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

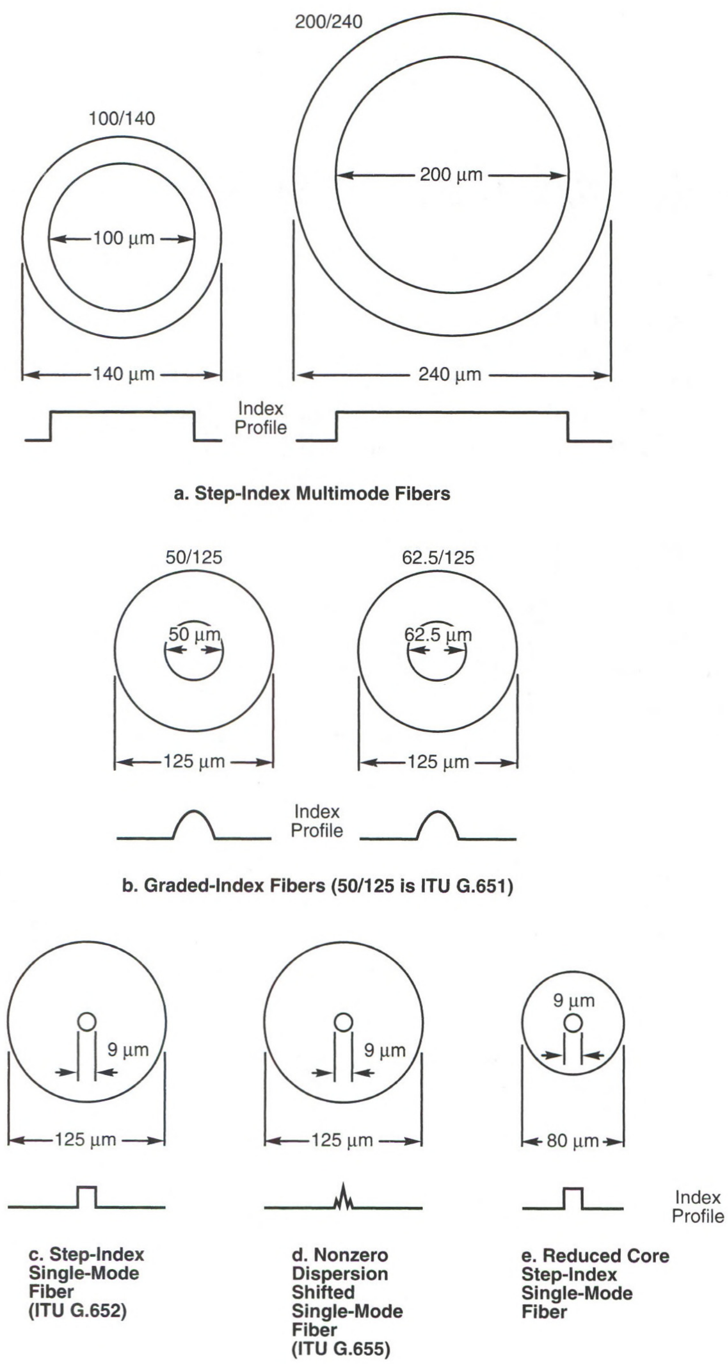


FIGURE 4.1
Common types of optical fiber (to scale). ITU designations are standards of the International Telecommunications Union.

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

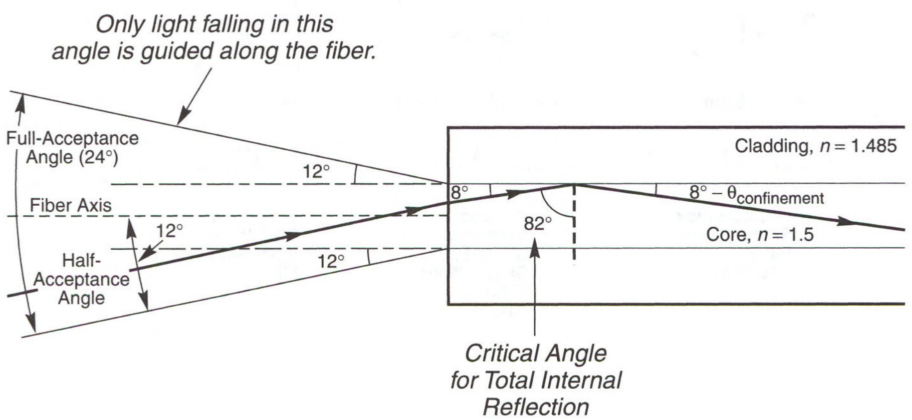


FIGURE 4.2
Light guiding in a large-core step-index fiber. The confinement angle measures the angle between guided light rays and the fiber axis; the acceptance angle is measured in air.

