c. telephone
d. wireless radio transmission

2. Which of the following statements are true for analog signals?
a. They vary continuously in intensity.
b. They are transmitted in parts of the telephone network.
c. They are compatible with human senses.
d. They can be processed electronically.
e. All of the above

3. Which of the following statements are true for digital signals?
a. They can encode analog signals.
b. They are transmitted in parts of the telephone network.
c. They can be processed electronically.
d. They are used in computer systems.
e. All of the above

4. You digitize a 10-kHz signal by sampling it at twice the highest frequency (i.e., 20,000 times a second) and encoding the intensity in 8 bits. What is the resulting data rate?
a. 20 kbit/s
b. 64 kbit/s
c. 144 kbit/s
d. 160 kbit/s
e. 288 kbit/s

5. What part of the telephone network is connected directly to your home telephone if you get your telephone service from a local telephone company?
a. subscriber loop
b. feeder cable
c. trunk line
d. backbone system

6. What part of the telephone network carries the highest-speed signals?
a. subscriber loop
b. feeder cable
c. trunk line
d. backbone system

7. Time-division multiplexing of eight signals at 150 Mbit/s each produces
a. eight optical channels each carrying 150 Mbit/s.
b. one channel carrying 120 Mbit/s.
c. one channel carrying 1.2 Gbit/s.
d. eight signals at 150 MHz.

8. What are the "pipes" used to broadcast television signals from a station on the ground?

a. air

b. optical fibers

c. coaxial cables

d. twisted pair

9. The carrier signal modulated to produce one optical channel in a fiber-optic system is

a. a single wavelength of light generated in the transmitter.

b. a radio-frequency signal supplied electronically to the transmitter.

c. an acoustic vibration in the optical fiber.

d. a combination of wavelengths generated by several light sources.

10. Who offers DSL and what service does it normally provide?

a. Television broadcasters offer it for Internet access.

b. Cable television carriers offer it for Internet access.

c. Telephone carriers offer it for Internet access.

d. Cable television carriers offer it for telephone service.

e. Internet service providers offer it for telephone service.

11. What is the only important telecommunications system that uses fiber to transmit analog signals?

a. local telephone service

b. long-distance telephone systems

c. Internet backbone systems

d. cable TV systems

e. none

12. What U.S. government agency regulates telecommunications?

a. Federal regulations have been abolished.

b. Department of Homeland Security

c. Department of Commerce

d. Federal Communications Commission

e. International Telecommunications Union

CHAPTER

4

Types of Optical Fibers

About This Chapter

Not all optical fibers are alike. Several different types, made for different applications, guide light in different ways. This chapter describes the basic concepts behind standard fibers, concentrating on fiber design and light guiding. It is closely linked to the chapters that follow. Chapter 5 describes the important properties of optical fibers. Chapter 6 covers fiber materials, structures, and manufacturing, which play a vital role in determining fiber properties. Chapter 7 covers specialty fibers used in amplifiers, wavelength selection, and applications other than merely guiding light.

Light Guiding

Chapter 2 showed how the total internal reflection of light rays can guide light along optical fibers. This simple concept is a useful approximation of light guiding in many types of fiber, but it is not the whole story. The physics of light guiding is considerably more complex, because a fiber is really a waveguide and light is really an electromagnetic wave with frequency in the optical range.

Like other waveguides, an optical fiber guides waves in distinct patterns called *modes,* which describe the distribution of light energy across the waveguide. The precise patterns depend on the wavelength of light transmitted and on the variation in refractive index that shapes the core, which can be much more complex than the simple, single cores described in Chapter 2. In essence, these variations in refractive index create boundary conditions that shape how electromagnetic waves travel through the waveguide, like the walls of a tunnel affect how sounds echo inside.

Total internal reflection is only a rough approximation of light guiding in optical fibers.

It's possible to calculate the nature of these transmission modes, but it takes a solid understanding of advanced calculus and differential equations, which is far beyond the scope of this book. Instead, we'll look at the characteristics of transmission modes, which are important in fiber-optic systems. By far the most important is the number of modes the fiber transmits. Fibers with small cores can transmit light in only a single mode. It can be hard to get the light into the fiber, but once it's inside, the light behaves very uniformly. It's easier to get light into fibers with larger cores that can support many modes, but light does not behave the same way in all the modes, which can complicate light transmission, as you will learn later in this chapter.

This chapter covers the many types of optical fibers that have been developed to meet a variety of functional requirements. Their designs differ in important ways. For example, bundles of fibers used for imaging need to collect as much light falling on their ends as possible, so their claddings are made thin compared to their cores. Communications fibers have thicker claddings, both to keep light from leaking out over long distances and to simplify handling of single fibers. Various types of communications have their own requirements. Fibers for short links inside cars or offices typically have large cores to collect as much light as possible. Long-distance fibers have small cores, which can transmit only a single mode, because this well-controlled light can carry signals at the highest speed.

Core-cladding structure and material composition are key factors in determining fiber properties.

The two considerations that affect fiber properties most strongly are the core-cladding structure and the glass composition. The size of the core and cladding and the nature of the interface between them determine the fiber's modal properties and how it transmits light at different wavelengths. The simple types of fiber discussed in Chapter 2 have a *step-index* structure, where the refractive index changes sharply at the abrupt boundary between a high-index core and a low-index cladding. Replacing that abrupt boundary with a gradual transition between core and cladding, or including a series of layers, changes fiber properties. Glass composition, covered in Chapter 6, strongly affects fiber attenuation, as well as influencing pulse spreading.

Combined with other minor factors, these parameters determine important fiber characteristics, including

- Attenuation as a function of wavelength.
- Collection of light into a fiber (coupling).
- Transmission modes.
- Pulse spreading and transmission capacity, as a function of wavelength.
- Tolerances for splicing and connecting fibers.
- Operating wavelengths.
- Tolerance to high temperature and environmental abuse.
- Strength and flexibility.
- Cost.

Figure 4.1 shows selected types of single fibers (as distinct from bundled fibers), along with a plot of refractive index across the core and cladding, called the *index profile.* Only the core and cladding are shown for simplicity; actual fibers have an outer plastic coating to protect them from the environment. The coating's thickness depends on fiber size. For

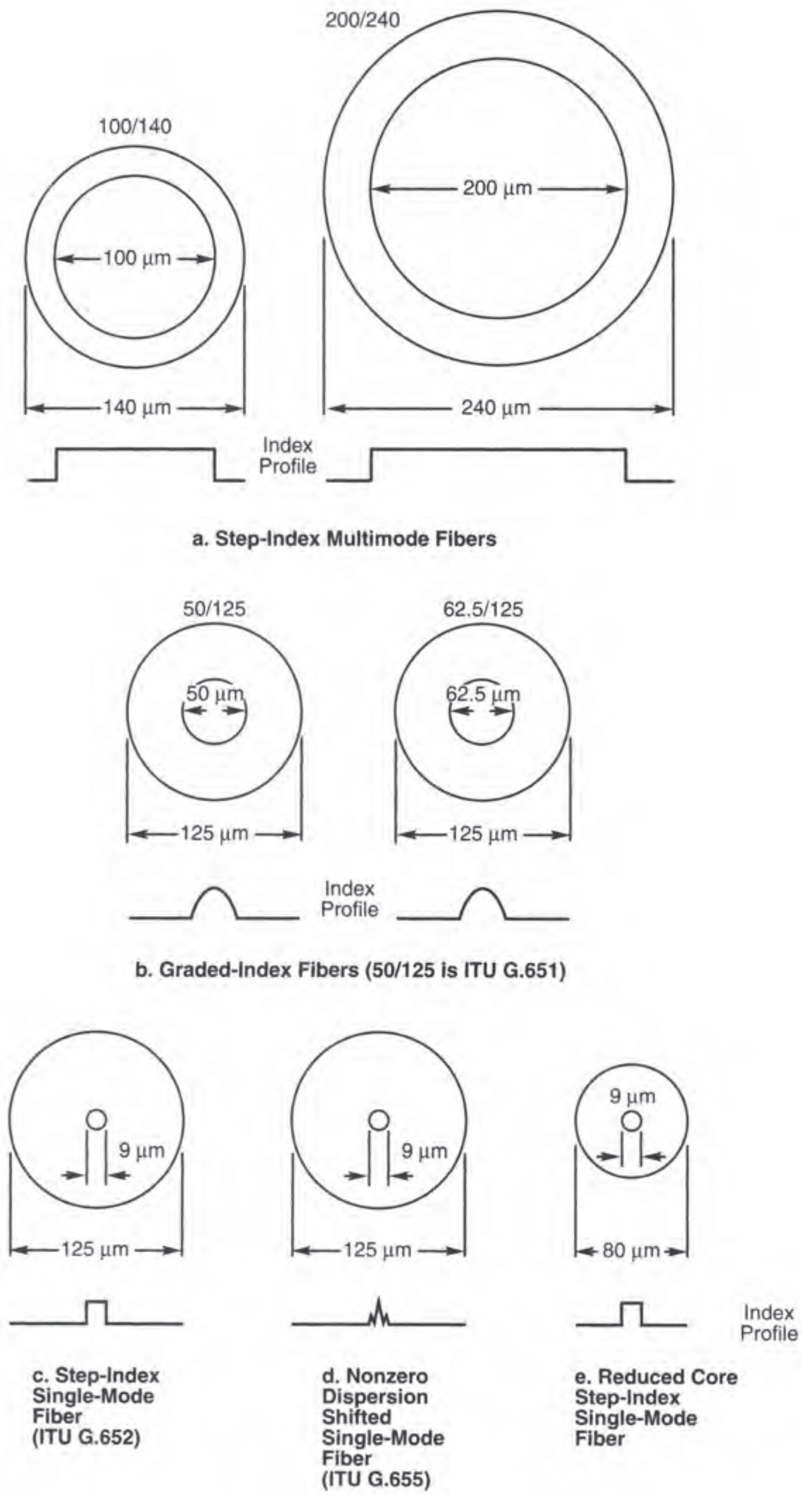


FIGURE 4.1

Common types of optical fiber (to scale). ITU designations are standards of the International Telecommunications Union.

a typical communications fiber with 125-μm cladding, the plastic coating is 250 μm. I will start with the fiber type that is simplest to explain in terms of total internal reflection, called step-index multimode fiber, because it transmits many modes.

Step-Index Multimode Fiber

As we saw in Chapter 2, bare, transparent filaments surrounded by air are the simplest type of optical fiber, but they don't work well in practice. Cladding the fiber with a transparent material having lower refractive index protects the light-carrying core from surface scratches, fingerprints, and contact with other cores of the same material, so the light will not escape from the surface. This simple fiber consists of two layers of material, the core and cladding, which have different refractive indexes. If you drew a cross section of the fiber and plotted the refractive index, as in Figure 4.1(a), you would see a step at the core-cladding boundary, where the index changes abruptly.

Light-Guiding Requirements

To guide light, the fiber core must have refractive index higher than the cladding.

As long as the core of a fiber has a diameter many times larger than the wavelength of light it carries, we can calculate fiber properties using the simple model of light as rays. The fundamental requirement for light guiding is that the core must have a higher refractive index than the cladding material. We saw in Chapter 2 that the critical angle for total internal reflection, θ_{crit}, depends on the ratio of core and cladding refractive indexes.

$$\theta_{crit} = \arcsin\left(\frac{n_{clad}}{n_{core}}\right)$$

For a typical fiber, the difference is small, about 1%, so the critical angle is arcsin (0.99), or about 82°. This means that light rays must be within 8° of the axis of the fiber to be confined in the core, as shown in Figure 4.2. This value is called the *confinement angle*, $\theta_{confinement}$, and equals $90° - \theta_{crit}$. The angle is not very sensitive to the refractive-index

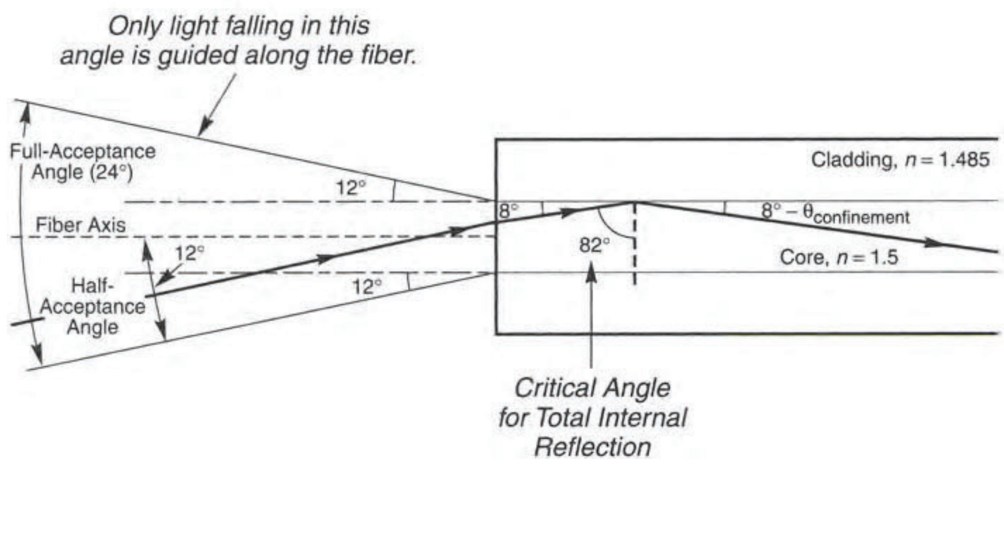


FIGURE 4.2
Light guiding in a large-core step-index fiber. The confinement angle measures the angle between guided light rays and the fiber axis; the acceptance angle is measured in air.

difference. If the difference is doubled to 2%, the confinement angle becomes 11.5°. You can directly calculate the confinement angle measured from the core-cladding boundary using the arc-cosine:

$$\theta_{\text{confinement}} = \arccos\left(\frac{n_{\text{clad}}}{n_{\text{core}}}\right)$$

The confinement angle gives the maximum angle at which guided light can strike the core-cladding boundary once it's inside the glass. However, refraction occurs when the light enters the glass from air, bending light toward the axis of the fiber. To calculate the *acceptance angle,* measured in air, you must account for this refraction using the standard law of refraction. As long as the light enters from air, you can simplify this to

The confinement angle is the largest angle at which light rays confined to a fiber core strike the core-cladding boundary.

$$\sin \theta_{\text{half-acceptance}} = n_{\text{core}} \times \sin \theta_{\text{confinement}}$$

which gives the sine of the largest possible angle from the axis of the fiber, called the *half-acceptance angle,* $\theta_{\text{half-acceptance}}$. You can calculate the half-acceptance angle directly by juggling the trigonometry a bit more:

$$\theta_{\text{half-acceptance}} = \arcsin(n_{\text{core}} \times \sin \theta_{\text{confinement}})$$

Doubling the half-acceptance angle gives the full-acceptance angle. The confinement angle is small enough that you can roughly approximate the half-acceptance angle by multiplying the confinement angle by the refractive index of the core, n_{core}.

Imaging Fibers

The first clad optical fibers developed for imaging were what we now call step-index multimode fibers. Developers tested a variety of cladding materials with low refractive indexes, including margarine, beeswax, and plastics. However, the key practical development was a way to apply a cladding of glass with lower refractive index than the core.

Step-index multimode fibers were the first fibers developed for imaging.

As we will see in Chapter 6, glass comes in many different formulations with varied refractive indexes. The simplest way to make glass-clad fibers is to slip a rod of high-index glass into a tube with lower refractive index, heat the tube so the softened glass collapses onto the rod, let them fuse together, then heat the whole *preform,* and pull a fiber from the molten end.

The cladding of imaging fibers generally is a thin layer surrounding a thicker core. The reason for this design is that imaging fibers are assembled in bundles, with light focused on one end of the bundle to emerge at the other. Light falling on the fiber cores is transmitted from one end to the other, but light falling on the cladding is lost. The thinner the cladding, the more light falls on the fiber cores and the higher the transmission efficiency.

Reducing the size of individual fibers increases the resolution of images transmitted through a bundle, but very fine fibers are hard to handle and vulnerable to breakage. Typically, the smallest loose fibers used in imaging bundles are about 20 μm (0.02 mm, or 0.0008 in.). Even at this size, they remain large relative to the wavelength of visible light (0.4 to 0.7 μm in air), and you can get away with considering light guiding as determined by total internal reflection of light rays at the core-cladding boundary. (The highest-resolution fiber bundles are made by melting fibers together and stretching the whole solid block.)

Illuminating and Beam-Delivery Fiber

Large-core step-index fibers are used to deliver laser power.

Single step-index fibers with large cores—typically 400 μm to 1 mm—can be used to guide a laser beam from the laser to a target or industrial workpiece. The large diameter serves two purposes. First, it can collect power from the laser more efficiently than a smaller core fiber. In addition, it spreads the laser power over a larger area at the ends of the fiber and through a larger volume within the fiber. This is important because some laser power inevitably is lost at the surfaces and within the fiber. If the beam must be focused tightly to concentrate it in the fiber, the power density (power per unit area) may reach levels so high it can damage exposed ends of the fiber.

The design of these large-core fibers is similar to those in Figure 4.1(a). The core diameters are proportionally larger, whereas cladding thicknesses do not increase as rapidly. As the fibers become thicker, they also become less flexible.

Communications Fibers

Light pulses stretch out in length and time as they travel through large-core step-index fiber.

Step-index multimode fibers with cores not quite as large can be used for some types of communications. One smaller type, shown in Figure 4.1(a), has a 100-μm core surrounded by a cladding 20 μm thick, for total diameter of 140 μm. It is typically called 100/140 fiber, with the core diameter written before the overall diameter of the cladding. Typically an outer plastic coating covers the whole fiber, protecting it from mechanical damage and making it easier to handle. The large core is attractive for certain types of communications, because it can collect light efficiently from inexpensive light sources such as LEDs.

If you think of light in terms of rays, you can see an important limitation of large-core step-index fibers for communication (see Figure 4.3). Light rays enter the fiber at a range of angles, and rays at different angles travel different paths through the same length of fiber. The larger the angle between the light ray and the axis, the longer the path. For example, a light ray that entered at 8° from the axis (the maximum confinement angle in the earlier example) of a perfectly straight 1-m length of fiber would travel a distance of 1.0098 m (1 m/cos 8°) before it emerged from the other end. Thus light just inside the confinement angle would emerge from the fiber shortly after light that traveled down the middle. This pulse-dispersion effect becomes larger with distance and can limit data-transmission speed.

In fact, the ray model gives a greatly simplified view of light transmission down optical fibers. As I mentioned earlier, an optical fiber is a waveguide that transmits lightwaves

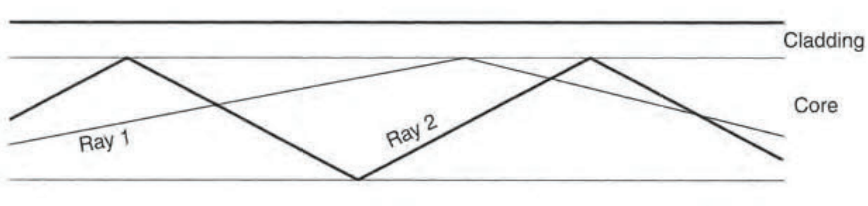


FIGURE 4.3
Light rays that enter multimode step-index fiber at different angles travel different distances through the fiber, causing pulse dispersion.

in one or more transmission modes. Stay tuned for the next section, and I'll explain more about these modes. The larger the fiber core, the more modes it can transmit, so a step-index fiber with a core of 20 μm or more is a multimode fiber. Light rays enter the fiber at different angles, and the various modes travel down the fiber at different speeds. What you have as a result is modal dispersion, which occurs in all fibers that carry multiple modes. It is largely irrelevant for imaging and guiding illuminating beams, but it is a serious drawback for communications. To understand why, we need to take a closer look at modes.

Modes and Their Effects

Modes are stable patterns that waves form as they pass through a waveguide. The number of modes that can travel along a waveguide depends on the wavelength of the wave and the size, shape, and nature of the waveguide. For an optical fiber, the dominant factor is the core diameter; the larger the core, the more modes the fiber can carry. This leads to a fundamental trade-off between the higher signal quality possible with single-mode transmission and the easier input coupling with larger-core fibers.

Small-core fibers carry a single mode.

Waveguide theory, which describes modes, originally was developed for microwaves, but can be applied to any guided electromagnetic waves—including light passing through the core of an optical fiber. You don't want to worry about the mathematical details of waveguide theory—and I certainly don't—but it is important to learn some basic concepts about waveguides and modes.

A fiber is a dielectric optical waveguide.

Electromagnetic waves are oscillating electric and magnetic fields, and how they oscillate in a waveguide depends on how they are confined. The best-known microwave waveguides are rectangular metal tubes, but flexible plastic rods called *dielectric waveguides* also can guide microwaves. (Dielectric means electrically insulating.) A dielectric microwave waveguide is equivalent to a bare optical fiber, with the surface guiding the waves—so anything touching the surface causes losses.

In a clad optical fiber, the guiding dielectric surface is the boundary between core and cladding, where the refractive index changes. In the ray model of light propagation, light guided in the fiber is totally reflected at this boundary. But waveguide theory reveals that a small fraction of the light actually extends beyond the core into the inner part of the cladding, which leads to some complications.

As long as the fiber core is big enough to accept any light, it can carry light in the lowest-order mode, where the electric field intensity is highest at the center of the core and drops to the sides, as shown at left in Figure 4.4. As the core diameter increases beyond a certain point, called the *cutoff wavelength,* the fiber can support transmission in additional modes. The two curves at right in Figure 4.4 show the second and third lowest-order modes. Fiber cores support many modes simultaneously, with the number increasing very rapidly with the core diameter. The difference in refractive index between the core and cladding also influences the number of modes.

An optical fiber is a cylindrical waveguide. It's also possible to make planar optical waveguides as stripes of high-index material on a substrate with lower refractive index. You will learn more about planar waveguides later.

Single-Mode Waveguides

Single-mode fibers must have small cores.

Conventional microwave waveguides carry a single mode. Multimode microwave waveguides don't work well because interactions between the modes generate noise. Single-mode transmission is cleaner and simpler, and it's also preferred for fiber-optic systems. The main limitation is that the core of the fiber must be small enough to restrict transmission to a single mode, yet large enough to collect most of the input optical signal.

