic form.

What's Next?

In Chapter 3, we will look at how fiber-optic systems are used in communications.

Further Reading

Introductory Level:

J. Warren Blaker and Peter Schaeffer, *Optics: An Introduction for Technicians and Technologists* (Prentice Hall, 2000)

David Falk, Dieter Brill, and David Stork, *Seeing the Light: Optics in Nature, Photography, Color, Vision and Holography* (Harper & Row, 1986)

B. K. Johnson, *Optics and Optical Instruments* (Dover, 1960)

Advanced Treatments:

Eugene Hecht, *Optics*, 4th ed. (Addison-Wesley, 2002)

Francis A. Jenkins and Harvey A. White, *Fundamentals of Optics* (McGraw-Hill, 1976)

Questions to Think About

1. Interference seems to be a strange effect. The total light intensity from two bulbs is the sum of the two intensities. Yet the light intensity is really the square of the amplitudes, and if the two waves are in phase, you double the amplitude, which when squared means the intensity should be four times the intensity of one bulb. Don't these views contradict each other?
2. One photon is a wave packet that doesn't last very long. A continuous light source emits a steady or continuous wave. How is the continuous light source emitting photons?
3. The sun emits an energy of about 3.8×10^{33} ergs per second. A photon with wavelength of 1.3 micrometers has an energy of about 1.6×10^{-12} erg. If you assume the sun emits all its energy at 1.3 μm, how much attenuation in decibels do you need to reduce the sun's entire output to a single 1.3-μm photon per second?
4. If an entire galaxy contains a billion stars, each one as luminous as the sun, how much attenuation does it take to reduce its entire output to a single 1.3-μm photon per second?
5. Suppose a material has attenuation of 10 dB/m at 1.3 micrometers. How thick a block of the material would you need to reduce the sun's entire output to a single photon as in Problem 3?
6. Medical imaging fiber has attenuation of 1 dB/meter at optical wavelengths. If the attenuation is the same at 1.3 μm, and you don't have to worry about the sun's energy melting the fiber, how long a fiber would reduce the sun's output in Problem 3?
7. Atoms and molecules in the atmosphere scatter light in the same way that atoms in glass scatter light in an optical fiber. The shorter the wavelength in the visible spectrum, the stronger the scattering. Where do you think the sky gets its blue color from and why?
8. Diamond has a refractive index of 2.4. What is its critical angle in air and what does that have to do with its sparkle?

Chapter Quiz

1. Which of the following is *not* electromagnetic radiation?
   a. radio waves
   b. light
   c. infrared radiation

d. X-rays

e. acoustic waves

2. Optical fibers have minimum loss near 1.5 μm. What is the frequency that corresponds to that wavelength?

a. 200 MHz

b. 20 GHz

c. 200 GHz

d. 20 THz

e. 200 THz

3. An electron-volt is the energy needed to move an electron across a potential of 1 V. Suppose you could convert all the energy from moving an electron across a potential of 1.5 V into a photon. What would its wavelength be?

a. 0.417 μm

b. 0.5 μm

c. 0.827 μm

d. 1.21 μm

e. 1.2399 μm

4. Light that passes from air into glass is

a. reflected.

b. refracted.

c. absorbed.

d. scattered.

5. Light is confined within the core of a simple clad optical fiber by

a. refraction.

b. total internal reflection at the outer edge of the cladding.

c. total internal reflection at the core-cladding boundary.

d. reflection from the fiber's plastic coating.

6. An optical fiber has a core with refractive index of 1.52 and a cladding with index of 1.45. Its numerical aperture is

a. 0.15.

b. 0.20.

c. 0.35.

d. 0.46.

e. 0.70.

7. Zircon has a refractive index of 2.1. What is its critical angle for total internal reflection in air?

a. 8°

b. 25°

c. 32°
d. 42°
e. 62°

8. The output of a 20-km fiber with attenuation of 0.5 dB/km is 0.005 mW. What is the input power to the fiber?
a. 0.5 mW
b. 0.1 mW
c. 0.05 mW
d. 0.03 mW
e. 0.01 mW

9. What fraction of the input power remains after light travels through 100 km of fiber with 0.3 dB/km attenuation?
a. 0.1%
b. 0.5%
c. 1%
d. 5%
e. 10%

10. If a 1-cm glass plate transmits 90% of the light that enters it, how much light will emerge from a 10-cm slab of the same glass? (Neglect surface reflection.)
a. 0%
b. 9%
c. 12%
d. 35%
e. 80%

11. What happens to light that is scattered in an optical fiber?
a. It escapes from the sides of the fiber.
b. Glass atoms absorb its energy.
c. Glass atoms store the light and release it later.
d. It is reflected back toward the light source.
e. It excites acoustic waves in the glass.

12. What effect does dispersion cause?
a. scattering of light out the sides of the fiber
b. stretching of signal pulses that increases with distance
c. shrinking of signal pulses that become shorter with distance
d. attenuation of signal pulses