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

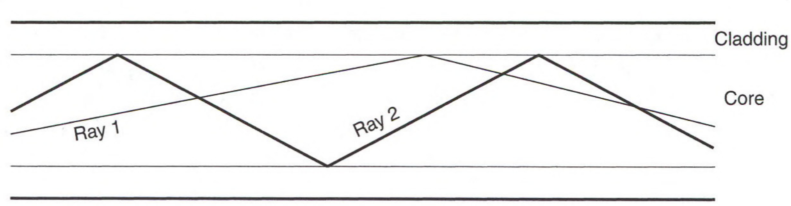


FIGURE 4.3
Light rays that enter multimode step-index fiber at different angles travel different distances through the fiber, causing pulse dispersion.

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

Small-core fibers carry a single mode.

A fiber is a dielectric optical waveguide.

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.

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.

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.

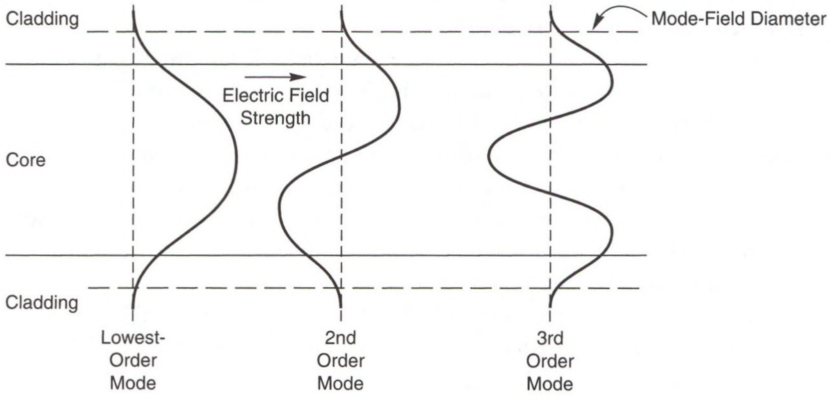


FIGURE 4.4 *Electric fields for the lowest-order mode in an optical fiber (left) and for the second-order and third-order modes (right). Higher-order modes are more complex.*

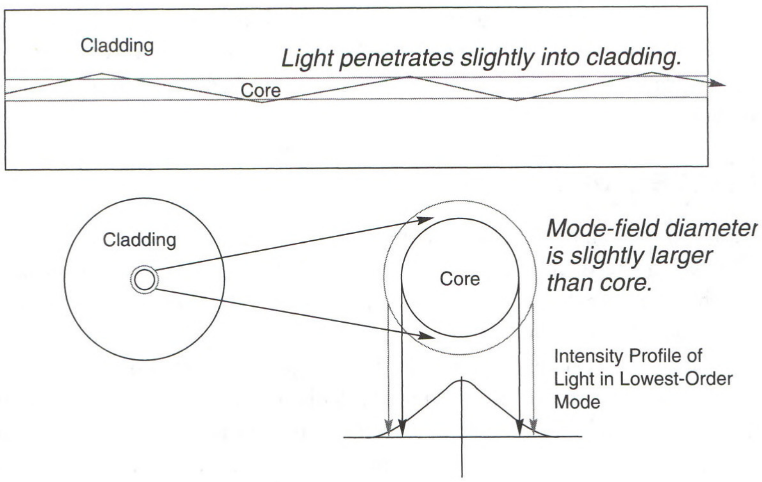


FIGURE 4.5
Light penetrates slightly into the cladding of a single-mode step-index fiber.

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

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.

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

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

$$\mathrm{DR} = \frac{\mathrm{DR}_0}{L}$$

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:

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

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

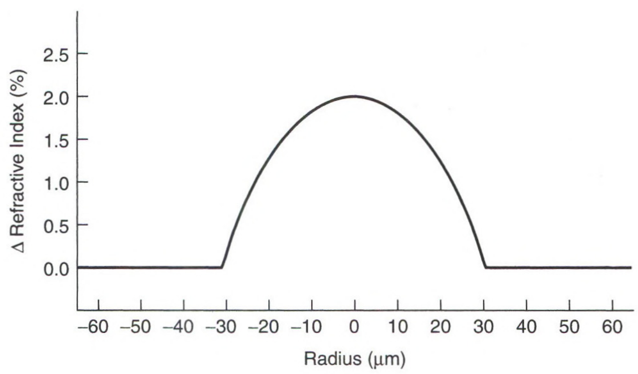
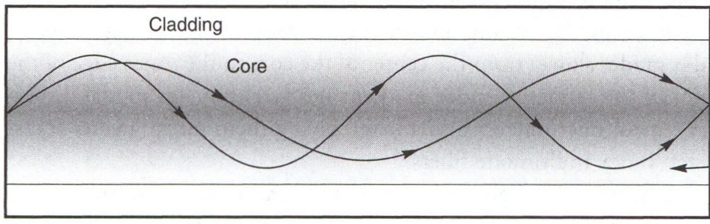


FIGURE 4.6
Refractive-index profile of a graded-index fiber with 62.5-μm core.