The balance is struck by adjusting the difference between core and cladding refractive index. The smaller the core-cladding difference, the larger the core can be. The refractive index difference is large for a bare glass fiber (with $n = 1.5$) in air (with $n = 1.000293$), so the core must be around 1 μm to transmit only a single mode at the usual transmission wavelengths. Standard single-mode telecommunications fibers have a cladding index only about 0.5% lower than the core index; this allows core diameters above 9 μm, which is several times the 1.5-μm wavelength used for long-haul transmission.

Larger-core fibers carry multiple modes. In practice, transmission is much better when a fiber carries many modes than when it carries a few, so there is a large gap between single-mode fibers with core diameters below 10 μm and multimode fibers with core diameters 50 μm or larger.

Modal Properties

Some light penetrates into the cladding.

Although the core-cladding boundary is nominally the surface of the waveguide in a clad optical fiber, the light energy does not really propagate along that boundary. Some light penetrates the boundary and goes a short distance into the cladding, while most of the light remains inside the core. This effect occurs in all types of clad fibers, but is most important in single-mode fibers, where it is characterized by the *mode-field diameter*, which is slightly larger than the core diameter. Technically, the mode-field diameter is the point where light intensity drops to $1/e^2(0.135)$ of the mode's peak intensity. Figure 4.4 shows the distribution of light energy in modes, while Figure 4.5 shows the path of light in a single-mode fiber.

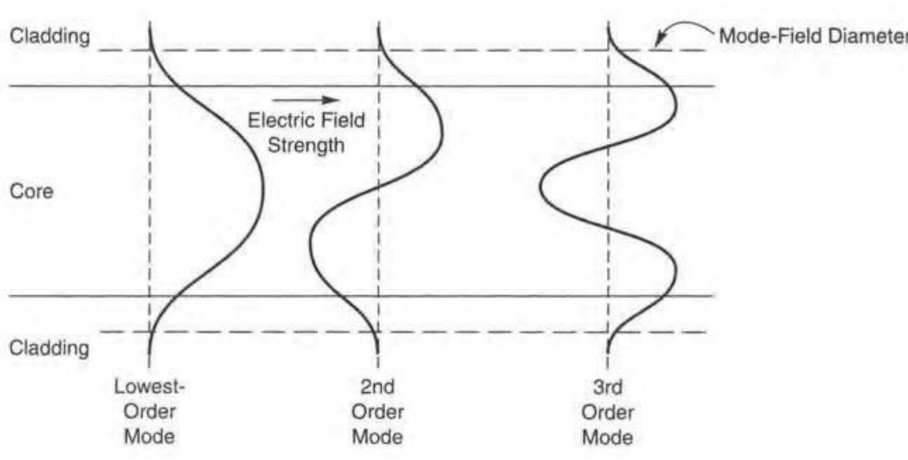


FIGURE 4.4
Electric fields for the lowest-order mode in an optical fiber (left) and for the second-order and third-order modes (right). Higher-order modes are more complex.

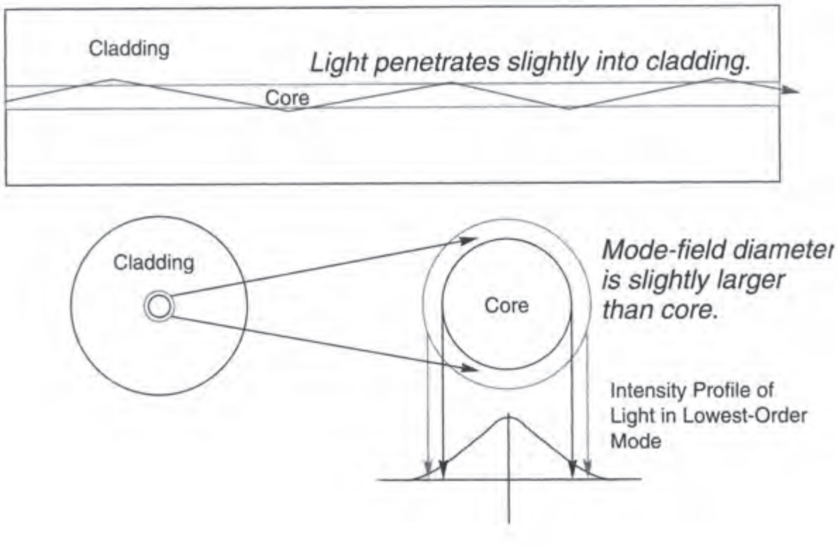


FIGURE 4.5
Light penetrates slightly into the cladding of a single-mode step-index fiber.

Light leakage into the cladding makes cladding transmission important, although not as critical as for the core. Guided waves travel mostly in the core in single-mode fibers. In multimode fibers, some modes may spend more time in the cladding than in the core.

Modes are sometimes characterized by numbers. Single-mode fibers carry only the lowest-order mode, assigned the number 0. Multimode fibers also carry higher-order modes. The number of modes that can propagate in a fiber depends on the fiber's numerical aperture (or acceptance angle) as well as on its core diameter and the wavelength of the light. For a step-index multimode fiber, the number of such modes, N_m, is approximated by

$$\text{Modes} = 0.5\left(\frac{\text{core diameter} \times \text{NA} \times \pi}{\text{wavelength}}\right)^2$$

or

$$N_m = 0.5\left(\frac{\pi D \times \text{NA}}{\lambda}\right)^2$$

where λ is the wavelength and D is the core diameter. To plug in some representative numbers, a 100-μm core step-index fiber with NA = 0.29 (a typical value) would transmit thousands of modes at 850 nm. This formula is only an approximation and does not work for fibers carrying only a few modes.

Leaky Modes

Some modes can propagate short distances in the cladding of a multimode fiber.

Low-order modes are better guided than the higher-order modes in a multimode fiber. Modes that are just beyond the threshold for propagating in a multimode fiber can travel for short distances in the fiber cladding. In this case, the cladding itself acts as an unclad optical fiber to guide those cladding modes.

Because the difference between guided and unguided modes is small, slight changes in conditions may allow light in a normally guided mode to leak out of the core. Likewise, some light in a cladding mode may be recaptured. Slight bends of a multimode fiber are enough to allow escape of these *leaky modes.*

Modal-Dispersion Effects

Modal dispersion in multimode step-index fibers is the largest type of pulse dispersion.

Each mode has its own characteristic velocity through a step-index optical fiber, as if it were a light ray entering the fiber at a distinct angle. This causes pulses to spread out as they travel along the fiber in what is called *modal dispersion.* The more modes the fiber transmits, the more pulses spread out.

Later we will see that there are other kinds of dispersion, but modal dispersion is the largest in multimode step-index fibers. Precise calculations of how many modes cause how much dispersion are rarely meaningful. However, you can make useful approximations by using the ray model (which works for multimode step-index fibers) to calculate the difference between the travel times of light rays passing straight through a fiber and bouncing along at the confinement angle. For the typical confinement angle of 8° mentioned earlier, the difference in propagation time is about 1%. That means that an instantaneous pulse would stretch out to about 30 ns (30 billionths of a second) after passing through a kilometer of fiber.

That doesn't sound like much, but it becomes a serious restriction on transmission speed, because pulses that overlap can interfere with each other, making it impossible to receive the signal. Thus pulses in a 1-km fiber have to be separated by more than 30 ns. You can estimate the maximum data rate for a given pulse spreading from the equation

$$\text{Data rate} = \frac{0.7}{\text{pulse spreading}}$$

Plug in a pulse spreading of 30 ns, and you find the maximum data rate is about 23 Mbit/s. In practice, the maximum data rate also depends on other factors.

Dispersion also depends on distance. The total modal dispersion is the product of the fiber's characteristic modal dispersion per unit length, D_0, multiplied by the fiber length, L:

$$D = D_0 \times L$$

Thus a pulse that spreads to 30 ns over 1 km will spread to 60 ns over 2 km and 300 ns over 10 km. (For very accurate calculations, you should replace L with L^γ, where γ is a factor normally close to 1, which depends on the fiber type.)

Because total dispersion increases with transmission distance, the maximum transmission speed decreases. If the maximum data rate for a 1-km length of fiber is DR_0, the maximum data rate for L kilometers is roughly

$$DR = \frac{DR_0}{L}$$

We will learn more about dispersion in Chapter 5. For now, the important thing to remember is that modal dispersion seriously limits transmission speed in step-index multimode fiber.

Graded-Index Multimode Fiber

As communications engineers began seriously investigating fiber optics in the early 1970s, they recognized modal dispersion limited the capacity of large-core step-index fiber. Single-mode fibers promised much more capacity, but many engineers doubted they could get enough light into the tiny cores. As an alternative, they developed multimode fiber in which the refractive index grades slowly from the center of the core to the inner edge of the cladding. Careful control of the refractive-index gradient nearly eliminates modal dispersion in fibers with cores tens of micrometers in diameter, giving them much greater transmission capacity than step-index multimode fibers.

Replacing the sharp boundary between core and cladding with a refractive-index gradient nearly eliminates modal dispersion.

Optically, graded-index fibers guide light by refraction instead of total internal reflection. The fiber's refractive index decreases gradually away from its center, finally dropping to the same value as the cladding at the edge of the core, as shown in Figure 4.6. The change refracts the light, bending rays back toward the axis as they pass through layers with lower refractive indexes, as shown in Figure 4.7. The refractive index does not change abruptly at the core-cladding boundary, so there is no total internal reflection. (Don't be fooled by the change in slope at the edge of the core in Figure 4.6; it's more like starting up a slow hill than hitting the cliff of a step-index transition.) Refraction bends guided light rays back into the center of the core before they reach the cladding boundary. (The refractive-index gradient cannot confine all light entering the fiber, only rays that fall within a limited confinement angle, as in step-index fiber. The refractive-index gradient determines that angle.)

As in a step-index fiber, light rays follow different paths in a graded-index fiber. However, their speeds differ because the speed of light in the fiber core changes with its refractive index. Recall that the speed of light in a material, c_{mat}, is the velocity of light in a vacuum, c_{vacuum}, divided by refractive index:

$$c_{mat} = \frac{c_{vacuum}}{n_{mat}}$$

Thus the farther the light goes from the axis of the fiber, the faster its velocity. The difference isn't great, but it's enough to compensate for the longer paths followed by the light

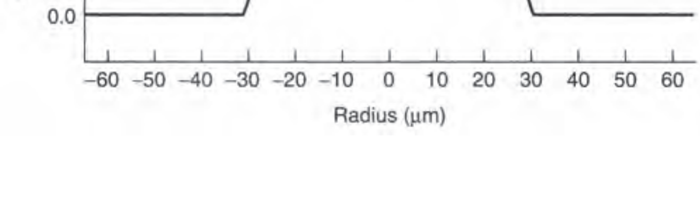
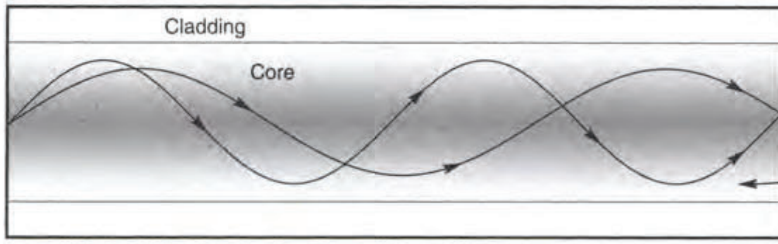


FIGURE 4.6
Refractive-index profile of a graded-index fiber with 62.5-μm core.

FIGURE 4.7
The refractive-index gradient in a graded-index fiber bends light rays back toward the center of the fiber.



rays that go farthest from the axis of the fiber. Careful adjustment of the refractive-index profile—the variation in refractive index with distance from the fiber axis—can greatly reduce modal dispersion by equalizing the transit times of different modes.

Practical Graded-Index Fiber

Standard graded-index fibers have 50- or 62.5-μm cores.

Graded-index fibers were developed especially for communications. Standard types have core diameters of 50 or 62.5 μm and cladding diameters of 125 μm, although some have been made with 85-μm cores and 125-μm claddings. The 50-μm core fiber is covered by the International Telecommunications Union (ITU) G.651 standard. The core diameters are large enough to collect light efficiently from a variety of sources. The cladding must be at least 20 μm thick to keep light from leaking out.

The graded-index fiber is a compromise, able to collect more light than small-core single-mode fiber and able to transmit higher-speed signals than step-index multimode fibers. It was used in telecommunications systems extending farther than a few kilometers until the mid-1980s, but gradually faded from use in telephone systems because single-mode fibers offered much higher bandwidth. Recent improvements have improved the modal dispersion of graded-index fibers so they can carry higher-speed signals, but they remain limited to data communications and networks that carry signals no farther than a few kilometers.

Limitations of Graded-Index Fiber

Residual dispersion and modal noise limit performance of graded-index fibers.

Graded-index fibers suffer some serious limitations that ultimately made them impractical for high-performance communications.

Modal dispersion is not the only effect that spreads out pulses going through optical fibers. Other types of dispersion arise from the slight variation of refractive index with the wavelength of light. These are present in graded-index fibers and became increasingly important as transmission moved to higher speeds. Chapter 5 will describe these dispersion effects.

Multimode transmission itself proved a serious problem. Different modes can interfere with each other, generating what is called *modal noise*. This appears as an uneven distribution of light across the end of the fiber, which continuously changes in response to very minor fluctuations, generating noise. Such modal effects also made it impossible to control precisely how fibers behaved when several were spliced together, because the light in some modes can shift into other modes or leak into the cladding at joints.

In addition, ideal refractive-index profiles are very difficult to realize in practice. The refractive-index gradient must be fabricated by depositing many thin layers of slightly different composition in a precisely controlled sequence. This is expensive, and some fluctuations from the ideal are inevitable.

These limitations do not prevent graded-index fibers from being used in short systems, even at high speeds, as long as dispersion does not accumulate to high enough levels to limit data rates. However, single-mode fibers are standard for long-distance, high-performance systems.

Single-Mode Fiber

The basic requirement for single-mode fiber is that the core be small enough to restrict transmission to a single mode. This lowest-order mode can propagate in all fibers with smaller cores. Because single-mode transmission avoids modal dispersion, modal noise, and other effects that come with multimode transmission, single-mode fibers can carry signals at much higher speeds than multimode fibers. They are the standard choice for virtually all kinds of telecommunications that involve high data rates and span distances longer than a couple of kilometers, and are often used at slower speeds and shorter distances as well.

The simplest type of single-mode fiber has a step-index profile, with an abrupt boundary between a high-index core and a lower-index cladding.

The simplest type of single-mode fiber, often called *standard* single mode and designated ITU G.652, has a step-index profile, with an abrupt boundary separating a high-index core and a lower-index cladding. The refractive-index differential is 0.36% for a widely used fiber, and is well under 1% in other standard types. Figure 4.8 shows cross sections of the two principal types of step-index single-mode fiber made from fused silica.

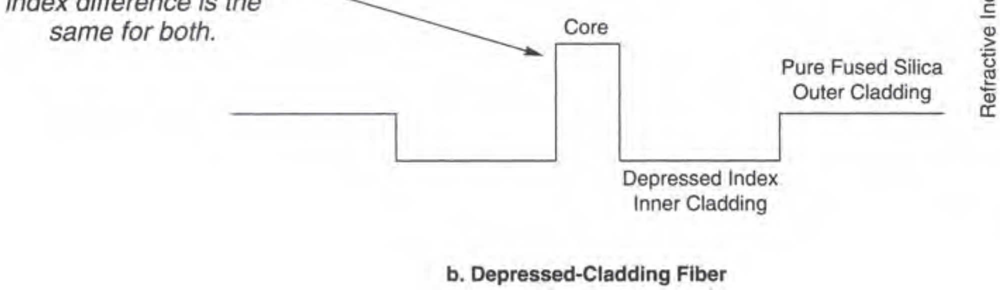


FIGURE 4.8
Two types of step-index single-mode fiber. The difference between core and cladding refractive index is the same, but in the depressed cladding fiber at the bottom, the inner cladding is doped with fluorine to reduce its refractive index.

The simplest design is the matched-cladding fiber shown at the top of Figure 4.8. The cladding is pure fused silica; germanium oxide (GeO_2) is added to the core to increase its refractive index.

An alternative design is the depressed cladding fiber shown at the bottom. In this case, the core is fused silica doped with less germanium oxide than is needed for a matched cladding fiber. The inner part of the cladding surrounding the core is doped with fluorine, which *reduces* its refractive index below that of pure fused silica. The outermost part of the core is pure fused silica, without the fluorine dopant.

Both these designs typically are widely used in telecommunications systems operating at 1.31 and 1.5 μm; core diameters are around 9 μm.

Conditions for Single-Mode Transmission

Fiber with a small enough core transmits only a single mode of light.

Earlier in this chapter, you saw that the number of modes, N_m, transmitted by a step-index fiber depends on the fiber core diameter, D, the refractive indexes of core (n_0) and cladding (n_1), and the wavelength of light λ. You can write the formula in terms of numerical aperture (NA):

$$N_m = 0.5\left(\frac{\pi D \times \mathrm{NA}}{\lambda}\right)^2$$

You also can replace NA with the core and cladding indexes—useful because NA as acceptance angle isn't very meaningful for single-mode fibers—and reformulate the equation:

$$N_m = 0.5\left(\frac{\pi D}{\lambda}\right)^2 (n_0^2 - n_1^2)$$

Reducing the core diameter sufficiently can limit transmission to a single mode. By manipulating the mode-number equation and calculating a constant using Bessel functions, you can find the maximum core diameter, D, which limits transmission to a single mode at a particular wavelength, λ:

$$D < \frac{2.4\lambda}{\pi\sqrt{n_0^2 - n_1^2}}$$

If the core is any larger, the fiber can carry two modes.

Note that D is the *maximum* allowable core diameter for single-mode transmission. To allow for the inevitable margins of error, single-mode fibers normally are designed with core diameters somewhat smaller than the maximum value. In practice the refractive-index difference in step-index single-mode fiber is typically less than about 0.5%, and the core diameter is typically several times the wavelength that the fiber is designed to transmit.

Since core area is proportional to the square of core diameter, it varies with the square of wavelength. If all other things are equal, this means that a single-mode fiber designed to transmit a 0.65-micrometer red beam would have a core only one-fourth the area of a fiber made to carry a single mode at 1.3 μm in the near infrared. As a result, coupling light into single-mode fibers gets harder at shorter wavelengths.

Although core diameter is the physical parameter used in the equations for single-mode transmission, the core of a dielectric waveguide does not confine *all* the light. Recall that the mode-field diameter is larger, as shown in Figure 4.5. The mode-field diameter depends on wavelength, increasing at longer wavelengths. Typically mode-field diameter of a step-index single-mode fiber is about 10% to 15% larger than the core diameter. One widely used step-index single-mode fiber with 8.2-μm core has mode-field diameter of 9.2 μm at 1310 nm and 10.4 μm at 1550 nm. Its numerical aperture (at 1310 nm) is 0.14.

Cutoff Wavelength

We saw before that the maximum core diameter for single-mode transmission depends on the wavelength. If you solve the equation for wavelength, you find that a fiber with a specific core diameter transmits light in a single mode only at wavelengths longer than a value called the *cutoff wavelength*, λ_c, given by

$$\lambda_c = \frac{\pi D \sqrt{n_0^2 - n_1^2}}{2.4}$$

A fiber with diameter D is single-mode at wavelengths longer than λ_c, but as wavelength decreases, it begins to carry two modes at λ_c.

The cutoff wavelength of a single-mode fiber is the shortest wavelength at which it carries only one mode. At shorter wavelengths it carries two or more modes.

Although core diameter is an important consideration in fiber *design*, cutoff wavelength is important in fiber *use*. If you want a fiber to carry signals in only one mode for a high-performance communication system, you must be sure that all wavelengths transmitted are longer than the cutoff wavelength. To give a safety margin, fibers are designed with their cutoff wavelength shorter than their shortest operating wavelength. For example, the common step-index single-mode fiber mentioned above, often used at 1310 nm, has a specified cutoff wavelength of 1260 nm.

What happens at wavelengths shorter than the cutoff? As the wavelength decreases, you first get a second mode, then additional modes. These extra modes can interfere with each other and with the primary mode, causing performance problems. Minor perturbations can affect propagation unpredictably, particularly in fibers with only a few modes.

Trade-offs with Single-Mode Fiber

The sheer simplicity of single-mode transmission is one of its primary attractions for fiber-optic communications. By confining light to a single mode, it greatly reduces pulse dispersion. Some dispersion remains, but it depends primarily on the range of wavelengths transmitted in the signal. The smaller the dispersion, the faster pulses can be turned off and on.

Single-mode fiber is a clean and simple transmission system.

Charles Kao recognized the advantages of single-mode fiber in the mid-1960s, but other early developers pointed to a trade-off that seemed inevitable. The smaller the core diameter, the harder it was to couple light into the fiber. Coupling light into single-mode fiber inevitably requires much tighter tolerances than coupling light into the larger cores of multimode fiber. However, those tighter tolerances have proved achievable, and single-mode fibers are widely used. The main applications of multimode fibers today are in systems where connections must be made inexpensively and transmission distances and speeds are modest.

On the other hand, the properties of step-index single-mode fiber are not ideal. Its dispersion is at a minimum at 1.31 μm, but its attenuation has a minimum at 1.55 to 1.6 μm. The best available optical amplifiers, erbium-doped fibers, operate at 1530 to 1610 nm, where dispersion of step-index single-mode fibers is relatively large. These and other limitations have led to development of other single-mode fibers with different structures, which alter their dispersion.

Dispersion-Shifted Single-Mode Fiber

More complex core-cladding designs can shift low dispersion to the 1.5-μm region.

Step-index single-mode fibers have much better properties than early developers dreamed were possible. However, they are not ideal. As we will see in Chapter 6, the attenuation of glass fiber has been reduced close to the theoretical minimum, and little improvement is possible without shifting to a new family of materials.

Pulse dispersion is another matter. The major concern in single-mode fiber is spectral or chromatic dispersion, caused by the variation in the speed of light through the fiber with wavelength. Chromatic dispersion is the sum of two quantities, dispersion inherent to the material and dispersion arising from the structure of the waveguide. These two can have opposite signs, depending on whether the speed of light increases or decreases with wavelength. (See Chapter 5 for a more thorough explanation.) Fortuitously, the two cancel each other out near 1.31 μm in standard step-index single-mode fiber, as shown in Figure 4.9.

This is a useful wavelength, but it is not ideal because loss is lower and optical amplifiers operate in the 1.55-μm window. Material dispersion is an inherent characteristic of silica fiber that cannot be readily changed without altering glass composition in ways that increase attenuation. However, it is possible to shift the dispersion minimum by changing waveguide dispersion.

Waveguide dispersion arises because light propagation in a waveguide depends on wavelength as well as the waveguide dimensions. The important number is the diameter divided

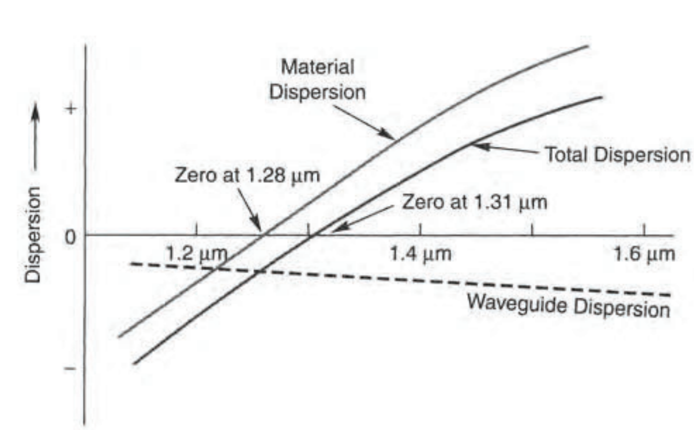


FIGURE 4.9 *Waveguide dispersion offsets chromatic dispersion to produce zero dispersion at 1.31 μm in step-index single-mode fiber.*

by wavelength. Measured that way, decreasing the wavelength serves to increase the waveguide diameter, whereas increasing wavelength effectively shrinks the waveguide. Thus the distribution of light between core and cladding changes with wavelength.

That change in light distribution affects how fast the light travels through the fiber. The core and cladding have different refractive indexes, which determine the speed of light through them. Because light spends time in both core and cladding, its effective speed through the whole fiber is an average that depends on the distribution of light between core and cladding. A change in wavelength changes that distribution, and thus the average speed, causing waveguide dispersion.

Changing the design of the core-cladding interface can alter waveguide dispersion, shifting the zero point of chromatic dispersion to other wavelengths. There are now several types of dispersion-modified fibers, based on designs that change waveguide dispersion. They are optimized in different ways to meet varying system requirements, particularly the transmission of multiple optical channels for wavelength-division multiplexing.

Zero Dispersion-Shifted Fiber (ITU G.653)

The first dispersion-shifted fibers had zero dispersion shifted to 1550 nm to match their minimum attenuation wavelength. This was done by increasing the magnitude of waveguide dispersion, as shown in Figure 4.10. They were introduced in the mid-1980s and were installed in some systems, but never came into wide use and are no longer manufactured. Originally called simply *dispersion-shifted fibers* they have been called *zero dispersion-shifted fibers* because their dispersion is zero in the middle of the erbium-doped fiber amplifier band. This type is covered by the International Telecommunications Union G.653 standard, and is identified by that number.

Some older fibers had zero dispersion shifted to 1.55 μm.

Designers increased the waveguide dispersion by adapting the layered core design shown in Figure 4.11(a). The *inner core* has a refractive index that decreases with increasing distance from the fiber axis at its center. The next layer, sometimes called the *inner cladding,* has a refractive index that drops as low as that of the outer cladding before starting to rise again. The next layer, called either the *ring* or the *outer core,* has a refractive index that rises to a peak smaller than that of the inner core, then declines to match that of the cladding.

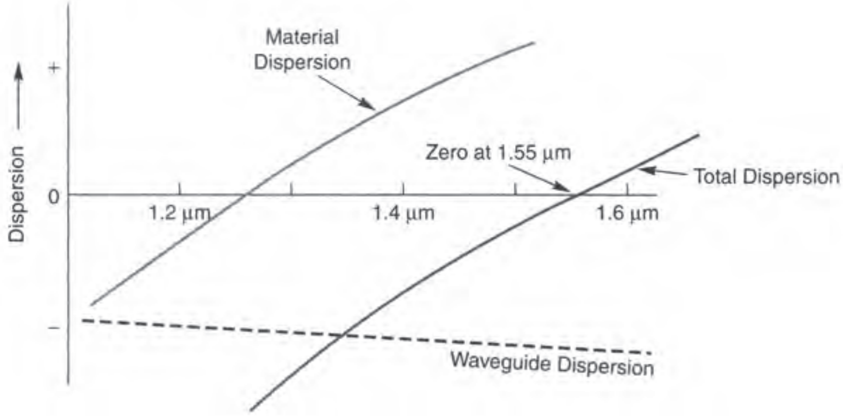
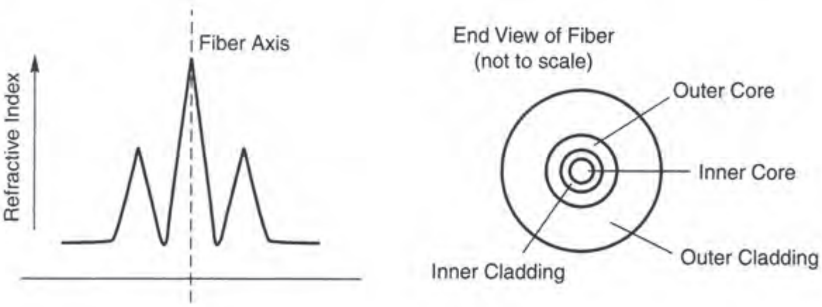
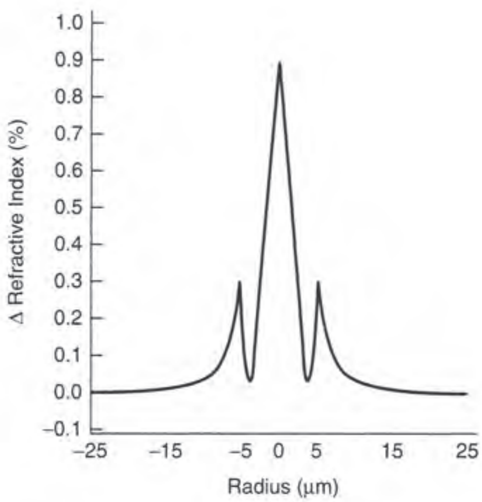


FIGURE 4.10
A fiber designed with more waveguide dispersion shifts the zero-dispersion wavelength to 1.55 μm.

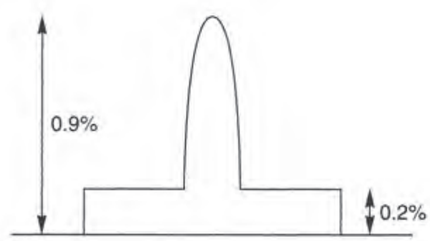
FIGURE 4.11
Refractive-index profiles of some dispersion-shifted fibers designed for specific applications



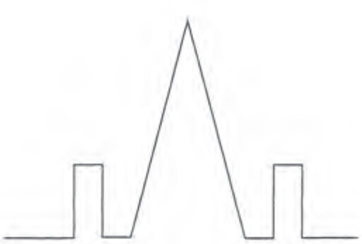
a. Zero Dispersion-Shifted Fiber. (ITU G.653)



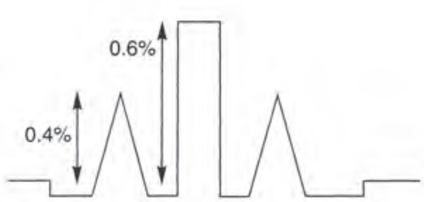
b. Nonzero Dispersion-Shifted Fiber. (ITU G.655) (Courtesy Corning, Inc.)



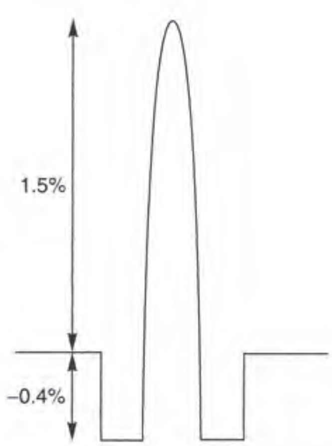
c. Another Design for Nonzero Dispersion-Shifted Fiber. (ITU G.655)



d. Large-Effective-Area Fiber.



e. Fiber with Flattened Dispersion Slope.



f. A Dispersion-Compensating Fiber.

In addition to increasing the waveguide dispersion, this elaborate structure also reduces mode-field diameter to about 8.1 μm at 1550 nm, compared to 10.4 μm for step-index single-mode fiber at the same wavelength.

Although this design worked well for single-channel systems, it proved unsuitable for wavelength-division multiplexing. When multiple optical channels pass through the same fiber at wavelengths where dispersion is very close to zero, they suffer from a type of crosstalk called four-wave mixing, described in Chapter 5. The degradation is so severe that zero dispersion-shifted fiber cannot be used for dense-WDM systems.

Nonzero Dispersion-Shifted Fiber (ITU G.655)

The way to avoid four-wave mixing is to move the zero-dispersion wavelength outside the transmission band. So-called *nonzero dispersion-shifted fibers* do this by using other layered core structures to adjust the amount of waveguide dispersion differently. Figures 4.11(b) and (c) illustrate two approaches, showing how their refractive-index profiles differ from that of zero dispersion-shifted fiber. As with other designs in this diagram, the dimensions are not exact.

Zero-dispersion wavelength must lie outside the transmission band for WDM systems.

The name comes from the fact that their dispersion is shifted to a value that is low—but not zero—in the 1550-nm band. The International Telecommunions Union G.655 standard defines nonzero dispersion-shifted fibers as having chromatic dispersion of 0.1 to 6 picoseconds per nanometer-kilometer, but does not specify the sign. (Chapter 5 explains chromatic dispersion.) This small dispersion prevents the crosstalk that can arise if signals at closely spaced wavelengths stay in phase over long distances.

This small dispersion can be provided by moving the zero-dispersion wavelength either above (at shorter wavelengths) or below (at longer wavelengths) the 1550-nm band, as shown in Figure 4.12. Various types of fibers have been developed.

For dense-WDM applications using erbium-doped fiber amplifiers, the current favorite is a zero-dispersion point at a wavelength of 1500 nm or less. This is shorter than the erbium-amplifier band, and no other optical amplifiers are well developed for this region.

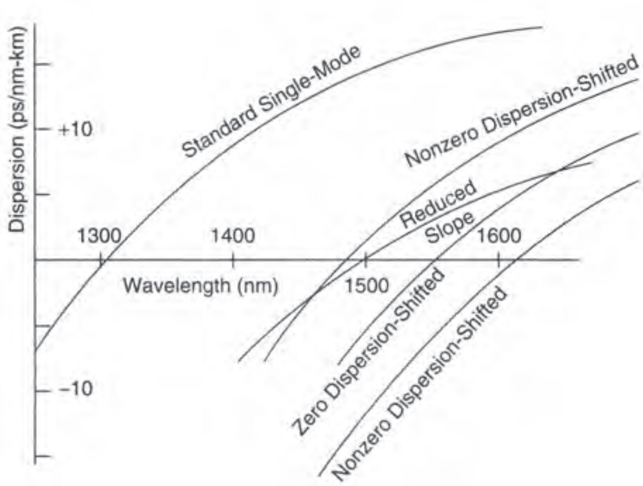


FIGURE 4.12
Dispersion profiles of several single-mode fiber types.

In addition, this choice means that the fiber has positive chromatic dispersion (above the X axis on Figure 4.12) in the entire erbium-fiber band from 1525 to 1620 nm. Positive dispersion is an advantage because it is easier to compensate than negative dispersion. In addition, the positive part of the dispersion curve slopes less, so the magnitude of the dispersion is more uniform across the erbium-fiber band.

Some early nonzero dispersion-shifted fibers had zero dispersion at wavelengths of 1580 to 1610 nanometers. Those fibers were dropped when *L-band* erbium amplifiers were developed for those wavelengths.

Longer-wavelength nonzero dispersion-shifted fibers have been developed with zero dispersion at about 1640 nm, well beyond the erbium-amplifier L-band. This leaves the entire band between 1280 and 1620 nm open, with no zero-crossing point in the middle. Potential uses for such fibers are in the metro network, where transmission distances are too short to require optical amplifiers. An added advantage is that the negative dispersion of these fibers partly offsets the positive wavelength chirp that comes from directly modulating semiconductor laser sources—allowing the use of relatively inexpensive laser transmitters at data rates to 2.5 gigabits per second.

Reduced Dispersion Slope Fibers

Reduced-slope fibers reduce the change in dispersion with wavelength, but also have smaller effective areas.

Another way to refine dispersion-modified fibers for dense-WDM systems is to reduce the slope of the dispersion curve. As you can see in Figure 4.12, the dispersion normally changes significantly over the 1550-nm band. For a typical nonzero dispersion-shifted fiber, the slope is about 0.08 ps/nm^2-km near 1550 nm.

This variation with wavelength complicates the task of dispersion compensation for systems with many optical channels. Wavelengths with higher dispersion require more compensation than those with lower dispersion. Proposals to use the entire 1280 to 1650 nm band for metro WDM systems also face problems if the dispersion slope is high. Although they don't require long-distance transmission or optical amplification, the large change in dispersion across the range can cause problems.

Sophisticated multilayer core designs such as the one in Figure 4.11(e) can reduce the dispersion slope below 0.05 ps/nm^2-km, but there are trade-offs. An important one is that reduced-slope designs tend to have smaller mode-field diameters—about 8.4 μm at 1550 nm, which concentrate optical power in a smaller volume. As you will learn in Chapter 5, raising the power density in fibers increases the strength of nonlinear effects, which can cause crosstalk. Systems with many WDM channels are particularly at risk.

Large-Effective-Area Fibers

Large-effective-area fibers reduce nonlinear effects.

Other nonzero dispersion-shifted fiber designs are intended to maximize the mode-field diameter, which determines the effective area over which optical power is spread in the fiber. This is important because dispersion shifting tends to reduce mode-field diameter below that of standard step-index fiber, typically about 9.2 μm at 1310 nm and 10.4 μm at 1550 nm, making dispersion-shifted fiber particularly sensitive to nonlinear effects.

Special multilayer core designs like the one in Figure 4.11(d) can spread the mode field over larger areas than in standard dispersion-shifted fiber. In this example, the outer high-index ring draws light outward, expanding the mode-field diameter. One commercial type has a mode-field diameter of about 9.6 μm at 1550 nm, corresponding to an effective area of 72 square micrometers. Although that doesn't sound much larger than the 8.4 μm mode-field diameter of a reduced-slope fiber, the critical dimension of area is only 55 μm^2 in a reduced-slope fiber. That means the larger fiber has 30% more area, allowing it to carry significantly more power without nonlinear effects.

Fibers can be designed with even larger mode-field diameters, reaching 10.8 μm at 1550 nm. That corresponds to a 100-μm^2 effective area, nearly double that of reduced-slope fiber. However, the trade-off is dispersion slopes that can reach about 0.11 ps/nm^2-km.

Dispersion-Compensating Fibers

Some dispersion is inevitable in optical fibers, so engineers have developed *dispersion-compensating fibers,* which have a very high waveguide dispersion. These fibers tend to have a high index difference between core and cladding, and often have a small effective area; Figure 4.12(f) shows the refractive-index profile of one design.

Dispersion-compensating fibers have very high waveguide dispersion.

The overall dispersion of these fibers is opposite in sign and much larger in magnitude than that of standard fibers, so they can be used to cancel out or compensate the dispersion in other single-mode fibers. Some have negative dispersion slopes. You'll learn more about dispersion compensation later; for now you only need to remember that special fibers are made for that purpose.

Evolving Fiber Designs

Optical fiber design is continually evolving with changing system requirements. Higher data rates on individual optical channels and increasing numbers of optical channels have pushed the need for better control of dispersion. New single-mode designs already are being fine-tuned and promoted for particular applications. Some fiber types may work better for short-distance, multichannel metro networks, while others fit better into long-distance terrestrial or submarine systems. Fibers with 80-μm cladding have been developed for applications where close packing is critical.

Commercial factors also play a role. Companies such as Corning and OFS press their own fiber designs, partly to gain advantage in the market. You'll hear different arguments from various companies about what fiber types are best for various systems. There may be no obvious right answer. In fact, different fibers may work best in different parts of a single system, depending on factors such as power levels at various points in the system.

Polarization in Single-Mode Fiber

Light transmission in single-mode fiber also is affected by a property of light that I so far have ignored: *polarization.* In Chapter 2, we saw that light waves consist of oscillating electric and magnetic fields. The fields are perpendicular to each other and to the direction light travels, as shown in Figure 4.13.

Light has two orthogonal polarizations.

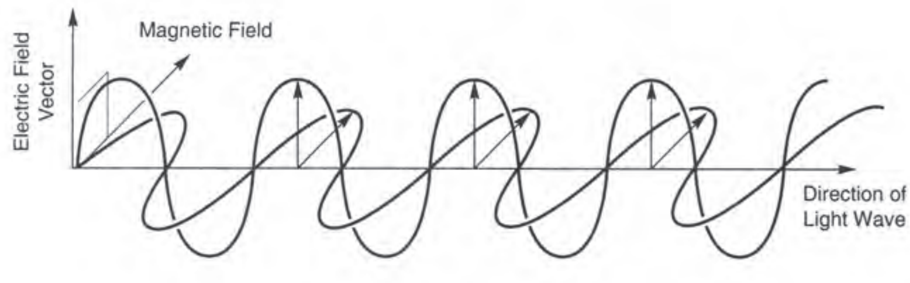


FIGURE 4.13
Electric and magnetic fields in a light wave. Note the two are perpendicular.

Ordinary unpolarized light is made up of many waves, with their electric and magnetic fields oriented randomly (although always perpendicular to each other for each wave). If all the electric fields (and hence the magnetic fields as well) were aligned parallel to one another, the light would be linearly polarized, which is the simplest type of polarization. Normal light is considered a combination of two polarizations, vertical and horizontal (determined by the direction of the electric field). A single light wave with its electric field oriented at a different angle is viewed as a combination of waves, one vertically polarized, the other horizontally polarized. Light can also be polarized circularly or elliptically, depending on how electric and magnetic fields oscillate with respect to each other's phase, but that is a matter beyond the scope of this chapter.

A single-mode fiber actually carries two modes with different polarizations.

Polarization doesn't matter in multimode fibers, but it can be important in single-mode fibers. The reason is that what we call single-mode fibers actually carry two modes with orthogonal polarization. Fibers with circularly symmetric cores can't differentiate between the two linear polarizations. From the standpoint of waveguide theory, the two modes are *degenerate,* meaning they're functionally identical and can't be told apart by the fiber, so light can shift easily between the two polarization modes.

If the circular symmetry of fibers were perfect, polarization would have little practical impact for communications. However, fiber symmetry is never absolutely perfect. Nor are the forces affecting the fiber applied in perfect symmetry around it. As a result, the two polarization modes may experience slightly different conditions and travel along the fiber at slightly different speeds. This effect is called *differential group delay,* which averaged over time becomes *polarization-mode dispersion.* It can cause problems in high-performance systems, such as those transmitting time-division multiplexed signals faster than about 2.5 Gbit/s.

Special single-mode fibers can control the polarization of light they transmit. There are two types: true single-polarization fiber and polarization-maintaining fiber. Both intentionally avoid circular symmetry, so they transmit vertically and horizontally polarized light differently. Their cores are asymmetric, and the fiber material may be strained in ways that affect light propagation. The two types have crucial differences in operation.

Single-polarization fiber has different attenuation for light of different polarizations. It transmits light of one polarization well but strongly attenuates light with the orthogonal polarization. Under the proper conditions, a single-polarization fiber attenuates the undesired polarization by a factor of 1000 to 10,000 within a few meters but transmits the desired polarization almost as well as standard single-mode fiber. Thus, only the desired polarization remains at the end.

THINGS TO THINK ABOUT

Why are Telecommunication Fiber Diameters 125 μm?

With a few rare exceptions, virtually all glass fibers used for telecommunications have an outer diameter of 125 micrometers. Why is there such uniformity?

One reason is manufacturing standards. Cable manufacturers want fibers to be interchangeable. But another reason is a trade-off in handling that goes back to the origins of low-loss optical fibers.

The outer diameter of the cladding has no real effect on the optical behavior of low-loss fibers. However, Corning physicists found that cladding diameter made a lot of difference in mechanical behavior when fiber was wound onto spools. If the fiber was too thin, it clung to the reel and was very hard to handle. If the fiber was too thick, it cracked easily as it was being wound onto the reel. Corning physicists picked a point in the middle and settled on 125 μm.

Other considerations can lead to different diameters. Thinner fibers are used for imaging or for applications that require tightly packed coils of fiber. Thicker fibers are used for short-distance data transmission or for delivering laser beams. Yet 125 μm works fine for general telecommunications applications, and it's remained the standard size for nearly 40 years.

Polarization-maintaining fiber has internal strain or asymmetry, which effectively splits the input light into two separate polarization modes. This property is called *birefringence*, which means that the refractive index of the fiber differs for the two polarizations. This prevents the light from shifting between polarizations, as it can while passing through other single-mode fibers. Attenuation of the two polarization modes is similar, but because of the difference in refractive index, they travel at different speeds. Polarization-maintaining fiber will transmit light in a single polarization if the input light is polarized and properly aligned with the polarization direction of the fiber, but otherwise it transmits both polarizations.

Other Fiber Types

Communication fibers generally are classed according to their modal and dispersion properties. However, fibers also can be classified in other ways, such as according to their composition, which are covered in other chapters. The most important examples are:

- Glass fibers with special compositions, such as purified of virtually all hydrogen to eliminate a broad absorption band near 1380 nm, described in Chapter 6.
- Fibers made of nonoxide glasses, which transmit longer infrared wavelengths, also in Chapter 6.
- Plastic fibers covered in Chapter 6.
- Fiber gratings, designed to have specific optical properties, covered in Chapter 7.
- Fibers where light is confined by so-called "photonic bandgap" structures, a new technology in the early research stages, covered in Chapter 7.

- Fibers designed specifically for sensing applications, covered in Chapter 29.
- Fused fiber bundles, covered in Chapter 30.

Planar optical waveguides are not true fibers, but they serve the same function of guiding light waves, and are described in Chapters 6 and 14.

What Have You Learned?