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, 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.

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.

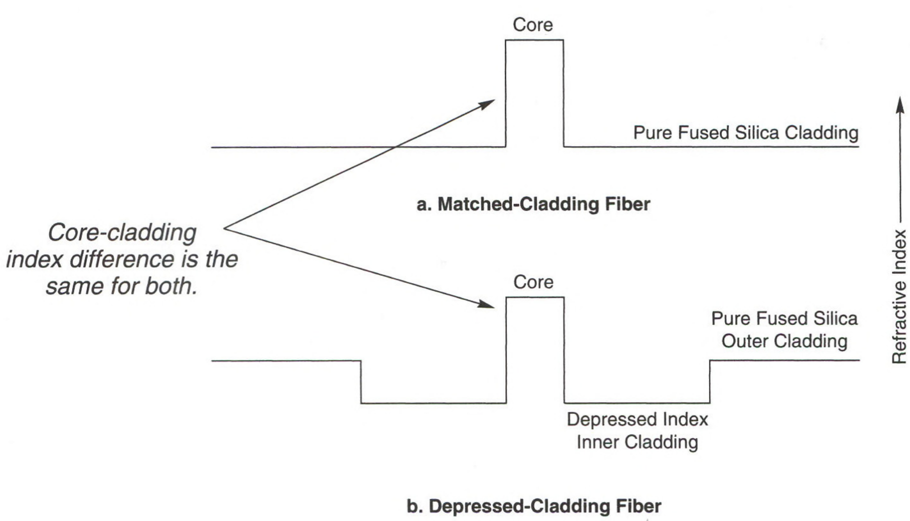


FIGURE 4.8
Two types of step-index single-mode fiber. The difference between core and cladding refractive index is the same, but in the depressed cladding fiber at the bottom, the inner cladding is doped with fluorine to reduce its refractive index.

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.

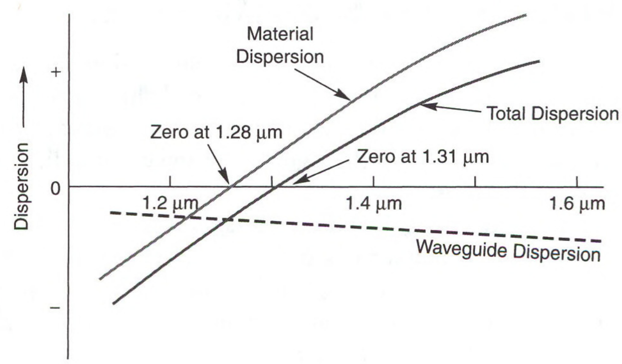
Step-index single-mode fibers have much better properties than early developers dreamed were possible. However, they are not ideal. As we will see in Chapter 6, the attenuation of glass fiber has been reduced close to the theoretical minimum, and little improvement is possible without shifting to a new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

Some older fibers had zero dispersion shifted to 1.55 μm.

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.

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.

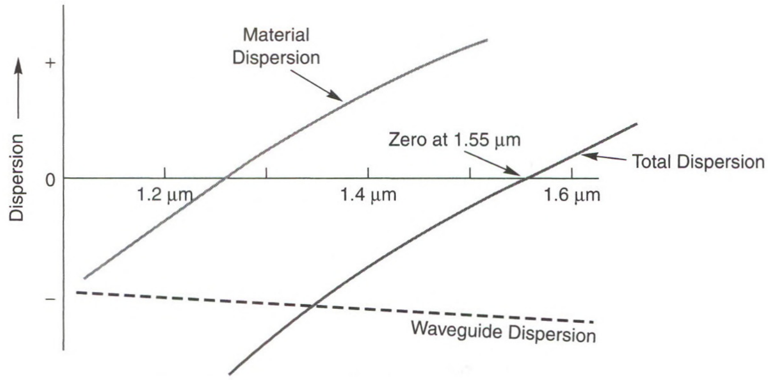
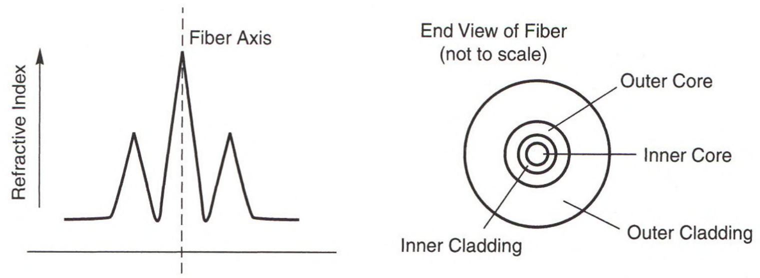
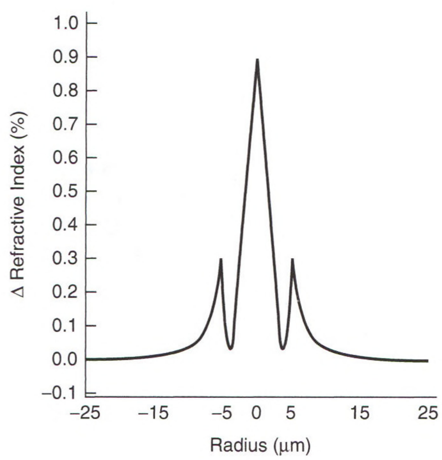