1. There are several different types of optical fibers, with distinct properties.
2. Total internal reflection of light rays only approximates the actual process of light guiding. An optical fiber actually is a dielectric optical waveguide, which propagates light in distinct modes.
3. Fiber properties depend on the core-cladding structure and the materials from which the fiber is made.
4. To guide light, a fiber must have a core with higher refractive index than the cladding.
5. Step-index multimode fibers have a core diameter tens of wavelengths of the light they are guiding. They are used for imaging and illumination, but modal dispersion limits their transmission speed for communications.
6. The number of modes carried by a fiber depends on its core diameter, the refractive indexes of core and cladding, and the wavelength.
7. As dielectric optical waveguides, optical fibers guide light along the core-cladding boundary, with some light in the cladding.
8. Fibers with core diameters only 6 to 10 μm transmit a single mode of light.
9. Grading the refractive-index differential between core and cladding can nearly eliminate modal dispersion in a multimode fiber.
10. Graded-index fibers have standard core diameters of 50 or 62.5 μm. They are used for transmission over distances to a few kilometers.
11. Single-mode fibers are used for high-speed communications over distances of more than a kilometer or two. They may be used over shorter distances.
12. Standard single-mode fibers have a step-index profile and zero chromatic dispersion at 1.31 μm.
13. The cutoff wavelength is the shortest wavelength at which a single-mode fiber transmits only one mode.
14. Chromatic dispersion is the sum of material dispersion and waveguide dispersion; all three depend on wavelength. It is the main type of dispersion in single-mode fiber.
15. Dispersion-shifted fiber has waveguide dispersion increased so it cancels material dispersion at a wavelength generally longer than 1.31 μm. Types now in use have dispersion shifted to wavelengths shorter or longer than the erbium-fiber amplifier band, usually to about 1500 nm or about 1640 nm.

16. Reducing dispersion slope makes dispersion change less with wavelength, but tends to decrease the effective area where light is confined in the fiber. Fibers with small effective area are more vulnerable to nonlinear effects.
17. Light can be polarized in vertical or horizontal directions. Normal single-mode fiber carries both polarizations and can suffer polarization-mode dispersion.
18. Single-polarization fibers transmit light in only one polarization. Polarization-maintaining fibers keep light in the same polarization that it had when entering the fiber.

What's Next?

In Chapter 5, you will learn about the most important properties of optical fibers. Chapter 6 will cover fiber materials and fabrication.

Further Reading

Luc B. Jeunhomme, *Single-Mode Fiber Optics: Principles and Applications* (Dekker, 1990)

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Gerd Keiser, *Optical Fiber Communications,* 3rd ed. (McGraw-Hill, 2000)

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John A. Buck, *Fundamentals of Optical Fibers* (Wiley InterScience, 1995)

Ajoy Ghatak and K. Thyagarajan, *Introduction to Fiber Optics* (Cambridge University Press, 1998)

Questions to Think About

1. A step-index multimode fiber has modal dispersion of about 30 ns/km. Using the formula for maximum data rate for a given dispersion, about how far could it transmit a signal at 1 Gbit/s?
2. Why doesn't dispersion affect imaging or illumination fibers?
3. Graded-index fiber typically is more expensive than step-index single-mode fiber. Yet, it is used to carry Gigabit Ethernet signals several hundred meters. What advantage does it offer?
4. What are the trade-offs between effective area and dispersion slope?
5. Your system has to transmit wavelength-division multiplexed signals at the 1530 to 1620 nm band of erbium-doped fiber amplifiers. What type of fiber is best?
6. Your cheapskate purchasing department just got a great deal on zero dispersion-shifted fiber. Why can't you use it in the erbium-amplifier system in Question 5?

Chapter Quiz

1. What is the half-acceptance angle for a large-core step-index fiber with core index of 1.5 and cladding index of 1.495?

a. 4.7°
b. 7.0°
c. 9.4°
d. 11°
e. 14°

2. Modal dispersion is largest in what type of fiber?

a. step-index multimode
b. graded-index multimode
c. step-index single-mode
d. dispersion-shifted single-mode
e. polarization-maintaining

3. A fiber has modal dispersion of 20 ns/km. If an instantaneous light pulse traveled through 8 km of such fiber, what would the pulse length be at the end?

a. 8 ns
b. 20 ns
c. 40 ns
d. 80 ns
e. 160 ns

4. What is the maximum data rate that the 8-km length of fiber in Problem 3 could carry?

a. 160 Mbit/s
b. 20 Mbit/s
c. 16 Mbit/s
d. 6 Mbit/s
e. 4.4 Mbit/s

5. What guides light in multimode graded-index fibers?

a. total internal reflection
b. mode confinement in the cladding
c. refraction in the region where core index decreases to match the cladding index
d. the optics that couple light into the fiber

6. What is the maximum allowable core diameter for a step-index single-mode fiber operating at 1.3 μm, with core index of 1.5 and cladding index of 1.0003 (air)?

a. 0.34 μm
b. 0.89 μm

c. 3.0 μm

d. 4.8 μm

e. 5.5 μm

7. What is the maximum core diameter for a step-index single-mode fiber operating at 1.3 μm, with core index of 1.5 and cladding index of 1.495?

a. 0.89 μm

b. 3.0 μm

c. 4.1 μm

d. 8.1 μm

e. 10.3 μm

8. What is the cutoff wavelength of a single-mode step-index fiber with core diameter of 8 μm, core index of 1.5, and cladding index of 1.495?

a. 0.89 μm

b. 1.15 μm

c. 1.28 μm

d. 1.31 μm

e. 1.495 μm

9. What is the cutoff wavelength of a single-mode step-index fiber with core diameter of 8 μm, core index of 1.5, and cladding index of 1.496?

a. 0.89 μm

b. 1.15 μm

c. 1.28 μm

d. 1.31 μm

e. 1.495 μm

10. What is done to design a dispersion-shifted fiber?

a. Waveguide dispersion is increased to offset material dispersion near 1.55 μm.

b. Material dispersion is reduced at 1.31 μm.

c. Material dispersion is increased to offset waveguide dispersion near 1.55 μm.

d. Core diameter is increased to allow multimode transmission.

e. The fiber core is made asymmetrical to control polarization.

11. For what application is nonzero dispersion-shifted fiber required?

a. single-wavelength transmission at 1.55 μm

b. short-distance data communications

c. single-wavelength transmission at 1.31 μm

d. dense wavelength-division multiplexing around 1.55 μm

e. dense wavelength-division multiplexing around 1.31 μm

12. Does single-polarization fiber transmit more or fewer modes than standard step-index single-mode fiber?

a. Both transmit the same number.

b. Single-mode fiber transmits fewer because polarization-sensitive fibers distinguish between the two orthogonal polarizations.

c. Single-polarization fiber carries fewer because standard step-index fibers do not distinguish between the two orthogonal polarizations.

d. More information is needed to answer the question.

CHAPTER

5

Properties of Optical Fibers

About This Chapter

Now that you have learned about the basic designs of optical fibers, the next step is to understand the properties of fibers important for light transmission. I have already touched upon many properties in Chapter 4; this chapter examines them more thoroughly.

The most important properties for communications are attenuation, light collection and propagation, fiber dispersion, and mechanical strength. Nonlinear effects can be important in some cases, particularly for sensing and high-performance systems. I will start with the property usually at the top of the list—attenuation.

Fiber Attenuation

The attenuation of an optical fiber measures the amount of light lost between input and output. Total attenuation is the sum of all losses. It is dominated by imperfect light coupling into the fiber and absorption and scattering within the fiber. Sometimes other effects can cause important losses, such as light leakage from fibers that suffer severe microbending. Attenuation limits how far a signal can travel through a fiber before it becomes too weak to detect.

Absorption and scattering are both cumulative, with their effects increasing with fiber length. In contrast, coupling losses occur only at the ends of the fiber. The longer the fiber, the more important are absorption and scattering losses, and the less important coupling losses. Conversely, attenuation and scattering may be much smaller than end losses for short fibers.

Loss during fiber transmission is the sum of scattering, absorption, and light-coupling losses.

To briefly review these losses, when you deliver an input power, P_0, to a fiber, a fraction of that light, ΔP, is lost. Thus only the power $P_0 - \Delta P$ gets into the fiber. This light then suffers absorption and scattering loss in the bulk of the fiber. As you learned in Chapter 2, these losses depend on length. If the light lost to absorption per unit length is α and the light lost to scattering per unit length is S, the fraction of light that remains is $(1 - \alpha - S)$. Outside the research laboratory, the quantity that matters is the attenuation per unit length, which is the sum of the absorption and scattering $(\alpha + S)$.

Recall that to calculate the power remaining after a distance D, you raise the fraction of light remaining after attenuation to the power D. This gives a formula for power at a distance D

$$P(D) = (P_0 - \Delta P)(1 - [\alpha + S])^D$$

That formula is more useful for looking at the process of light loss than for calculations. It reminds us that absorption and scattering combine to make attenuation. It also reminds us that attenuation acts only on light that gets into the fiber, because some light is lost on entry.

Now let's look at each of these components of loss.

Absorption

Absorption depends on wavelength and is cumulative with distance.

Every material absorbs some light energy. The amount of absorption depends on the wavelength and the material. A thin window of ordinary glass absorbs little visible light, so it looks transparent to the eye. The paper this book is printed on absorbs much more visible light, so it looks opaque. (You can read these words because the blank paper reflects more light than the ink, which absorbs most light striking it and reflects little.) The amount of absorption can vary greatly with wavelength. The clearest glass is quite opaque at an infrared wavelength of 10 μm. Air absorbs so strongly at short ultraviolet wavelengths that scientists call wavelengths shorter than about 0.2 μm the *vacuum ultraviolet* because only a vacuum transmits them.

Absorption depends very strongly on the composition of a substance. Some materials absorb light very strongly at wavelengths where others are quite transparent. For glass, this means that adding small amounts of certain impurities can dramatically increase absorption at wavelengths where glass is otherwise transparent. Removing such impurities is crucial for making the extremely transparent fibers used for communications. Typically, absorption is plotted as a function of wavelength. Some absorption peaks can look quite narrow because the material absorbs light in only a narrow range of wavelengths; others spread across a wider range.

Absorption is uniform. The same amount of the same material always absorbs the same fraction of light at the same wavelength. If you have three blocks of the same type of glass, each 1-centimeter thick, all three will absorb the same fraction of the light passing through them.

Absorption also is cumulative, so it depends on the total amount of material the light passes through. That means a material absorbs the same fraction of the light for each unit length. If the absorption is 1% per centimeter, it absorbs 1% of the light in the first centimeter, and 1% of the *remaining* light the next centimeter, and so on. If the only thing affecting light is absorption, the fraction of light absorbed per unit length is α, and the total length is D, the fraction of light remaining after a distance D is

$$(1 - \alpha)^D$$

In our example, this means that after passing through 1 m (100 cm) of glass, the fraction of light remaining would be

$$(1 - 0.01)^{100} = 0.366, \qquad \text{or } 36.6\%$$

Scattering

Atoms scatter a small fraction of passing light.

Atoms and other particles inevitably scatter some of the light that hits them. The light isn't absorbed, just sent in another direction in a process called *Rayleigh scattering*, after the British physicist Lord Rayleigh, as shown in Figure 5.1. However, the distinction between scattering and absorption doesn't matter much if you are trying to send light through a fiber, because the light is lost from the fiber in either case.

Like absorption, *scattering* is uniform and cumulative. The farther the light travels through a material, the more likely scattering is to occur. The relationship is the same as for light absorption, but the fraction of scattered light is written S.

$$\text{Remaining light} = (1 - S)^D$$

Scattering depends not on the specific type of material but on the size of the particles relative to the wavelength of light. The closer the wavelength is to the particle size, the more scattering. In fact, the amount of scattering increases quite rapidly as the wavelength λ decreases. For a transparent solid, the scattering loss in decibels per kilometer is given by

$$\text{Scattering} = A\lambda^{-4}$$

where A is a constant depending on the material. This means that dividing the wavelength by 2 multiplies scattering loss (in dB/km) by a factor of 16.

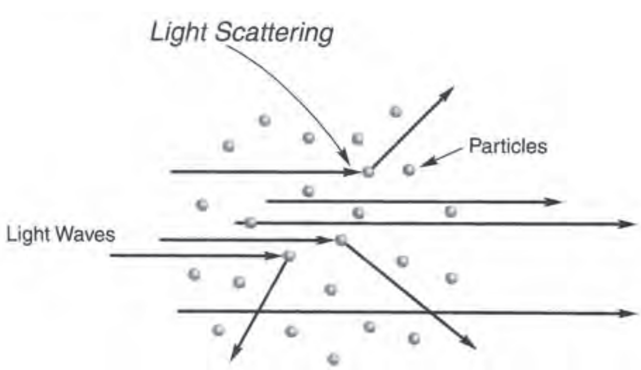


FIGURE 5.1
Rayleigh scattering of light.

Total Loss or Attenuation

Total attenuation, or loss, is the sum of scattering and attenuation; it is measured in decibels per kilometer.

Scattering and absorption combine to give total loss, or attenuation, which is the important number in communication systems. Figure 5.2 plots their contributions across the range of wavelengths used for communications. Attenuation normally is measured in decibels per kilometer for communication fibers. The plot shows small absorption peaks from traces of metal impurities remaining in the glass and other absorption arising from bonds that residual hydrogen atoms form with oxygen in the glass. (I picked this scale to emphasize the peaks, which look lower on other scales, and are smaller in many communications fibers.) The absorption at wavelengths longer than 1.6 μm comes from silicon-oxygen bonds in the glass; as the plot shows, the absorption increases rapidly at longer wavelengths. As a result, silica-based fibers are rarely used for communications at wavelengths longer than 1.62 μm.

Rayleigh scattering accounts for most attenuation at shorter wavelengths. As you can see in Figure 5.2, it increases sharply as wavelength decreases. The space between measured total attenuation and the theoretical scattering curve represents the absorption loss. The closer the two lines, the larger the fraction of total attenuation that arises from scattering. The rapid decrease in scattering at longer wavelengths makes loss lowest in the "valley" around 1.55 μm, where both Rayleigh scattering and infrared absorption are low. Except for the infrared absorption of silica, fiber loss would decrease even more at longer wavelengths.

Total attenuation is what matters for system performance.

The plot in Figure 5.2 compares theoretical scattering and the absorption of pure silica with attenuation measured across the spectrum. It is total attenuation that is important in fiber-optic communications, and that is what is generally measured. Absorption and scattering are hard to separate, and outside the laboratory there is little practical reason to bother. It's most useful to think of the power *(P)* at a distance *D* along the fiber as defined by

$$P(D) = (P_0 - \Delta P)(1 - A)^D$$

where A is attenuation per unit length, P_0 is initial power, and ΔP is the coupling loss, as before. In practice, it is simpler to make calculations if you first separate fiber attenuation from coupling losses by starting with the power that *enters* the fiber rather than the input power you *attempt* to couple into the fiber.

Calculating Attenuation in Decibels

Attenuation normally is calculated on the logarithmic decibel scale.

As we saw in Chapter 2, attenuation measures the ratio of output to input power: P_{out}/P_{in}. It normally is measured in decibels, as defined by the equation

$$\mathrm{dB(attenuation)} = -10 \log_{10}\left(\frac{P_{out}}{P_{in}}\right)$$

Output power is less than input power, so the result would be a negative number if the equation didn't include a minus sign. You should remember that in some publications decibels are defined so that a negative number indicates loss.

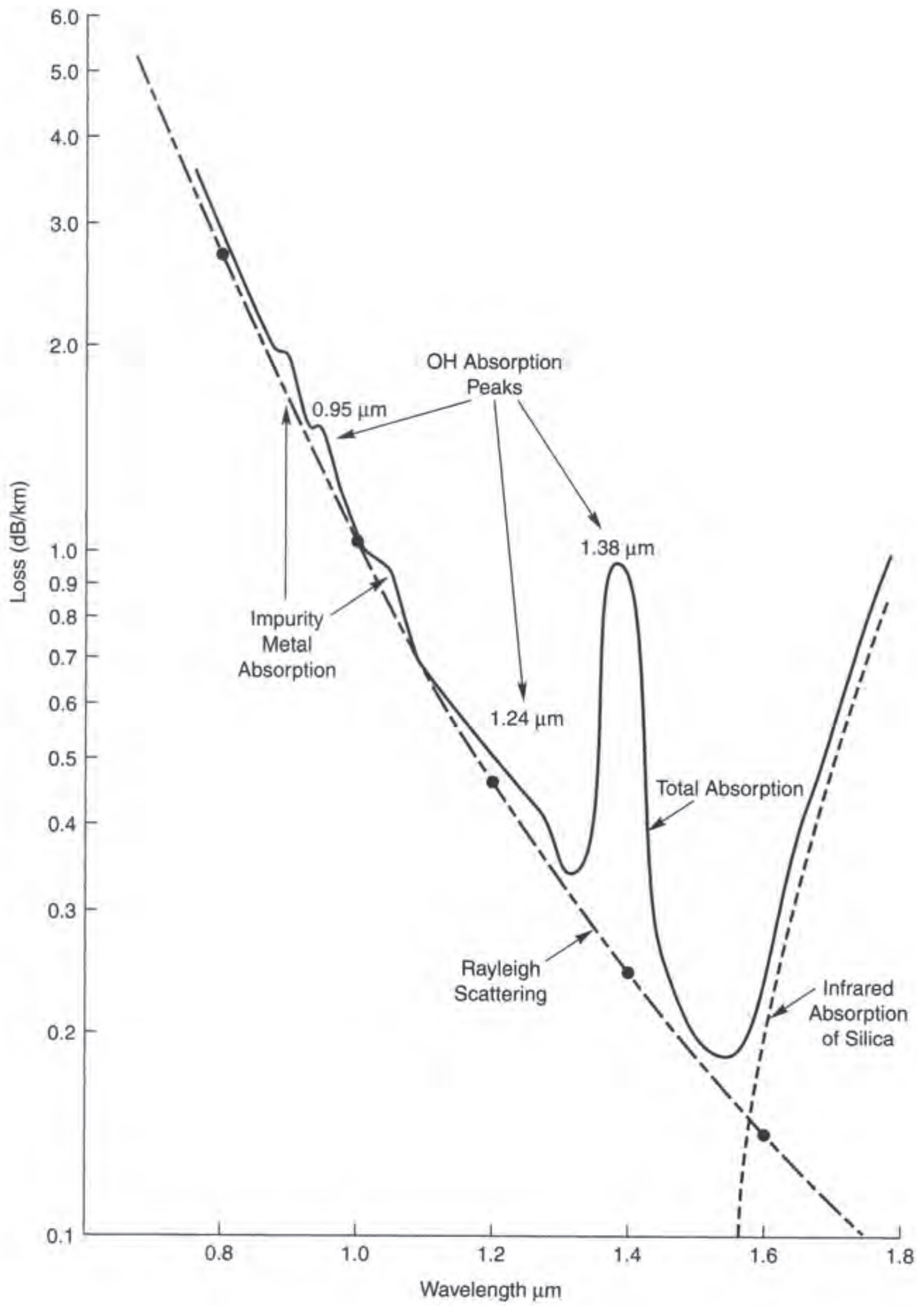


FIGURE 5.2
Total attenuation in a fiber is the sum of absorption and scattering losses.

Decibels may seem to be rather peculiar units, which appear to understate high attenuation. For example, a 3-dB loss leaves about half the original light, a 10-dB loss leaves 10%, and a 20-dB loss leaves 1%. The larger the number, the larger the apparent understatement. A 100-dB loss leaves only 10^{-10} of the original light, and a 1000-dB loss leaves 10^{-100}—a ratio smaller than one atom in the whole known universe. Appendix B translates some representative decibel measurements into ratios. You can also use the simple conversion

$$\text{Fraction of power remaining} = 10^{(-\text{dB}/10)}$$

The decibel scale simplifies calculations of power and attenuation.

Decibels are very convenient units for calculating signal power and attenuation. Suppose you want to calculate the effects of two successive attenuations. One blocks 80% of the input signal, and the second blocks 30%. To calculate total attenuation using fractions, you must convert both absorption figures to the fractions of power transmitted, then multiply them, and convert that number from the fraction of light transmitted to the fraction attenuated. If you use decibels, you merely add attenuations to get total loss.

$$\text{Total loss (dB)} = \text{loss (dB)}_1 + \text{loss (dB)}_2 + \text{loss (dB)}_3 + \cdots$$

The calculations are even simpler if you know the loss per unit length and want to know total loss of a longer (or shorter) piece of fiber. Instead of using the exponential formula mentioned previously, you simply multiply loss per unit length times the distance:

$$\text{Total loss} = \text{dB/km} \times \text{distance}$$

You can also measure power in decibels relative to some particular level. In fiber optics, the two most common decibel scales for power are decibels relative to 1 mW (*dBm*) and relative to 1 μW (*dB*μ). Powers above those levels have positive signs; those below have negative signs. Thus 10 mW is 10 dBm, and 0.1 mW is −10 dBm, or 100 dBμ.

If everything is in decibels, simple addition and subtraction suffice to calculate output power from input power and attenuation. You also can write the equation in other ways:

$$P_{out} = P_{in} - \text{loss (dB)}$$

$$\text{Loss (dB)} = P_{in} - P_{out}$$

$$P_{in} = P_{out} + \text{loss (dB)}$$

Note that it is vital to keep track of the plus and minus signs. In this case, we give loss in decibels a positive sign, as we did earlier. If you ever feel confused, you can do a simple truth test, by checking to see if the output power is less than the input. (The only way output can be more than input is if you have an optical amplifier or regenerator somewhere in the system.)

As an example of how the calculations work, consider a fiber system in which 3 dB is lost at the input end and that contains 6 km of fiber with loss of 0.5 dB/km. If the input power is 0 dBm (exactly 1 mW), the output is

$$P_{out} = 0 \text{ dBm} - 3 \text{ dB (input loss)} - (6 \text{ km} \times 0.5 \text{ dB/km}) = -6.0 \text{ dBm}$$

If you rewrite this as milliwatts, you have 0.25 mW.

Spectral Variation

As we saw before, fiber attenuation is the sum of absorption and scattering, both of which vary with wavelength. The spectral variation depends on the fiber composition. The attenuation curve in Figure 5.2 is fairly typical for single-mode communication fibers, except low-water types.

Attenuation varies with wavelength, depending on the material.

Most single-mode communication fibers are used at wavelengths between about 1280 and 1620 nm, where attenuation is generally below 0.5 dB/km except at the water peak where it may reach 1 dB/km. The traditional transmission bands in that region are at 1310 nm, and in the region from about 1530 to 1620 nm where erbium-doped fiber amplifiers are used. Fibers are available that have water content reduced to such low levels that the 1380-nm water peak almost vanishes, allowing them to be used across the entire 1280 to 1620-nm range.

Attenuation generally is higher in multimode fibers, with typical values about 2.5 dB/km at 850 nm, 0.8 dB/km at 1310 nm, and no more than 3 dB/km at the 1380 nm water peak. As can be seen from Figure 5.2, attenuation is not particularly low at 850 nm; the attraction of that wavelength is its match to the output of commercially available light sources.

Other materials are used in fibers to improve transmission at other wavelengths. Special grades of quartz are used for ultraviolet-transmitting fibers. Some plastics have relatively even transmission across the visible spectrum. *Fluoride* compounds are transparent at longer infrared wavelengths than silica glass. Chapter 6 will cover various materials in more detail.

Light Collection and Propagation

Several factors enter into how fibers collect light and propagate it. Most arise from the structure of fibers, described in Chapter 4. This section examines the impact of those considerations.

Core Size and Mode-Field Diameter

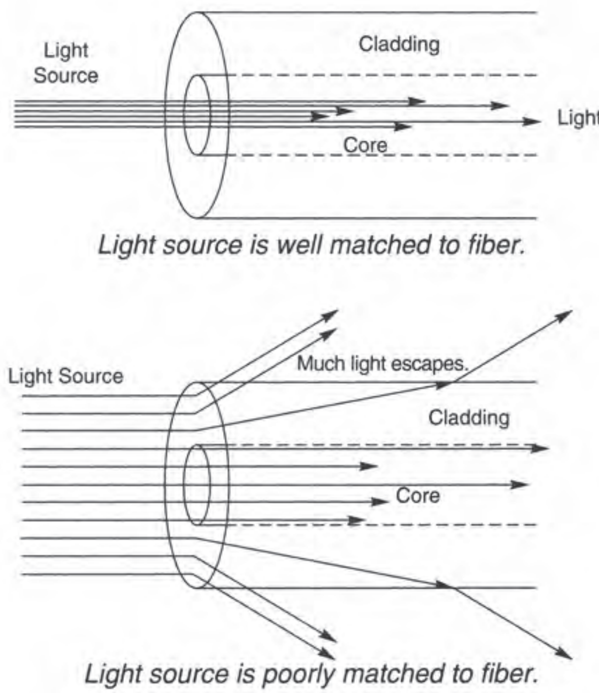
Core size is important in coupling light into a fiber. To collect light efficiently from a light source, the core should be at least as large as the source's emitting area. As shown in Figure 5.3, if the light source is larger than the core, much of its light goes into the cladding. Some of the light escapes quickly, whereas other light may be guided for a distance in the cladding, as if it were in a bare fiber. The larger the core size, the easier it is to align the fiber with the light source and the better the light coupling. Core size does not affect the acceptance angle, which is the range of angles over which a fiber collects light.

The larger the core diameter, the easier it is to align with a light source.

Core size is the physical dimension of the core, but light spreads through a slightly larger volume, including the inner edge of the cladding. This *mode-field diameter* or *effective area* is the critical dimension for light transfer between single-mode fibers. (The difference is not enough to matter in multimode fiber.)

Transferring light between fibers is the business of splices and connectors; details are covered in Chapter 13.

FIGURE 5.3
The match between light-source dimensions and core diameter helps determine light transfer.

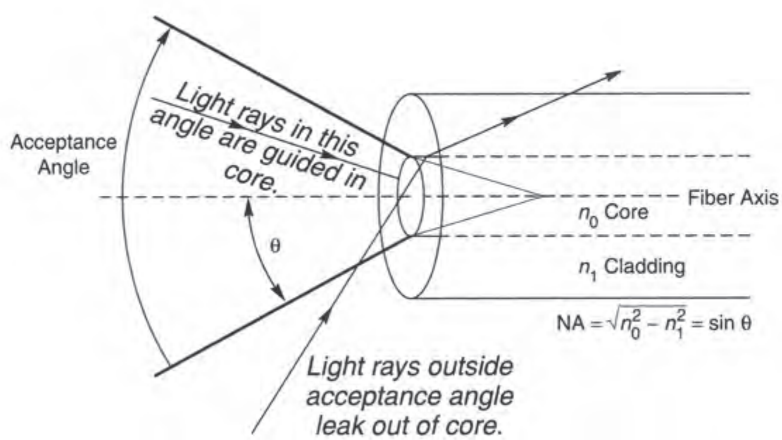


Numerical Aperture

Numerical aperture (NA) measures the fiber's acceptance angle.

A second factor in determining how much light a fiber collects is its acceptance angle, the range of angles over which a light ray can enter the fiber and be trapped in its core. The full-acceptance angle is the range of angles at which light is trapped; it extends both above and below the axis of the fiber. The half-acceptance angle is the angle measured from the fiber axis to the edge of the cone of light rays trapped in the core; it is shown in Figure 5.4.

FIGURE 5.4
Light rays have to fall within a fiber's acceptance angle, measured by NA, to be guided in the core.



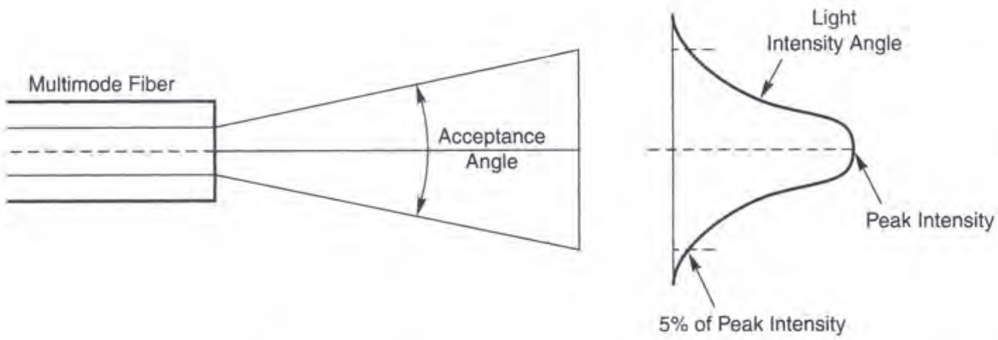


FIGURE 5.5
Intensity of light emerging from a multimode fiber falls to about 5% of peak value at the edge of its acceptance angle.

The standard measure of acceptance angle is the *numerical aperture*, NA, which is the sine of the half-acceptance angle, θ, for reasonably small angles. For a step-index fiber, it is defined as

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

where n_0 is the core index and n_1 is the cladding index. A typical value for step-index single-mode fiber is around 0.14.

Numerical aperture is not calculated the same way in graded-index fibers; strictly speaking it varies across the core with the refractive index. However, you can measure numerical aperture by monitoring the divergence angle of light leaving a fiber core. As shown in Figure 5.5, the light emerging from a multimode fiber spreads over an angle equal to its acceptance angle. For practical measurements, care must be taken to eliminate modes guided in the cladding, and the *edge* of the beam is defined as the angle where intensity drops to 5% that in the center. NA can be calculated easily from the acceptance angle. Typical NA values are 0.20 for 50/125 graded-index fiber, and about 0.28 for 62.5/125 graded-index fiber.

Core diameter does not enter into the NA equation, but light rays must enter the core as well as fall within the acceptance angle to be guided in the core. Large core size and large NA do not have to go together, but in practice larger-core fibers tend to have larger core-cladding index differences and thus larger NAs. For example, step-index multimode fibers typically have NAs of at least 0.3, more than twice the value for single-mode step-index fibers.

The numerical aperture of single-mode fibers is defined by the same equation as for multimode fibers, but light does not spread out from them in the same way. (They carry only a single mode, and their cores are so small that another wave effect called *diffraction* controls how light spreads out from the end.) NA generally is not as important for single-mode fibers as it is for multimode fibers.

Cladding Modes and Leaky Modes

Light can be guided in cladding modes.

Light can enter the cladding either from a source at the end of the fiber or by escaping from the core when it hits the cladding boundary at an angle greater than the confinement angle. The resulting *cladding modes* can propagate in the cladding, guided by total internal reflection, if the material surrounding the core—air or a plastic coating—has a refractive index lower than that of the core. This phenomenon can introduce noise in communications fibers and crosstalk between fibers in an imaging bundle. To prevent this, manufacturers often coat fiber with a plastic that has a refractive index higher than that of the cladding, which prevents total internal reflection. (Light-absorbing materials generally have a high refractive index at wavelengths they absorb.) Fibers in rigid bundles may be separated by light-absorbing dark glass.

There is no sharp distinction between the highest-order modes guided in the core of a multimode fiber and the lowest-order modes that escape from the core. Modes in this hazy zone are called *leaky modes* because they are partly guided in the core, but escape into the cladding over longer distances. This makes them prone to leakage and loss.

Cladding and leaky modes must be removed to ensure accurate measurements. Devices called *mode strippers* surround a length of fiber with a high-index material that prevents total internal reflection at the outer edge of the cladding, removing these undesired modes. A long length of fiber with high attenuation in the cladding also can function as a mode stripper.

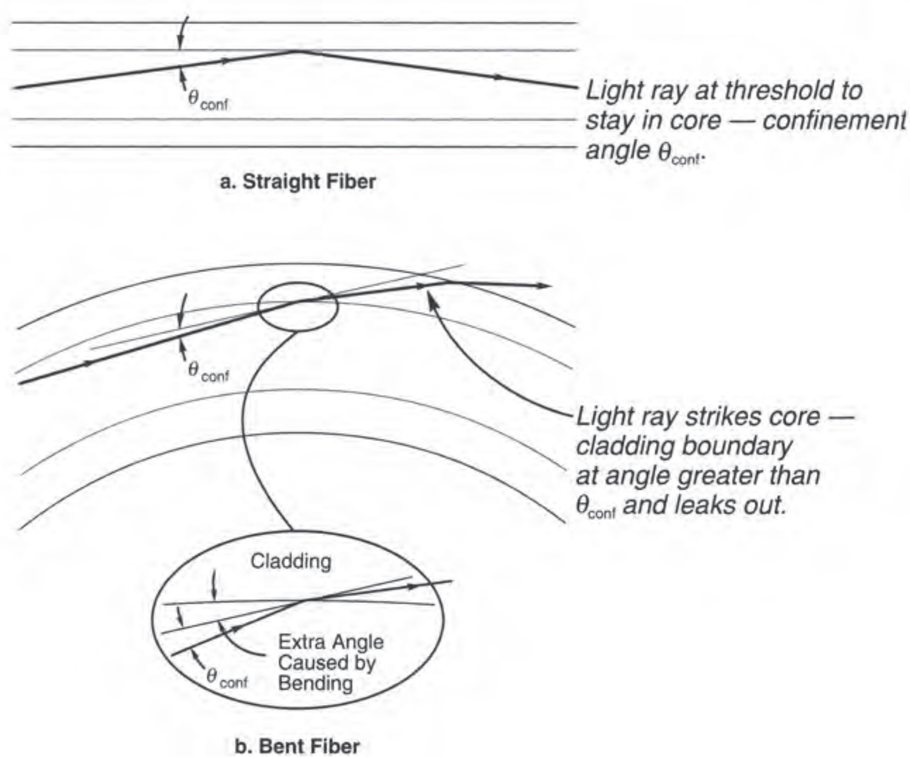
Bending Losses

Bends can cause excess fiber loss.

A variety of outside influences can change the physical characteristics of optical fibers, affecting how they guide light. Typically these effects are modest and must be enhanced or accumulated over long distances to make the kind of sensors described in Chapter 29. However, significant losses can arise if the fiber is bent so sharply that light strikes the core-cladding interface at a large enough angle that the light can leak out.

Bending loss is easiest to explain using the ray model of light in a multimode fiber. When the fiber is straight, light falls within its confinement angle. Bending the fiber changes the angle at which light hits the core-cladding boundary, as shown in Figure 5.6.

FIGURE 5.6
Light can leak out of a bent fiber.



If the bend is sharp enough, it hits the boundary at an angle outside the confinement angle θ_{conf}, and is refracted into the cladding where it can leak out.

Bend losses fall into two broad categories. *Macrobends* are single bends obvious to the eye, such as a fiber bent sharply where a cable ends at a connector. The case shown in Figure 5.6 is typical. *Microbends* are tiny kinks or ripples that can form along the length of fibers that become squeezed into too small a space. This can happen in a cable when the cabling material shrinks relative to the fiber, or the fiber stretches relative to the cable. Microbends are smaller, but they cause similar light leakage because they also affect the angle at which light hits the core-cladding boundary.

Dispersion

The principal types of dispersion are modal, material, waveguide, and polarization.

Dispersion is the spreading out of light pulses as they travel along a fiber. It occurs because the speed of light through a fiber depends on its wavelength and the propagation mode. The differences in speed are slight, but like attenuation, they accumulate with distance. The four main types of dispersion arise from multimode transmission, the dependence of refractive index on wavelength, variations in waveguide properties with wavelength, and transmission of two different polarizations of light through single-mode fiber.

Like attenuation, dispersion can limit the distance a signal can travel through an optical fiber, but it does so in a different way. Dispersion does not weaken a signal; it blurs it. If you send one pulse every nanosecond but the pulses spread to 10 ns at the end of the fiber, they blur together. The signal is present, but it's so blurred in time that it is unintelligible.

In its simplest sense, dispersion measures pulse spreading per unit distance in nanoseconds or picoseconds per kilometer. Total pulse spreading, Δt, is

$$\Delta t = \text{dispersion (ns/km)} \times \text{distance (km)}$$

This equation actually gives dispersion in two different forms. One is the unit or characteristic dispersion of the fiber, written as *dispersion* and measured per unit length (in units of time per kilometer). The other is the total pulse spreading in units of time over the entire length. As long as the same fiber is used throughout the cable, the total pulse spreading is simply the characteristic fiber dispersion times the fiber length. If different types of fibers are used, you need to calculate pulse spreading separately for each section, then add them.

The simple equation above holds for modal dispersion, which is the type most important for step-index multimode fibers, where modes travel at different speeds through the fiber. Graded-index fibers nominally equalize the speeds of all transmitted modes, but things don't work that perfectly in the real world. It's functionally impossible to achieve the ideal refractive-index profile needed to make all modes travel at exactly the same speed. That profile depends on wavelength, and fibers carry signals at a range of wavelengths. In practice, you have to rely on manufacturer specifications for the unit dispersion of graded-index fibers, typically specified in units of bandwidth (described below) rather than in time units.

Total pulse spreading is the square root of the sum of the squares of the pulse spreading from modal, chromatic, and polarization-mode dispersion.

Other types of dispersion also add to total pulse spreading. We'll get to them in a minute, but first let's look at how to calculate the total pulse spreading. Material and waveguide dispersion add together to give a wavelength-dependent *chromatic dispersion*, mentioned in Chapter 4. Fibers also experience polarization-mode dispersion. Both quantities are independent of each other and of modal dispersion. That means you have to take the square root of the sum of the squares to get total pulse spreading:

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

Polarization-mode dispersion is small enough that it doesn't matter in multimode fibers, so for that case the equation becomes

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{modal}})^2 + (\Delta t_{\text{chromatic}})^2}$$

Likewise, single-mode fibers have no modal dispersion (other than polarization-mode dispersion), so the equation becomes

$$\Delta t_{\text{total}} = \sqrt{(\Delta t_{\text{chromatic}})^2 + (\Delta t_{\text{polarization-mode}})^2}$$

Chromatic Dispersion and Wavelength

Chromatic dispersion depends on the range of wavelengths in the optical signal.

Chromatic dispersion is the pulse spreading that arises because the velocity of light through a fiber depends on its wavelength. It is measured in units of picoseconds (of pulse spreading) per nanometer (of spectral width of the optical signal) per kilometer (of fiber length). The total pulse spreading due to chromatic dispersion, $\Delta t_{\text{chromatic}}$, is calculated by multiplying the fiber's characteristic chromatic dispersion by the range of wavelengths generated by the light source ($\Delta\lambda$) and the fiber length:

$$\Delta t_{\text{chromatic}} = \text{chromatic dispersion (ps/nm-km)} \times \Delta\lambda \text{ (nm)} \times \text{fiber length (km)}$$

The characteristic chromatic dispersion of a fiber is a function of wavelength. It is normally the largest type of dispersion in single-mode fiber systems. As you learned in Chapter 4, chromatic dispersion is the sum of two components, material and waveguide dispersion, which can cancel each other at certain wavelengths. In standard step-index single-mode fiber, material and waveguide dispersion add to zero near 1310 nm. Dispersion shifting moves the zero-dispersion point to other wavelengths, generally longer. To understand chromatic dispersion, we need to look at both material and waveguide dispersion.

Material dispersion arises from variations in refractive index with wavelength.

Material dispersion arises from the change in a material's refractive index with wavelength. The higher the refractive index, the slower light travels. Thus as a pulse containing a range of wavelengths passes through a material, it stretches out, with the wavelengths with lower refractive index going faster than those with higher indexes. Like absorption, dispersion is a function of the individual material, which changes with wavelength. Communication fibers are nearly pure silica (SiO_2), so their characteristic material dispersion is essentially the same as that of pure fused silica. Figure 5.7 plots both refractive index and material dispersion of fused silica against wavelength.

Note that material dispersion has a positive or negative sign, unlike the modal dispersion. You can think of this sign as indicating how the refractive index is changing with wavelength, although that's an oversimplification. The physical meaning of the sign is a bit

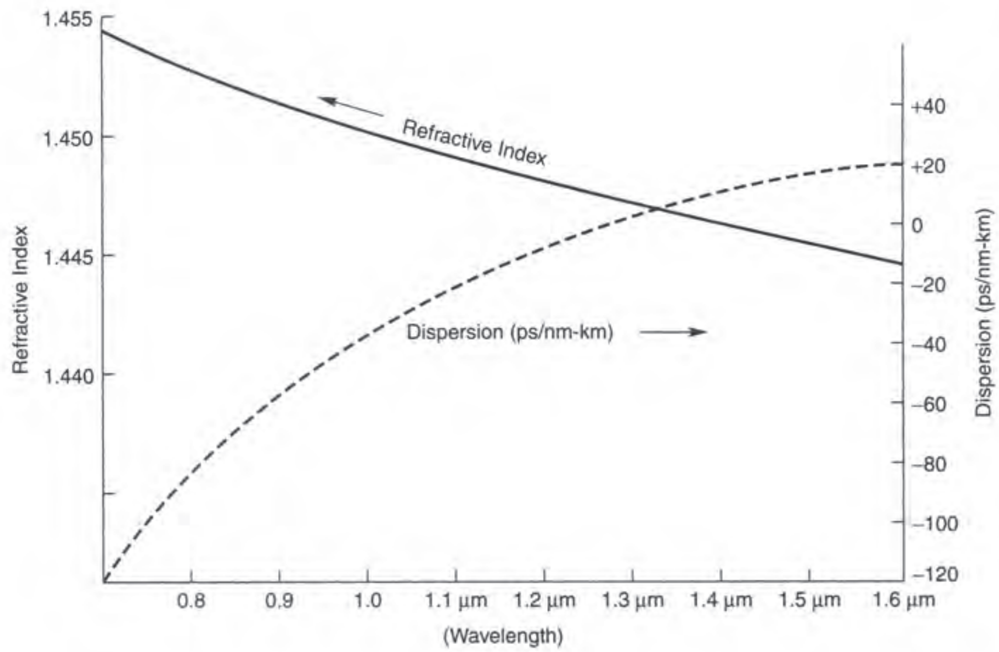


FIGURE 5.7
Material dispersion and refractive index of silica as a function of wavelength.

obscure, but the signs are important in combining material dispersion and waveguide dispersion to calculate total chromatic dispersion. Although chromatic dispersion also has a sign, the calculations for total pulse spreading cancel it out because the formula uses the square of the pulse spreading caused by chromatic dispersion.

As Figure 5.7 shows, the magnitude of material dispersion is large at wavelengths shorter than 1.1 μm. High material dispersion at 850 nm makes chromatic dispersion high at that wavelength, limiting the transmission speed possible even in single-mode fiber. The real benefits of single-mode transmission come from operating at longer wavelengths where the material dispersion is small.

Waveguide dispersion is a separate effect, arising from the distribution of light between core and cladding. Recall that waveguide properties are a function of the wavelength. This means that changing the wavelength affects how light is guided in a single-mode fiber. For a step-index single-mode fiber, the waveguide dispersion is relatively small, but can be important. More complex refractive index profiles can increase waveguide dispersion, such as the dispersion-compensating fiber in Figure 4.11(f). Like material dispersion, waveguide dispersion has a sign that indicates how changing wavelength affects dispersion.