FIGURE 4.10
A fiber designed with more waveguide dispersion shifts the zero-dispersion wavelength to 1.55 μm.

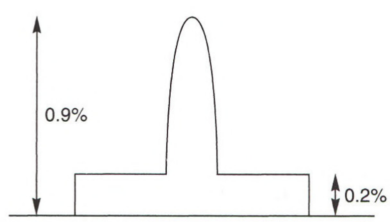
FIGURE 4.11
Refractive-index profiles of some dispersion-shifted fibers designed for specific applications



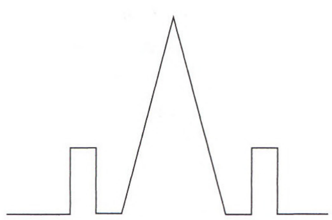
a. Zero Dispersion-Shifted Fiber. (ITU G.653)



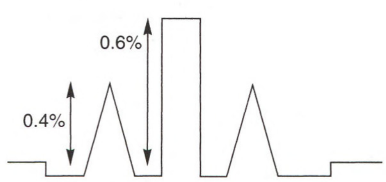
b. Nonzero Dispersion-Shifted Fiber. (ITU G.655)
(Courtesy Corning, Inc.)



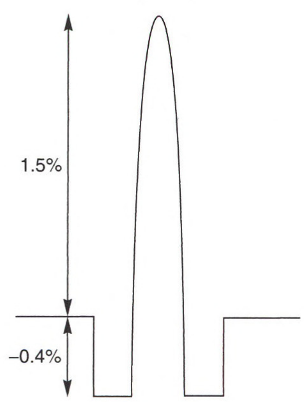
c. Another Design for Nonzero Dispersion-Shifted Fiber. (ITU G.655)



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.

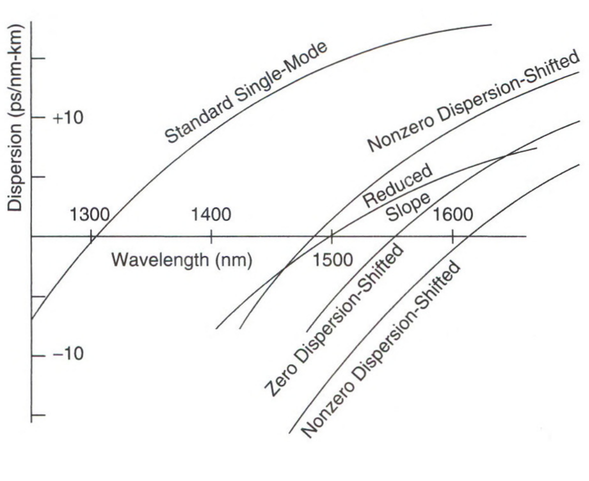


FIGURE 4.12
Dispersion profiles of several single-mode fiber types.

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.

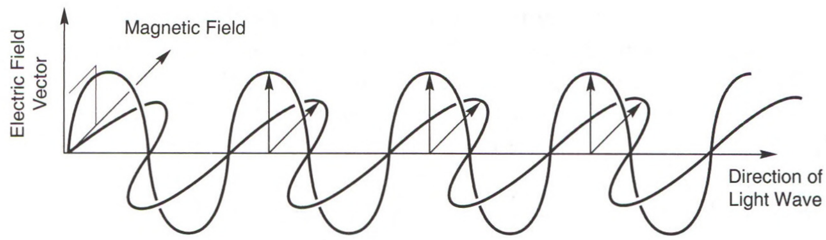


FIGURE 4.13 *Electric and magnetic fields in a light wave. Note the two are perpendicular.*

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)

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. 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.