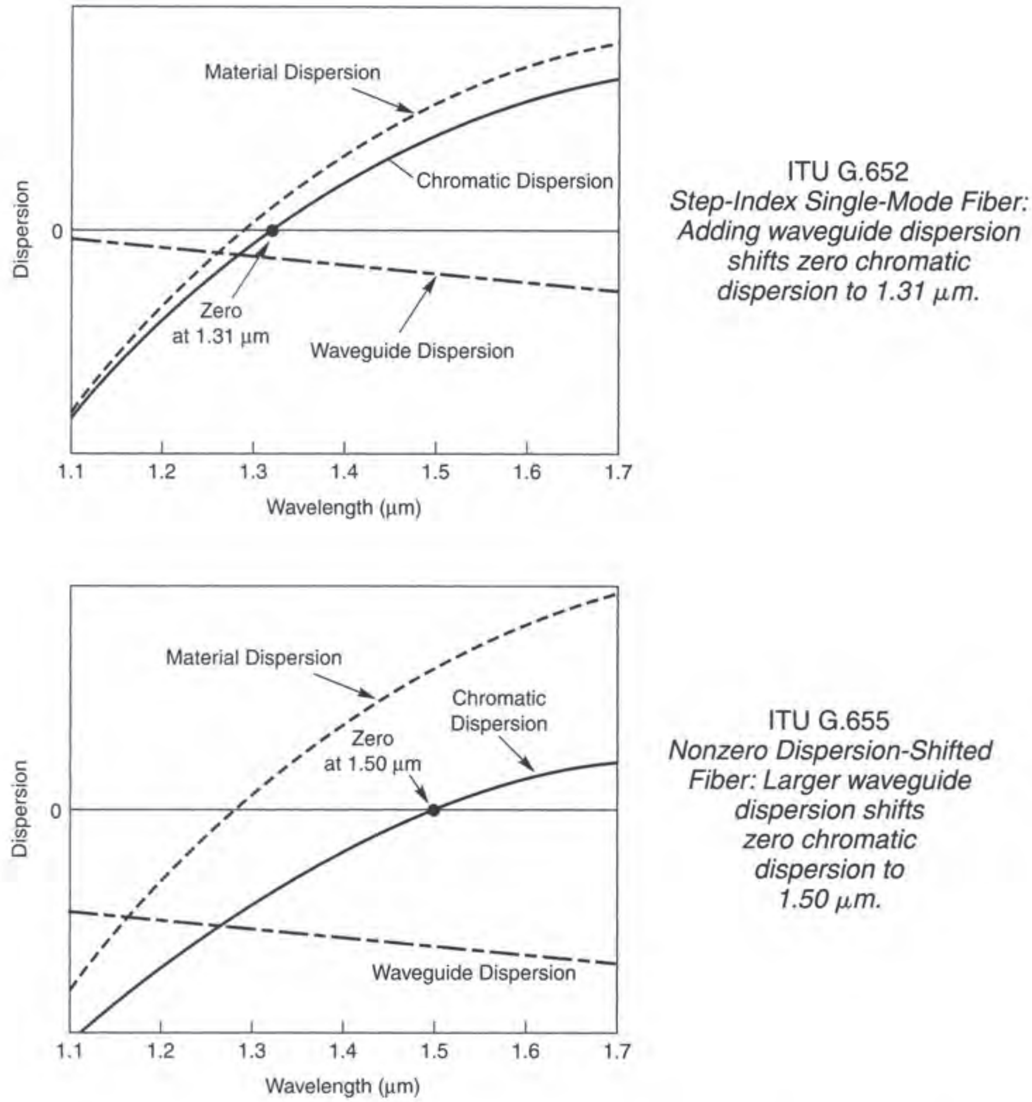
Waveguide dispersion arises from changes in light distribution between core and cladding.

For most practical purposes, chromatic dispersion is the sum of material and waveguide dispersion.

$$\text{Disp}_{\text{chromatic}} = \text{Disp}_{\text{material}} + \text{Disp}_{\text{waveguide}}$$

Remember that the signs are important. From a physical standpoint, what happens is that the variation with wavelength caused by waveguide dispersion can offset (or add to) that caused by material dispersion. Dispersion shifting is done by designing fibers to have large negative waveguide dispersion, which offsets positive material dispersion at wavelengths longer than 1.28 μm, shifting the region of low chromatic dispersion near the erbium-fiber

FIGURE 5.8
Different amounts of waveguide dispersion combine with material dispersion to produce different chromatic dispersion.



amplifier band. As mentioned earlier, generally the zero-dispersion wavelength is chosen to be a little longer or shorter than the 1530- to 1620-nm erbium-fiber band. Figure 5.8 shows how waveguide and material dispersion combine for step-index single-mode fiber and one type of nonzero dispersion-shifted fiber.

A Closer Look at Chromatic Dispersion

The descriptions of material, waveguide, and chromatic dispersion have been a bit vague because the formal definitions depend on some concepts that require a bit of extra work, a few equations, and a dash of calculus to understand. To delve more deeply, let's consider the case of material dispersion, which is the simplest because it depends only on how the refractive index of the material varies with wavelength. (Chromatic and waveguide dispersion work similarly, but the details are more complex.)

Recall that the velocity of light passing through a material depends on its refractive index. Since the refractive index varies with wavelength, so does the velocity of light in the material. Suppose that the material has a refractive index n_1 at wavelength λ_1 and an index n_2 at wavelength λ_2. The time each wavelength takes to pass through a length of glass L is

$$t = \frac{Ln}{c}$$

If you calculate the difference between the transit times at the two wavelengths, you get what is called the *group delay time*,

$$\text{Group delay} = t_1 - t_2 = \frac{Ln_1}{c} - \frac{Ln_2}{c} = \frac{L}{c}(n_1 - n_2)$$

which measures the difference in travel time for the two wavelengths. This is the same as the pulse spreading through a fiber denoted by Δt.

From a physical standpoint, the group delay is the slope of the curve that plots refractive index as a function of wavelength, shown in Figure 5.9(a) on a different scale that shows its curvature better than Figure 5.7. If you know elementary calculus, that slope is the first derivative of how refractive index n varies with wavelength:

Group delay is the slope of the plot of refractive index versus wavelength.

$$\text{Group delay} = \frac{L}{c}\left(n - \lambda \frac{dn}{d\lambda}\right) = \Delta t$$

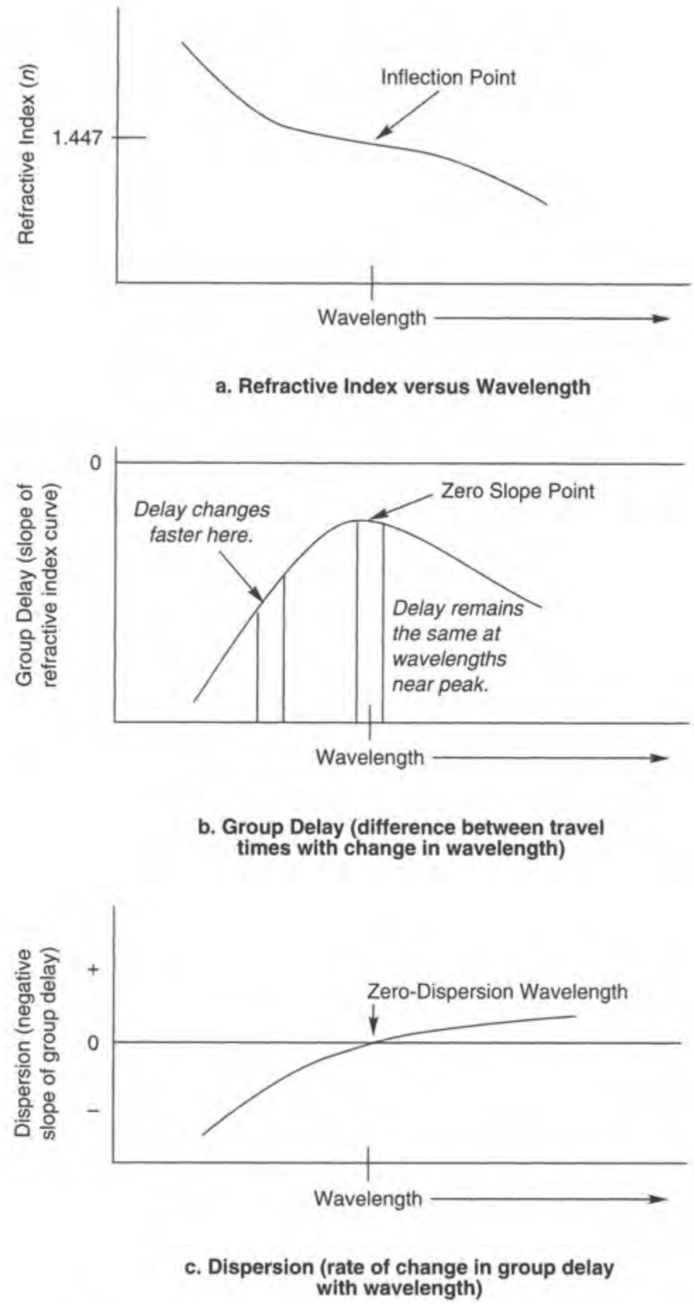
This group delay is plotted in Figure 5.9(b). You can think of group delay time as the actual pulse spreading Δt—measured in units of time—caused by the change in refractive index over a range of wavelengths. Remember, however, that this is a time delay, *not* the characteristic material dispersion of the fiber. Characteristic dispersion measures not the *magnitude* of the delay in units of time, but how fast the group delay is *changing* with wavelength (generally for a unit length of the fiber rather than for the entire length). This *characteristic material dispersion* is measured in units of picoseconds (of time) per nanometer (of wavelength range) per kilometer (of fiber length). Multiply it by the length of the fiber and the range of wavelengths, and you get the group delay Δt.

You calculate characteristic material dispersion D_{material} as the rate of change of the group delay with wavelength, which is equivalent to measuring the slope of the group delay curve with respect to wavelength. If you divide through by fiber length, and take the differential rate of change in group delay with wavelength, you get

$$D_{\text{material}} = \frac{1}{L} \times \left(\frac{d\,(\text{group delay})}{d\lambda}\right) = \frac{-\lambda}{c} \times \frac{d^2 n}{d\lambda^2}$$

This is the characteristic material dispersion, plotted in Figure 5.9(c), and it represents the slope of the group delay curve. To see what it means graphically, compare it with the plot of group delay in Figure 5.9(b). The group delay is nearly constant at its peak value, so the values are virtually the same at the two wavelengths near the peak (vertical lines). However, at shorter wavelengths the group delay is changing much faster, so the values differ much more at two wavelengths the same distance apart (vertical lines at the left).

FIGURE 5.9
Material dispersion is the slope of the slope (or the second derivative) of a plot of refractive index versus wavelength.



You can calculate the total pulse spreading over the length of the fiber, Δt, by multiplying this characteristic dispersion by fiber length L and wavelength range $\Delta\lambda$. This gives:

$$\Delta t = D_{\text{material}} \times L \times \Delta\lambda = \frac{-L\lambda\Delta\lambda}{c} \times \frac{d^2 n}{d\lambda^2}$$

Thus the characteristic material dispersion is proportional to the *second derivative* (or, equivalently, to the slope of the slope) of the plot of refractive index versus wavelength, not directly to the slope of the refractive index curve itself. To reiterate, it's also the slope of the group delay, which measures the travel time through the fiber as a function of wavelength. The *slope* of the group delay curve, in contrast, measures how *fast* the group delay changes with wavelength, which is the characteristic material dispersion. This rate of change of group delay is zero at the peak of the group delay curve, which comes at 1.28 μm in silica fibers. This also is the point where the slope of the refractive-index curve stops decreasing with increasing wavelength and starts increasing again. (Because the refractive index decreases as wavelength increases, the slope is a negative number, plotted below zero on Figure 5.9(b).) Mathematically, the zero material-dispersion wavelength is a maximum of the group velocity curve and a point of inflection in the refractive-index plot.

Dispersion is the slope of group delay, or the second derivative of the plot of refractive index versus wavelength.

Figure 5.9(c) plots characteristic material dispersion. Recall that the formula carries a negative sign, which it gets from the negative value of group delay. The minus sign means that characteristic material dispersion is negative at wavelengths where the group delay curve is rising (i.e., has positive slope), and positive where the middle curve is dropping (i.e., has negative slope).

The components of waveguide dispersion work in a similar way, but the physical relationships are more complex. As you saw earlier, waveguide dispersion has a sign, which matters when adding it to material dispersion to get chromatic dispersion, the number given in product specifications. The sign also matters when compensating for chromatic dispersion to reduce pulse spreading. Chromatic dispersion works like material dispersion; it measures the rate of change of the group delay for all chromatic dispersion, not just for material dispersion.

The signs don't matter when combining the effects of chromatic dispersion with other dispersion, because the pulse spreading enters those equations as squares. As you've probably learned the hard way, it's easy to lose track of signs that don't have an obvious physical meaning. This can happen very easily with material, waveguide, and chromatic dispersion, so don't be surprised if you spot the wrong signs. In normal single-mode fibers, the dispersion should be negative at wavelengths shorter than the zero-dispersion wavelength, and positive at longer wavelengths.

Dispersion Slope and Specifications

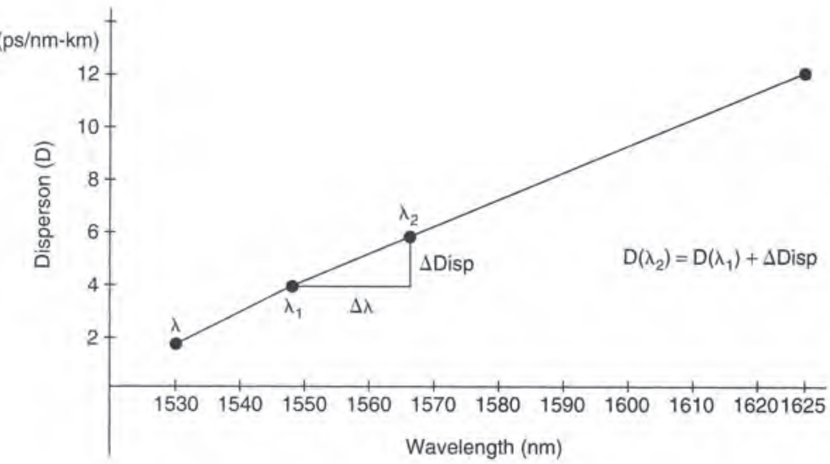
In practice, engineers approximate chromatic dispersion by assuming it varies linearly over a defined limited range of wavelengths. That is, they plot dispersion at a pair of wavelengths, draw a straight line between them, and assume that the dispersion at intermediate wavelengths falls between them, as shown in Figure 5.10. If the two wavelengths are λ_1 and λ_2, and the characteristic chromatic dispersions at those wavelengths are $D(\lambda_1)$ and $D(\lambda_2)$, this means that dispersion $D_{\text{chromatic}}$ at intermediate wavelength λ is

$$D_{\text{chromatic}}(\lambda) = \left(\frac{D(\lambda_2) - D(\lambda_1)}{\lambda_2 - \lambda_1} \times (\lambda - \lambda_2)\right) + D(\lambda_2)$$

Specification sheets often give these equations with the ranges of dispersion and wavelength for which they are valid. Typically there are separate equations for the 1530- to 1565-nm range of C-band erbium-doped fiber amplifiers and the 1565- to 1625-nm L-band.

Look closely at the equation, and you can see that it actually multiplies the *dispersion slope* (change in dispersion over a range of wavelength) by the change in wavelength from

FIGURE 5.10
Extrapolating fiber dispersion at an intermediate wavelength.



Dispersion slope gives change in dispersion over a range of wavelengths.

one endpoint, and adds the dispersion at that endpoint. Thus the equation translates in more descriptive terms to

$$D_{\text{chromatic}}(\lambda) = [(\text{dispersion slope}) \times (\Delta\lambda)] + D(\text{ endpoint})$$

Remember this is the slope of *chromatic* dispersion, although the normal term is just "dispersion slope."

Dispersion slope tells how dispersion changes with wavelength. Normally this change is very small over the range of wavelengths generated by a single laser transmitter. However, it is important in wavelength-division multiplexed systems, which carry many optical channels spanning tens of nanometers in wavelength. We will take a closer look later in this chapter.

Specification sheets typically do *not* plot chromatic dispersion directly as a function of wavelength, but give the chromatic dispersion that may be found at a range of wavelengths, such as 2.6 to 6.0 ps/nm-km at 1530 to 1565 nm. These numbers do not mean that the fibers have 2.6 ps/nm-km dispersion at 1530 nm and 6.0 ps/nm-km at 1565—they mean that the values in this range of wavelengths fall within this "box." As with other specified values, they allow for a range of manufacturing tolerances, so the specified dispersion slope will not always match the slope calculated from the extremes of chromatic dispersion and wavelength.

Source Bandwidth and Chromatic Dispersion

Unlike the pulse spreading caused by other types of fiber dispersion, the spreading caused by chromatic dispersion depends strongly on the light source. If we take $D_{\text{chromatic}}(\lambda)$ as the characteristic dispersion of a unit length (1 km) of fiber, the total pulse spreading from chromatic dispersion $\Delta t_{\text{chromatic}}$ is

$$\Delta t_{\text{chromatic}} = D_{\text{chromatic}}(\lambda) \times \Delta\lambda \times \text{Length}$$

where Δλ is the range of wavelengths in the optical signal in nanometers and *Length* is the fiber length in kilometers. This means that the spectral bandwidth of the light source is a parameter that system designers can adjust to limit the effects of chromatic dispersion. The higher the data rate, the more important narrow-band sources become, as you will learn in later chapters.

Chromatic Dispersion Compensation and Tailoring

We saw earlier that pulse dispersion is cumulative, building up along the length of a fiber system. In general, this means that adding more fiber only makes pulse dispersion worse. However, it is possible to reduce total *chromatic* dispersion by adding a length of fiber with chromatic dispersion of the opposite sign. For example, you could add a length of fiber with negative chromatic dispersion at 1550 nm to a system containing fiber with positive dispersion in that band. The idea is similar to using waveguide dispersion to offset material dispersion, but in this case the compensation is done by splicing together two fibers with different chromatic dispersion, as shown in Figure 5.11. The dispersion-compensating fiber could be added in a length of cable, but it's often installed in modular form in an equipment rack near a receiver or optical amplifier. In long-distance systems, lengths of the two types of fiber alternate, so chromatic dispersion does not build up to excessive levels before being reduced.

Combining fibers with chromatic dispersion of opposite signs can compensate for chromatic dispersion, yielding low overall pulse spreading.

A typical dispersion-compensating fiber has high negative waveguide dispersion that gives it a negative chromatic dispersion that typically is several times the magnitude of the positive chromatic dispersion of the transmission fiber. Thus compensation requires a shorter length of the dispersion-compensating fiber. That is important because compensating fiber typically has higher attenuation than transmission fibers. Compensating fiber also usually has a small effective area, making it more vulnerable to nonlinear effects, so it is used at the receiving end of the system, where lower power reduces nonlinear effects.

Typically, dispersion is compensated over a range of wavelengths, but it's easiest to calculate requirements if you look just at one wavelength. Suppose you want to have total chromatic dispersion of +2 ps/nm-km at the 1530-nm short end of the erbium-fiber band over a 1000-km system. You are using nonzero dispersion-shifted transmission fiber with

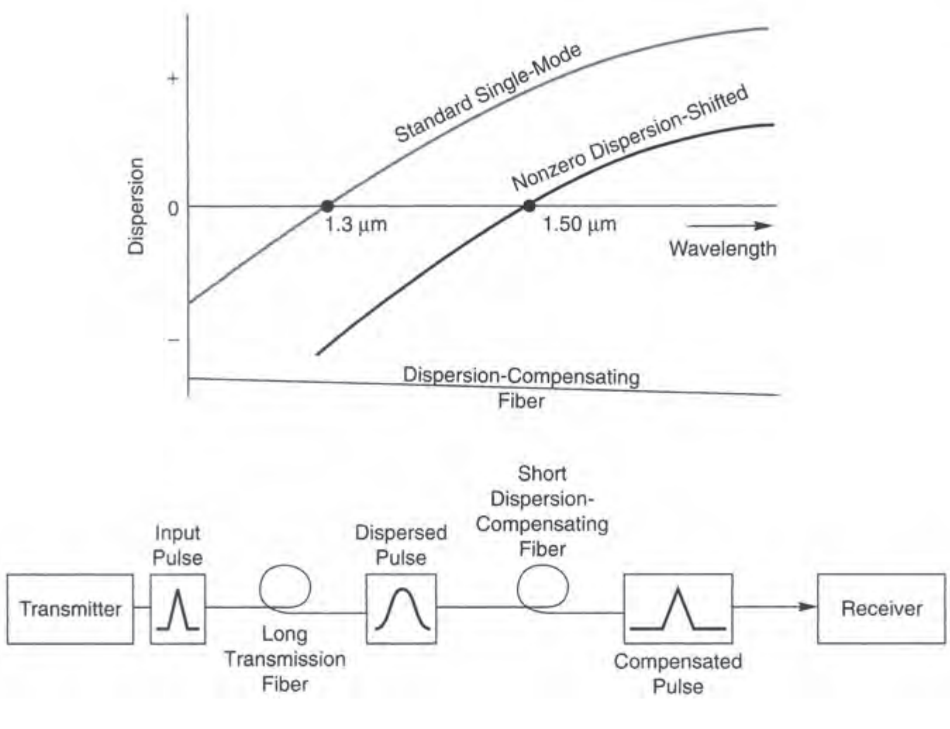


FIGURE 5.11
Dispersion compensation.

dispersion of +8 ps/nm-km at that wavelength, and you can buy dispersion-compensating fiber with dispersion of −100 ps/nm-km at 1530 nm. You can use the general formula

$$D_{net}\, L_{total} = D_{transmission}\, L_{transmission} + D_{comp}\, L_{comp}$$

where D_{net} is the net dispersion for the entire system, L_{total} is the total length (assuming the compensating fiber is part of the transmission path), $D_{transmission}$ and $L_{transmission}$ are the dispersion and length of the transmission fiber, and D_{comp} and L_{comp} are dispersion and length of the compensating fiber. Plug the numbers in, and you see

$$2000 \text{ ps/ns} = +8\, L_{transmission} - 100\, L_{comp}$$

Since you know that $L_{transmission} + L_{comp} = 1000$ km, you can work out that you need 944 km of nonzero dispersion-shifted transmission fiber and 56 km of compensating fiber. Thus you need about 1 km of compensating fiber for every 17 km of transmission fiber.

You can use the same ideas to calculate the dispersion compensation needed for upgrading existing fiber systems. Other approaches to chromatic dispersion also are possible. One example is an optical delay line that would delay signals a certain amount depending on their wavelength, so the slower signals could catch up. A dispersion-compensating fiber in a box could serve as such a delay line.

Multiwavelength Transmission and Dispersion

WDM transmission requires dispersion compensation over a range of wavelengths.

Dealing with chromatic dispersion is more complex in systems that carry multiple wavelengths. Wavelength-division multiplexing requires management of chromatic dispersion over the entire range of wavelengths that are transmitting optical channels. Typically that can span tens of nanometers in systems with fiber amplifiers, 35 nm in systems with *C-band* erbium-fiber amplifiers, 55 nm in systems with *L-band* erbium-fiber amplifiers, or 95 nm in systems with both.

That range of wavelength is large enough for chromatic dispersion to differ significantly among optical channels. Just in the erbium-fiber C-band, the difference can accumulate to 2 ps/nm-km with reduced-dispersion-slope (0.045 ps/nm^2-km) fibers, and to 4 ps/nm-km with other nonzero dispersion-shifted fibers. This becomes important because it means different optical channels may require different amounts of dispersion compensation.

Dispersion management also becomes more complex as the range of wavelengths increases. The dispersion slopes of dispersion-compensating fibers do not match and offset those of transmission fibers, so residual differences remain. These accumulate over distance and can become significant for long-distance, high-speed systems. Additional components or a mix of dispersion-compensating and transmission fibers may be needed.

Polarization-Mode Dispersion

Fibers have low levels of birefringence that affect light in the two polarization modes differently.

In Chapter 4, you learned that a single-mode fiber actually transmits light in two distinct polarization modes. The electric fields of the two modes are perpendicular to each other, or *orthogonal* in the jargon of physics. Normally the two behave just the same in the fiber, so from a physical standpoint they are called *degenerate*, which means they can't be distinguished.

The existence of two polarization modes wouldn't matter if optical fiber and all the forces applied to it were perfectly symmetrical. However, nothing is perfect. Stresses within the fiber and forces applied to it from the outside world cause slight differences in the refractive index experienced by light in the two polarization modes. This effect is called *birefringence.*

Internal stresses make some crystals strongly birefringent. In calcite the refractive index differs more than 10% for the two polarization axes, which makes objects seen through a calcite prism look double-exposed. Manufacturing stresses produce only a tiny difference—around one part in 10 million (10^{-7})—in optical fibers, but that tiny effect can become significant when very fast pulses go through long lengths of fiber. If that birefringence was uniform along the length of the fiber, light in the faster polarization mode would travel about one wavelength farther ahead of the slower mode every 10 meters, as shown in Figure 5.12. However, the effect is not that simple because the difference—called *differential group delay*—fluctuates in a seemingly random manner, producing *polarization-mode dispersion* (PMD).

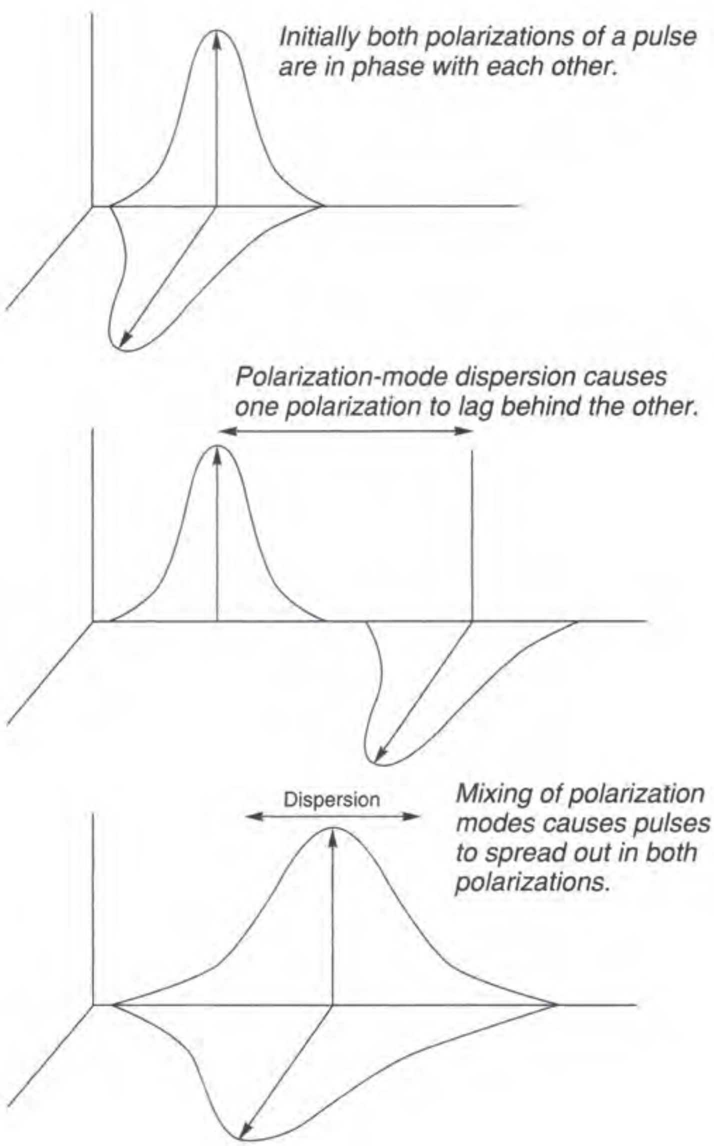


FIGURE 5.12
Polarization-mode dispersion.

Pulse spreading due to PMD varies statistically over time.

The effects that cause differential group delay are basically random background effects. Minor fluctuations in manufacturing processes generate very-low-level stresses that vary along the length of the fiber. The environmental stresses on fibers change continually, with such factors as temperature, wind loading, and low-level vibrations. Thus the differential group delay varies with time all along the length of the fiber, like a low-level background noise. In addition, light can shift randomly between polarization modes in normal single-mode fibers. Thus differential group delay, $\Delta\tau_{DGD}$, does not accumulate consistently along the fiber, but on average grows larger with distance, as shown at the bottom of Figure 5.12. The increase in the average value is proportional to the square root of fiber length L times a characteristic polarization-mode dispersion for the fiber D_{PMD}.

$$\Delta t_{DGD} = D_{PMD} \times \sqrt{\text{fiber length}}$$

The instantaneous differential group delay is what matters for signal transmission, and this quantity varies statistically around the average value. When it exceeds the allowable value for the system, it can cause transmission errors. Usually these errors appear as a brief series of incorrect bits in a random outage.

Typical values of polarization-mode dispersion for installed fiber are 0.05 to 1 picosecond per root kilometer. Fiber now in production has characteristic PMD values below 0.1 $\text{ps/km}^{-1/2}$, but cabling and installation can change that value. Environmental conditions also can change the value. For example, winds blowing on overhead cables can raise the instantaneous values of characteristic PMD to more than 1 $\text{ps/km}^{-1/2}$.

The potential effects of polarization-mode dispersion were not considered significant until several years ago, so manufacturers did not specify PMD values for earlier fibers. Because cabling and installation also are important, the best way to be sure of PMD in installed fibers is to measure them in place. Other components also exhibit polarization-mode dispersion, which must be considered in budgeting for overall system PMD.

Polarization-mode dispersion is less of a problem than chromatic dispersion, and PMD compensation technology is still in the early stages of development. In practice, PMD is not significant at data rates of 2.5 Gbit/s or less. But careful control is required for long-distance transmission at higher speeds.

Dispersion and Transmission Speeds

So far we have considered the effects of dispersion on instantaneous pulses, but real pulses are not instantaneous. In digital systems, the initial pulse starts with a duration Δt_{input}, then experiences spreading due to dispersion of $\Delta t_{dispersion}$. The output pulse length is not the direct sum of the two pulse durations but the square root of the sum of their squares:

$$\Delta t_{output} = \sqrt{\Delta t_{input}^2 + \Delta t_{dispersion}^2}$$

This gives the pulse width at the end of the system, and it is these pulses that have to be resolved for the system to operate properly.

Dispersion limits maximum data rate.

The degree of overlap at which *pulse dispersion* causes problems in digital systems depends on the design. One rough guideline for estimating the maximum bit rate is that the interval between pulses should be four times the dispersion, or, equivalently,

$$\text{Maximum bit rate} = \frac{1}{4\ \Delta t_{\text{dispersion}}}$$

Thus, if pulses experience about 1 ns of dispersion, the maximum bit rate is about 250 Mbit/s. It isn't quite this simple in practice because performance depends on other factors as well as dispersion, but it's a useful guideline. For polarization-mode dispersion the usual guideline is more stringent, that the dispersed pulse should be no more than 1/10th as long as the interval between pulses, to allow a safety margin for brief periods of more pulse spreading. Note that these figures consider only dispersion, not the input pulse length, jitter, or receiver rise time. Different guidelines relate total system rise time to maximum bit rate, which depend on data transmission format.

Dispersion also affects analog transmission in roughly the same way that it limits bit rates in digital systems. Instead of lengthening digital pulses, dispersion smears out the whole analog waveform, effectively attenuating the highest frequencies in the signal. This limits the analog bandwidth, the frequency at which the detectable signal has dropped 3 dB (50%) compared to lower frequencies.

Transmission capacities of graded-index and step-index multimode fiber often are specified in terms of bandwidth, typically megahertz-kilometers, rather than as dispersion. You can roughly convert that to total system response time Δt_{total} using the formula

$$\text{Bandwidth (MHz)} = \frac{350}{\Delta t_{\text{total}}}$$

Nonlinear Effects

Normally light waves or photons transmitted through a fiber have little interaction with each other, and are not changed by their passage through the fiber (except for absorption and scattering). However, there are exceptions arising from the interactions between light waves and the material transmitting them, which can affect optical signals. These processes generally are called *nonlinear effects* because their strength typically depends on the square (or some higher power) of intensity rather than simply on the amount of light present. This means that nonlinear effects are weak at low powers, but can become much stronger when light reaches high intensities. This can occur either when the power is increased, or when it is concentrated in a small area—such as the core of an optical fiber.

Nonlinear effects are interactions between light waves, which can cause noise and crosstalk.

Nonlinear optical devices have become common in some optical applications, such as to convert the output of lasers to shorter wavelengths by doubling the frequency (which halves the wavelength). Most nonlinear devices use exotic materials not present in fiber-optic systems in which nonlinear effects are much stronger than in glass. The nonlinearities in optical fibers are small, but they accumulate as light passes through many kilometers of fiber.

Nonlinear effects are weak in optical fibers, but accumulate over long distances.

Nonlinear effects are comparatively small in optical fibers transmitting a single optical channel. They become much larger when *dense wavelength-division multiplexing* (DWDM) packs many channels into a single fiber. DWDM puts many closely spaced wavelengths into the same fiber where they can interact with one another. It also multiplies the total power in the fiber. A single-channel system may carry powers of 3 milliwatts near the transmitter. DWDM multiplies the total power by the number of channels, so a 40-channel system carries 120 mW. That's a total of 2 mW per square micrometer—or 200,000 watts per square centimeter!

Several nonlinear effects are potentially important in optical fibers, although some have proved more troublesome than others. Some occur in systems carrying only a single optical channel, but others can occur only in multichannel systems. We'll look at each of them in turn, focusing on the more important ones.

Brillouin Scattering

Brillouin scattering scatters light back toward the transmitter, limiting transmitted power.

Stimulated Brillouin scattering occurs when signal power reaches a level sufficient to generate tiny acoustic vibrations in the glass. This can occur at powers as low as a few milliwatts in single-mode fiber. Acoustic waves change the density of a material, and thus alter its refractive index. The resulting refractive-index fluctuations can scatter light, called *Brillouin scattering.* Since the light wave being scattered itself generates the acoustic waves, the process is called *stimulated Brillouin scattering.* It can occur when only a single channel is transmitted.

In fibers, stimulated Brillouin scattering takes the form of a light wave shifted slightly in frequency from the original light wave. (The change is 11 gigahertz, or about 0.09 nanometer for a 1550-nm signal.) The scattered wave goes back toward the transmitter. The effect is strongest when the light pulse is long (allowing a long interaction between light and the acoustic wave), and the laser linewidth is very small, around 100 megahertz. Under such conditions, it can occur at power levels as little as 3 mW in single-mode fibers. However, the power level needed to trigger stimulated Brillouin scattering increases as pulse length decreases, so the effect becomes less severe at higher data rates.

Brillouin scattering directs part of the signal back toward the transmitter, effectively increasing attenuation. The small frequency shift effectively confines the effect to the optical channel generating the effect at present channel spacings, so it does not create crosstalk with other channels. However, it does limit the maximum power a single length of fiber can transmit in one direction. As input power increases, the fraction of power scattered in the opposite direction rises sharply, and the fiber essentially becomes saturated.

Optical signals going in the wrong direction can cause serious problems, so optical isolators must be added to block Brillouin scattering. In general, isolators are placed at transmitters and optical amplifiers, limiting the effects of stimulated Brillouin scattering to a single fiber span between isolators. Special modulation schemes and careful design also can reduce the effects of Brillouin scattering.

Self-Phase Modulation

An optical channel modulates its own phase by self-phase modulation, which can broaden the range of wavelengths.

The refractive index of glass varies slightly with the intensity of light passing through it, so changes in signal intensity cause the speed of light passing through the glass to change. This process causes intensity modulation of an optical channel to modulate the phase of the optical channel that creates it, so the effect is called *self-phase modulation.* As the optical power rises and falls, these phase shifts also effectively shift the frequencies of some of the light; the shifts are in opposite directions at the rising and falling parts of the pulse. The overall result is to spread the bandwidth of the optical channel by an amount that depends on the rate of change in optical intensity as well as on the nonlinear coefficient of the fiber material. Like stimulated Brillouin scattering, it can occur in a single-channel system.

The spectral broadening caused by self-phase modulation produces dispersion-like effects, which can limit data rates in some long-haul communication systems, depending on the fiber type and its chromatic dispersion. For ultrashort pulses (less than one picosecond) with very high peak powers, self-phase modulation can be very strong, generating a broad continuum of wavelengths. Self-phase modulation also stabilizes pulses called solitons, so they propagate along the fiber with a constant shape, although attenuation reduces their amplitude. This makes soliton transmission an effective way to overcome self-phase modulation.

Cross-Phase Modulation

Systems carrying multiple-wavelength channels are vulnerable to *cross-phase modulation* as well as self-phase modulation. In this case, variations in the intensity of one optical channel cause changes in the refractive index affecting other optical channels. These changes modulate the phase of light on other optical channels, in addition to self-phase modulation of the same channel.

In cross-phase modulation, one channel modulates the phase of other channels.

The strength of cross-phase modulation increases with the number of channels, and becomes stronger as the channel spacing becomes smaller. There are ways to mitigate this effect, but it can limit transmission speed.

Four-Wave Mixing

Normally multiple optical channels passing through the same fiber interact with each other only very weakly, making wavelength-division multiplexing possible. However, these weak interactions in glass can become significant over long fiber-transmission distances. The most important is four-wave mixing (sometimes called four-photon mixing) in which three wavelengths interact to generate a fourth.

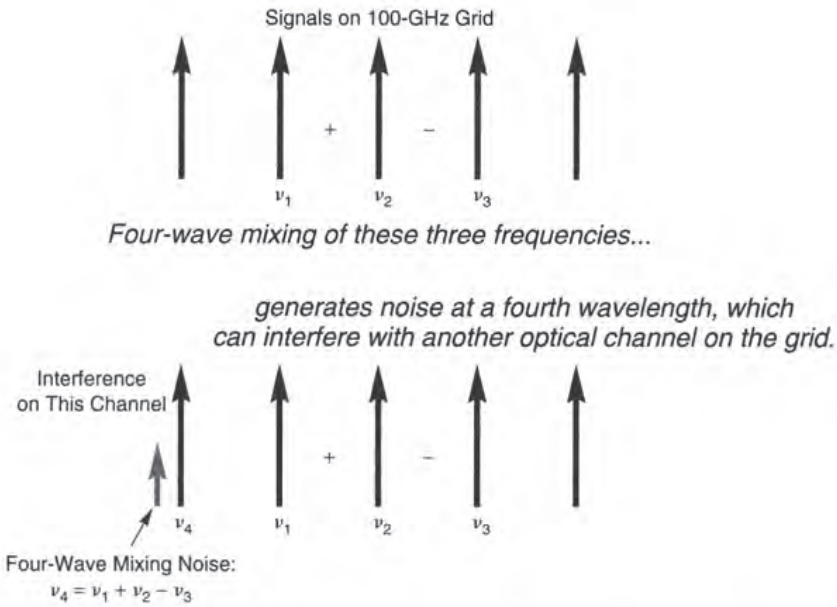
Four-wave mixing generates crosstalk among optical channels, noise that can limit WDM systems.

Four-wave mixing is one of a broad class of *harmonic mixing* or *harmonic generation* processes. The idea is that two or more waves combine to generate waves at a different frequency that is the sum (or difference) of the signals that are mixed. Second-harmonic generation or frequency doubling is common in optics; it combines two waves at the same frequency to generate a wave at twice the frequency (or, equivalently, half the wavelength). This can happen in optical fibers, but the second harmonic of the 1550 nm band is at 775 nm, far from the communications band, so it doesn't interfere with any signal wavelength.

Four-wave mixing is the strongest nonlinear effect that mixes the frequencies of optical channels in the 1550-nm band to generate noise in that band. As shown in Figure 5.13, three waves combine to generate a fourth frequency. If each frequency is designated by ν, the new frequency, ν_4, is

$$\nu_4 = \nu_1 + \nu_2 - \nu_3$$

FIGURE 5.13
Four-wave mixing produces noise that interferes with other optical channels in a DWDM grid.



In DWDM systems, the optical channels are typically close and spaced on a frequency grid typically separated by 100 or 200 GHz. This means that if ν_1 is the starting point, ν_2 is at a frequency 100 GHz higher, and ν_3 is another 100 GHz higher,

$$\nu_4 = \nu_1 + \nu_1 + 100 \text{ GHz} - \nu_1 - 200 \text{ GHz} = \nu_1 - 100 \text{ GHz}$$

which falls smack on top of another optical channel on the grid. The beating together of two frequencies, ν_1 and ν_2, also can cause four-wave mixing:

$$\nu_4 = \nu_1 + \nu_1 - (\nu_1 + 100 \text{ GHz}) = \nu_1 - 100 \text{ GHz}$$

Four-wave mixing accumulates if signals remain in phase over long distances, which occurs when dispersion is near zero.

Four-wave mixing is a weak effect, but it can accumulate if the signals on the optical channels remain in phase with each other over long distances. This happens when chromatic dispersion is very close to zero. Pulses transmitted over different optical channels, at different wavelengths, stay in the same relative positions along the length of the fiber because the signals experience near-zero dispersion. This amplifies the effect of four-wave mixing, and builds up the noise signal, which interferes with a fourth channel on the grid. (This problem led to abandonment of zero dispersion-shifted fibers.) To overcome this problem, the zero-dispersion point has to be moved out of the DWDM band. With even modest dispersion, the signals at different wavelengths quickly drift out of phase with each other, reducing four-wave mixing.

Raman Scattering

Stimulated Raman scattering transfers power between signals at different wavelengths.

Stimulated Raman scattering occurs when light waves interact with molecular vibrations in a solid lattice. In simple Raman scattering, the molecule absorbs the light, then quickly re-emits a photon with energy equal to the original photon, plus or minus the energy of a molecular vibration mode. This has the effect of both scattering light and shifting its wavelength.

When a fiber transmits two suitably spaced wavelengths, stimulated Raman scattering can transfer energy from one to the other. In this case, one wavelength excites the molecular vibration, then light of the second wavelength stimulates the molecule to emit energy—

at the second wavelength. The Raman shift between the two wavelengths is relatively large, about 13 terahertz (100 nm in the 1550-nanometer window for silica fibers), but it can produce some crosstalk between optical channels. It also can deplete signal strength by transferring light energy to other wavelengths outside the operating band. (This process also can be used to amplify signals, as you will learn in Chapter 12.)

Careful choice of wavelengths can reduce the interference between Raman scattering and other channels. Nonetheless, Raman scattering does impose limits on DWDM systems with many optical amplifiers. Its effects are more serious on the shorter wavelengths in a multiwavelength system.

Mechanical Properties

So far, I have concentrated on the optical properties of fibers. You also need to understand their most important mechanical properties. Although most fibers are assembled into cables with highly automated equipment, installation of cables, connectors, and other components often requires handling individual fibers.

Glass fibers are coated with plastic as they are drawn into fiber form. The plastic coating eases handling and protects the fiber's outer surface from physical damage. The standard cladding diameter of communications fibers is 125 μm or 0.125 mm (0.005 in.), thin enough to be difficult to handle or process mechanically. Plastic coating doubles this diameter to 250 μm (0.01 in.), making them easier to pick up and process. Typically this coating consists of two layers, an inner one with outer diameter 245 μm that provides mechanical protection, and a thin outer coating that color-codes the fiber for cabling.

A plastic coating with outer diameter 250 μm covers glass fibers.

Thin glass fibers are reasonably flexible. Individual telecommunications fibers can be bent into a loop with 5-cm (2-in.) diameter without damage or significant effect on the signal, and left that way indefinitely. Equipment used in installation is designed to accommodate that degree of bending. You sometimes can get away with bending fibers more but don't count on it—and you'll never get away with the sort of sharp bend that can be used for copper wires. Thicker glass fibers cannot be bent as tightly. Plastic optical fibers (described in Chapter 6) are more flexible than thick glass fibers.

In theory, a mechanically perfect glass fiber can withstand a tension of 2 million pounds per square inch (14 gigapascals or 14 giganewtons per square meter). In practice, inevitable minor surface flaws reduce this to about 500,000 lb/in^2 (3.5 GPa) or less.

The fact that fibers break at randomly distributed surface flaws has some important consequences. The longer the fiber, the more likely it is to contain a flaw that will cause it to break when a certain stress is applied. To weed out the most harmful of these weak points, fiber manufacturers use a simple *proof test* that applies a load to a length of the fiber as they wind it onto the reel. The load applies a specified tension along the length of the fiber. If any part of the fiber cannot withstand that tension, it breaks at the weak point.

Fibers are subjected to a proof test to assure they have a minimum strength.

Manufacturers typically proof test fibers under a load of 100,000 lb/in^2 (0.7 GPa), so weaker fibers don't make it out of the plant because they break during the stress test. This doesn't mean you can hold an elephant in the air on a single fiber—fibers are small, and pounds per square inch measures the load applied to a solid square inch of glass, not a thin fiber. (Figure it out yourself and you'll be surprised.) But the numbers do show that glass fibers can withstand reasonable handling, despite our instinctive feeling that glass is fragile.

A glass fiber will snap if pulled sharply, apparently without stretching at all. Fiber is difficult to break with your hands, but can snap if you trip on them. Fibers can break inside a cable without obvious damage to the cable. But a closer look would reveal that the glass does stretch elastically until it reaches its breaking strength, and it stretches several percent beyond its original length before snapping. Copper wires deform plastically, stretching by more than 20% before breaking.

Fiber failure normally starts at a flaw or microcrack in the glass surface. Application of stress spreads the crack, leading quickly to failure if the applied force is beyond the fiber's strength. Flaws are distributed randomly along the surface, and statistics can be used to estimate the chance of failure.

Fibers can suffer from two types of aging. *Dynamic fatigue* arises from the short-lived stresses applied to the fiber either by installation or the temporary environmental effects. Underground cables are affected by the stress of pulling them into a duct, while aerial cables are affected by gusts of wind and snow loading during winter.

Static fatigue is the growth of flaws that occurs while the fiber is maintained under constant conditions. The flaws may grow because of moisture or other environmental factors, or because the cable structure is pulling on the fiber. Moisture is the most common problem because it slowly reacts with silica. Static fatigue is very low unless the stress is more than 20% of the proof-test stress.

The plastic coating on the fiber is important as a protection against moisture and physical damage to the surface. Experience has shown these coatings to be quite effective.

What Have You Learned?

1. Signal loss is the sum of loss coupling light into a fiber, and of scattering and absorption in the fiber.
2. Material absorption depends on wavelength and is cumulative with distance. Impurities cause absorption peaks.
3. Losses from atomic scattering are higher at shorter wavelengths; scattering losses also are cumulative with distance.
4. Fiber attenuation is the sum of scattering and absorption, measured together in decibels per kilometer.
5. The logarithmic decibel scale is preferred for calculating attenuation and transmission losses. Total attenuation of a fiber is the characteristic loss in decibels per kilometer times the length in kilometers.
6. The larger the fiber core, the more easily it can collect light from a light source.
7. Some light is guided short distances along the cladding in cladding modes. Leaky modes are only partly confined in the fiber core.
8. Dispersion produces pulse spreading that can limit transmission speeds in both analog and digital systems. The main types of dispersion are modal, chromatic, and polarization. Total pulse spreading is the square root of the sum of the squares of the pulse spreading from all three types of dispersion.

9. Material and waveguide dispersion add together to give chromatic dispersion; both can have a positive or negative sign. The pulse spreading caused by chromatic dispersion is proportional to the spectral bandwidth of the transmitter as well as the length of fiber.
10. Material dispersion is a characteristic of the fiber material, which varies with wavelength. It measures the change in group delay with wavelength, which in turn measures the change in refractive index with wavelength.
11. Waveguide dispersion arises from changes in waveguide properties and the distribution of light in the fiber with wavelength.
12. Waveguide and material dispersion can cancel each other to give zero chromatic dispersion if their signs are opposite. Adjusting waveguide dispersion can shift the zero-dispersion wavelength.
13. Fibers with opposite signs of chromatic dispersion can be combined in sequence to compensate for chromatic dispersion in a system.
14. Long wavelength-division multiplexed (WDM) systems require dispersion management over their entire range of wavelengths. Dispersion slope, the change in dispersion with wavelength, is an important consideration.
15. Polarization-mode dispersion arises from slight fluctuations in the refractive index experienced by light of different polarizations. The pulse spreading varies randomly with time.
16. Nonlinear effects are interactions between light waves, which generate noise and crosstalk. They become important at high power densities that can occur in single-mode fibers.
17. Four-wave mixing among optical channels is the most important potential noise source in WDM systems. It accumulates over long distances when fibers have very low dispersion.
18. Bare glass fibers are coated with plastic to protect their surfaces and ease handling. Glass fibers are quite strong, if they lack surface flaws.

What's Next?

Now that we've talked about fiber structures and characteristics, Chapter 6 will cover fiber materials and manufacture.

Further Reading

Paul Hernday, "Dispersion Measurements," in Dennis Dirickson, ed., *Fiber Optic Test and Measurement* (Prentice Hall, 1998)

Luc B. Jeunhomme, *Single-Mode Fiber Optics: Principles and Applications* (Dekker, 1990)

Donald B. Keck, ed., *Selected Papers on Optical Fiber Technology* (SPIE Milestone Series, Vol. MS38, 1992)

Gerd Keiser, *Optical Fiber Communications*, 3rd ed. (McGraw-Hill, 2000)

Advanced Treatments:

John A. Buck, *Fundamentals of Optical Fibers* (Wiley InterScience, 1995)

Ajoy Ghatak and K. Thyagarajan, *Introduction to Fiber Optics* (Cambridge University Press, 1998)

Questions to Think About

1. The amount of Rayleigh scattering by atoms is proportional to λ^{-4}. How is this related to why the sky looks blue?
2. Can you write a formula that converts loss in decibels into the fraction of power remaining?
3. You have a fiber that transmits a single mode at 850 nm, and a light source with bandwidth of 1 nm. Its chromatic dispersion is about −80 ps/nm-km. What is the maximum data rate that fiber could transmit 100 km, neglecting attenuation, based only on the guideline on page 115 (bit rate $= 1/(4 \times \Delta t_{disp})$)?
4. Estimate the attenuation at 850 nm from Figure 5.2. Assume you need an optical amplifier to boost signal strength after every 30 dB of fiber loss. How far can the fiber transmit signals before it requires an optical amplifier? Which of the limitations in Questions 3 and 4 do you think was the main reason 850-nm systems were never viable for long-distance transmission?
5. Why is it more difficult to compensate for dispersion in a DWDM system than in one transmitting only a single optical channel?
6. Write a formula for how much dispersion-compensating fiber you need to add to an existing system with $L_{existing}$ km of fiber to reduce dispersion to a desired value D_{net}.
7. Four-wave mixing normally occurs only at high powers in glass, yet it can cause significant crosstalk in single-mode fibers. If you have a fiber with effective area of 50 μm^2, what is the power per square centimeter in the fiber if it carries 100 optical channels at 3 mW each?

Chapter Quiz

1. A 1-m length of fiber transmits 99.9% of the light entering it. How much light will remain after 10 km of fiber?
   a. 90%
   b. 10%
   c. 1%

d. 0.1%

e. 0.0045%

2. A fiber has attenuation of 0.00435 dB/m. What is the total attenuation of a 10-km length?

a. 0.0435 dB

b. 1.01 dB

c. 4.35 dB

d. 43.5 dB

e. We cannot tell without knowing the wavelength.

3. If 10 mW of light enters the 10-km fiber in Problem 2, how much light remains at the output end?

a. 0.00045 mW

b. −33.5 dBm

c. −3.5 dBμ

d. all of the above

e. none of the above

4. You lose 1.0 dB coupling a 1-mW light source into an optical fiber. You need a signal of 0.1 mW at the other end. How far can you send a signal through fiber with attenuation of 0.5 dB/km?

a. 1.8 km

b. 10 km

c. 18 km

d. 20 km

e. 40 km

5. You transmit an instantaneous pulse through a 20-km multimode fiber with total dispersion of 10 ns/km at the signal wavelength. What will the pulse length be at the end?

a. 200 ns

b. 100 ns

c. 50 ns

d. 20 ns

e. 10 ns

6. You transmit a 100-ns pulse through the same fiber used in Problem 5. What will the pulse length be at the end?

a. 300 ns

b. 224 ns

c. 200 ns

d. 150 ns

e. 100 ns

7. You transmit an instantaneous pulse through a 20-km single-mode fiber with chromatic dispersion of 10 ps/nm-km at the signal wavelength. The spectral width of the input pulse is 2 nm. What is the pulse length at the end of the fiber?

a. 400 ps

b. 250 ps

c. 200 ps

d. 100 ps

e. 32 ps

8. You transmit an instantaneous pulse through a 20-km single-mode fiber with chromatic dispersion of 10 ps/nm-km at the signal wavelength. This time you've spent an extra $2000 for a super-duper laser with spectral width of only 0.002 nm. What is the pulse length at the end of the fiber?

a. 30 ps

b. 20 ps

c. 4 ps

d. 1 ps

e. 0.4 ps

9. A single-mode fiber has material dispersion of 20 ps/nm-km and waveguide dispersion of −15 ps/nm-km at the signal wavelength. What is the total chromatic dispersion?

a. 35 ps/nm-km

b. 25 ps/nm-km

c. 5 ps/nm-km

d. 0 ps/nm-km

e. −35 ps/nm-km

10. You send 200-ps pulses through a 100-km length of the fiber in Problem 9, using a laser with spectral width of 0.002 nm. What is the width of the output pulse?

a. 1 ps

b. 200 ps

c. 250 ps

d. 400 ps

e. 500 ps

11. Your boss says you can't have the extra $2000 for the super-duper narrow-bandwidth laser, so you have to use the cheap model with 2-nm spectral linewidth in the system in Problem 10. What's the width of the output pulse?

a. 200 ps

b. 250 ps

c. 500 ps

d. 1000 ps
e. 1020 ps

12. An optical fiber 125 μm in diameter can withstand a force of 600,000 lb/in^2. What's the heaviest load it could support?

a. a 4-ton elephant
b. a 1/2-ton cow
c. a 95-lb weakling
d. a 10-lb rock
e. a 5-oz. hamster

13. Your job is to send a signal at the highest data rate possible through 2500 km of fiber with polarization-mode dispersion of 1 $ps/km^{-1/2}$. Neglecting all other types of dispersion, what is the best you can do, remembering that polarization-mode dispersion should accumulate to no more than 1/10th the interval between pulses?

a. 10 Gbit/s
b. 5 Gbit/s
c. 2 Gbit/s
d. 1 Gbit/s
e. 100 Mbit/s

14. Suppose you only had to transmit signals 400 km through the same fiber. What is the maximum data rate, again neglecting all other dispersion and remembering that polarization-mode dispersion should accumulate to no more than 1/10th the interval between pulses?

a. 10 Gbit/s
b. 5 Gbit/s
c. 2 Gbit/s
d. 1 Gbit/s
e. 100 Mbit/s

CHAPTER

6

Fiber Materials, Structure, and Manufacture

About This Chapter

Materials are crucial to the performance of optical fibers. Without ultrapure glass, fiber-optic communications would be impractical. This chapter describes requirements for fiber-optic materials, the types of materials used, and how they are made into fibers. It also covers a few unusual types of fibers, including photonic fibers and planar wave-guides. Specialty fibers used for functions other than light transmission are covered in Chapter 7.

Requirements for Making Optical Fibers

The fundamental requirements for making optical fibers sound deceptively simple. You need a material that is transparent and can be drawn into thin fibers with a distinct core-cladding structure that is uniform along the length of the fibers and will survive in the desired working environment. Meeting those requirements turns out to be a challenge, particularly achieving the extreme transparency needed for communications.

Look around and you're sure to see many transparent objects but comparatively few different transparent materials. Ice is transparent, but it melts at room temperature. Salt and sugar crystals are transparent, but both dissolve too easily in water to be used at normal humidity levels. Most other transparent solids are glass or plastic.

Making thin, uniform fibers is another problem. The usual approach is to heat a material until it softens into a very thick or viscous liquid and then stretch the thick

Optical fibers are made by stretching transparent materials into thin filaments.

fluid into thin filaments. You can test this for yourself with a glass rod and a flame. Hold both ends, heat the middle until it softens, and then pull the ends apart. The thick liquid holds together as you stretch it finer and finer; it cools rapidly to make a thin filament, although simple stretching doesn't make it very uniform. You can do something similar with thick sugar syrup, spinning and pulling it to make cotton candy. Some plastics also work well, but thin liquids don't make fibers, because they tend to fall apart, like water.

Durability is vital. Common sodium chloride is very transparent, but it also soaks up moisture from the atmosphere, so optics made of salt have a distressing tendency to turn into salty puddles unless they are sealed in a dry environment. Some materials are too fragile to survive as long, thin fibers. Plastics and many other materials can't withstand extreme temperatures.

Over the years, silica-based glass and certain plastics have proven the best materials for optical fibers, although you need special glasses and plastics to make low-loss communication fibers. They are most transparent at a limited range of wavelengths in the visible spectrum (0.4 to 0.7 μm) and the near-infrared (0.7 to about 2 μm). The clearest *window* for glass fibers is about 1.2 to 1.7 μm, but they are usable at other wavelengths. Plastic fibers have a window at 0.65 μm and also are reasonably transparent to other visible light.

If you need to transmit wavelengths longer than about 2 μm, you need one of the few exotic compounds that can be made into reasonably transparent fibers, which are described at the end of this chapter.

Glass Fibers

What Is Glass?

Ordinary glass is a noncrystalline compound of silica and other oxides. Many different variations have been developed.

Glass is by far the most common material used in optical fibers, but glass takes many forms, so we should define our terms carefully.

From a scientific standpoint, a glass is a noncrystalline solid—that is, a solid in which the atoms are arranged randomly, not lined up in the neat arrangements of a crystal. You can think of a glass as a sort of liquid with atoms frozen in place by very fast cooling, but it does not flow like a liquid, even over hundreds of years. Typically glasses are compounds such as oxides, but many compounds do not form glasses because they always crystallize. Even compounds such as *silica* (SiO_2), which readily form good glasses, will crystallize when cooled slowly. Quartz is natural crystalline silica.

The stuff we think of as glass in everyday life is made by melting sand with lime, soda, and some other materials and then cooling the melt quickly. Chemically, the main constituents of ordinary window glass are silica, calcium oxide (CaO), and sodium oxide (Na_2O). Silica accounts for the bulk of the compound. Calcium and sodium compounds improve its properties for glassmaking, notably by reducing its melting temperature. You can make many other types of glass by mixing in other materials. Lead compounds make fine crystal; a dash of cobalt turns the glass a striking deep blue. The glass industry has developed a vast array of glass recipes for different purposes, many going back generations.

Ordinary window glass looks transparent because you don't look through very much glass. Look into the edge of a pane of window glass and you find a strong green color; the wider the pane, the darker the green. The color comes from impurities in the glass. You

THINGS TO THINK ABOUT

Does Glass Flow?

Spend a while reading about glass, and you're bound to come across the claim that window glass flows like a liquid. It makes sense on a certain level. Like the atoms in a liquid, the atoms in glass are arranged randomly rather than in the ordered ranks of a crystal. The atoms are trapped in that position by rapid cooling of a liquid, which becomes increasingly thicker. Indeed, from a theoretical standpoint you can consider glass as a very thick liquid, like the proverbial "molasses in January". It might flow, but only very slowly.

Many sources, including some materials textbooks, claim that glass really does flow. They cite reports that stained glass panels in twelfth-century cathedrals are thicker at the bottom, although they don't give references.

It's not unreasonable that medieval stained glass might be thicker at one end than the other, but that doesn't mean it flowed. Making a perfectly flat pane of glass is difficult, and the technology wasn't perfected until the twentieth century. You can see for yourself if you look closely at original old windows in colonial homes. Craftsmen installing the glass usually put the thicker end at the bottom to balance the pane better, so the windows were likely to start out with the glass thickest at the bottom.

Glass will flow very slowly if it's heated, but cathedral windows wouldn't get hot enough to flow even if they sat in the sun. Edgar Zanotto of the Federal University of Sao Carlos in Brazil calculated the flow rates for glass by extrapolating the viscosity curves for hot glass to lower temperatures. He found that typical medieval window glass would have to have remained at a temperature of 414°C for significant flow over 800 years. At room temperature, the flow would have taken a time "well beyond the age of the universe." So rest assured that your optical fibers, and even the glass window in your oven, are not going to wind up in a puddle on the floor during your lifetime.

Source: E. Zanotto, *American Journal of Physics 66,* 392 (May 1998).

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don't notice their effects when light passes through a few millimeters of window glass, but they add up if you look through the edge of a pane.

Since the 1800s, the optics industry has developed a large family of optical glasses, made of materials that are purer, clearer, and freer of tiny flaws than window glass. Compounds are blended to give glasses with different refractive indexes, important for designers of optical devices. Standard optical glasses have indexes between about 1.44 and 1.8 at visible wavelengths, with pure silica having nearly the lowest refractive index.

Refractive indexes of most optical glasses are between 1.44 and 1.8.

Early fiber-optic developers turned to optical glasses after finding that ordinary glasses absorbed too much light for use in optical fibers. They initially tried coating glass fibers with low-index plastic to serve as the cladding, but when results were poor, they turned to glass cladding.

Rod-in-Tube Glass Fibers

Simple glass-clad fibers are made by collapsing a low-index tube onto a higher-index rod.

The simplest way to make a glass-clad fiber is by inserting a rod of high-index glass into a tube with lower refractive index. The two are heated so the tube melts onto the rod, forming a thicker solid rod. Then this rod (called a *preform*) is heated at one end and a thin fiber is drawn from the soft tip. The process is used for image-transmission and illuminating fibers but not for communication fibers.

For the fiber to transmit light well, the core-cladding interface must be very clean and smooth. This requires that the rod inserted into the tube must have its surface fire-polished, *not* mechanically polished. Although mechanical polishing gives a surface that looks very smooth to the eye, tiny cracks and debris remain, and if that surface becomes the core-cladding boundary, they can scatter light, degrading transmission.

Another way to draw glass fibers is to pull them from the bottom of a pair of nested crucibles with small holes at their bottoms. Raw glass is fed into the tops of the crucibles, with core glass going into the inner one and cladding going into the outer one. The fiber is pulled continuously from the bottom, with the cladding glass covering the core glass from the inner crucible. The double-crucible process is very rare today, but it has been used in the past and may be used with some special materials.

Limitations of Standard Glasses

Impurities limit transmission of standard glasses.

Fibers made from conventional optical glasses typically have attenuation of about 1 dB/m, or 1000 dB/km. This is adequate for an image-transmitting bundle to look into a patient's stomach but not for communications from town to town.

The main cause of this high loss is absorption by impurities in the glass. Traces of metals such as iron and copper inevitably contaminate the raw materials used in glass manufacture, and those metals absorb visible light. To make extremely clear glass, you need to start with extremely pure silica, which has virtually no absorption at wavelengths from the visible to about 1.6 μm in the near infrared. The concentrations of critical impurities that absorb light at 0.6 to 1.6 μm—including iron, copper, cobalt, nickel, manganese, and chromium—must be reduced to a part per billion (1 atom in 10^9). That level is impractical with standard glass-processing techniques.

Fused-Silica Fibers

Fused silica is the basis for modern communication fibers.

The starting point for modern communication fibers is fused silica, an extremely pure form of SiO_2. It is made synthetically by burning silicon tetrachloride ($SiCl_4$) in an oxyhydrogen flame, yielding chloride vapors and SiO_2, which settles out as a white, fluffy soot. The process generates extremely pure material, because $SiCl_4$ is a liquid at room temperature and boils at 58°C (136°F). Chlorides of troublesome impurities, such as iron and copper, evaporate at much higher temperatures than $SiCl_4$, so they remain behind in the liquid when $SiCl_4$ evaporates and reacts with oxygen. The result is much better purification than you can get with wet chemistry, reducing impurities to the part-per-billion level required for extremely transparent glass fibers.

Dopants, Cores, and Claddings

Silica must be doped to change the refractive index for core and/or cladding.

You cannot make optical fibers from pure silica alone. Optical fibers require a high-index core and a low-index cladding, but all pure silica has a uniform refractive index, which declines from 1.46 at 0.550 μm to 1.444 at 1.81 μm. You need to add dopants to change the refractive index of the silica, but they must be chosen carefully to avoid materials that absorb light or have other harmful effects on the fiber quality and transparency.

Most glasses have higher refractive index than fused silica, and most potential dopants tend to increase silica's refractive index. This allows them to be used for the high-index core of the fiber, with a pure silica cladding having a lower refractive index. The most common core dopant is germanium, which is chemically similar to silicon. Germanium has very low absorption, and germania (GeO_2), like silica, forms a glass.

Cladding index may be matched to pure silica or depressed by the addition of fluorine.

Only a few materials reduce the refractive index of silica. The most widely used is fluorine, which can reduce the refractive index of the cladding, allowing use of pure silica cores. Boron also reduces refractive index, but not as much as fluorine. In practice, single-mode and multimode step-index silica fibers fall into the three broad categories shown in Figure 6.1. The fiber core may be doped to raise its refractive index above that of pure silica, which is used for the entire cladding. Alternatively, a smaller level of dopant may raise the core index less, but the surrounding inner part of the cladding may be doped—generally with fluorine—to reduce its refractive index. This design is called a *depressed-clad* fiber; normally the fluorine-doped zone is surrounded by a pure silica outer cladding. (Doping at the proper

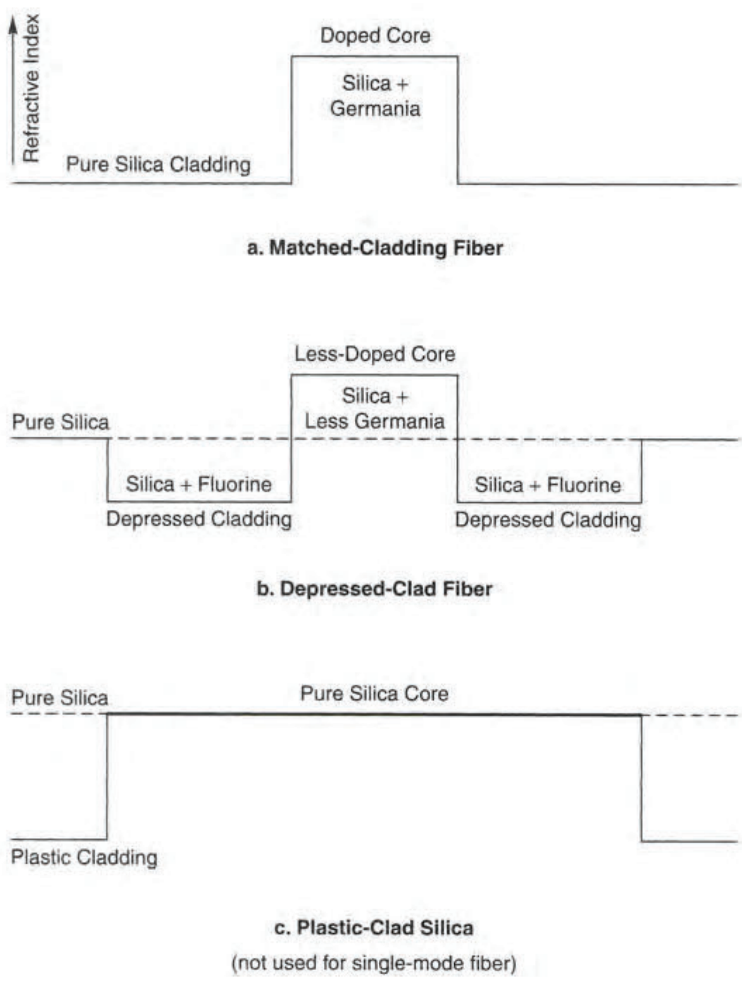

FIGURE 6.1
Refractive-index profiles of matched-clad and depressed-clad single-mode fibers and plastic-clad silica multimode fibers.