CHAPTER

7

Specialty Fibers

About This Chapter

Chapters 4 through 6 covered standard optical fibers whose main function is to guide light over relatively long distances, whether for communications or imaging. Other optical fibers are optimized for a variety of applications, from use in optical components to serving as pigtails that connect optical devices to standard transmission fibers. This chapter introduces the concept of specialty fibers, then describes important types and how they are used.

The first types covered are made by changing the standard properties of the fiber, such as chromatic dispersion, polarization properties, cladding size, and bending sensitivity. A second group is made by adding materials to the fiber to change its properties, such as light-emitting elements for fiber amplifiers. Fiber Bragg gratings don't fit neatly into these categories because their properties are altered by exposure to ultraviolet light after the fiber is drawn. Some graded-index fibers are made to serve as lenses. Finally, the chapter describes emerging types of special-purpose fibers based on photonic crystal technology. The operation and applications of fiber amplifiers are covered in Chapter 12, and those of fiber Bragg gratings are covered in Chapter 15. Fibers made specifically for sensing are covered in Chapter 29.

What Are "Specialty" Fibers?

In the early days of fiber optics, only a few types of fibers were available, and they were used for everything. Today, some types are mass-produced for signal transmission. However, other fibers have been developed for special-purpose applications that don't require large volumes of fiber. These specialty fibers are produced in smaller quantities, so they are more like clothes made specifically for a sport like winter skiing rather than general-purpose off-the-rack clothing.

Specialty fibers have properties different from those of standard transmission fibers.

There is no standard definition of "specialty" fibers. Standard step-index single-mode fiber, as well as the other transmission fibers described in Chapter 4, are clearly not specialty fibers, although their range of applications is limited. The special fibers doped with erbium for use in optical amplifiers, on the other hand, clearly are specialty fibers. Some other types fall into a hazy zone, such as large-core step-index multimode fibers, which have a limited range of applications. For purposes of this book, we consider most step-index multimode fibers as general-purpose, so they are covered in Chapter 4.

This chapter covers fibers considered to be "specialty" because their properties fall outside the normal range of transmission fibers. These properties are created by tailoring the refractive index profile to meet specific needs, by changing the size of the fiber, by adding materials to the fiber core, or by developing new structures for fiber manufacture.

Dispersion-Compensating Fibers

As you learned in Chapter 5, the total chromatic dispersion in a single fiber is the sum of the waveguide dispersion and the material dispersion, which can have opposite signs and thus offset each other. The zero-dispersion wavelength can be shifted by designing fibers so their waveguide dispersion exactly offsets their material dispersion at one wavelength; but it's neither practical nor desirable for the fiber to have zero dispersion at a broad range of wavelengths. The ideal balance to avoid crosstalk from four-wave mixing is to have local dispersion in the fiber greater than zero, but total dispersion along a fiber-optic route close to zero. This can be accomplished by using two (or more) different types of fibers along the route, with the dispersion in one offsetting the dispersion in the other.

Dispersion-compensating fibers have high negative chromatic dispersion.

One approach is to pick two or more types of standard transmission fibers with different dispersion characteristics and combine them along the transmission route. An alternative is to use special *dispersion-compensating fibers* with high negative chromatic dispersion in the 1550-nm window. These fibers have small cores with a large refractive-index step between core and cladding, as shown in Figure 4.11(f). This design creates high negative material dispersion, so one kilometer of dispersion-compensating fiber can compensate chromatic dispersion in several kilometers (typically 5 km) of standard single-mode fiber. This design also involves trade-offs, because the small core increases nonlinear effects, and the losses are somewhat higher than in standard transmission fibers.

Dispersion-compensating fibers are classed as specialty fibers because they are designed specifically for one purpose: balancing the chromatic dispersion in a transmission line. In practice, they generally are installed in coils at the ends of a transmission line, not in cables along the transmission route. Although dispersion-compensating fibers are part of the transmission path, they are not actually part of the transmission cable, which is a subtle but significant difference. That means their function can be performed by other dispersion-compensating devices. As you will learn later, dispersion compensation is complex because it must be done across a range of wavelengths, not at a single wavelength, so the slope as well as the magnitude of the dispersion is important.

Polarization-Maintaining Fibers

Chapter 4 briefly mentioned that single-mode fibers could be made to maintain polarization by applying an internal stress to them that prevents light from shifting polarization as it does in a radially symmetric fiber. *Polarization-maintaining fibers* are another important type of special-purpose fiber. They are used where polarization is important, such as in couplers, certain modulators, and fiber-optic gyroscopes.

Fibers with internal stress maintain polarization of transmitted light.

The stress is applied by adding structures across the width of the fiber. Three designs are shown in Figure 7.1. In the PANDA fiber shown in Figure 7.1(a), two stress members are placed within the cladding in the same plane on opposite sides of the fiber core. In the bow-tie fiber shown in Figure 7.1(b), a pair of wedges on opposite sides of the core induce stress in the fiber. A third approach is to grind down both sides of a preform that has a circular boron-doped region surrounding the core. A fiber drawn from the preform is circular, with the boron-doped region stretched into an elliptical stress layer around the core, as shown in Figure 7.1(c). In all three cases the stress produces birefringence in the fiber, with light polarized along the axis of the stress traveling slower (i.e., seeing a higher refractive index) than light polarized in the perpendicular direction. A variety of other designs are possible, but not as widely used.

Polarization-maintaining fibers are used in some advanced transmission systems that remain in the experimental stages; but their main applications are in sensors and optical devices that require polarization control, such as couplers and modulators. The largest-volume use of polarization-maintaining fibers is in coils for the fiber-optic gyroscopes described in Chapter 29.

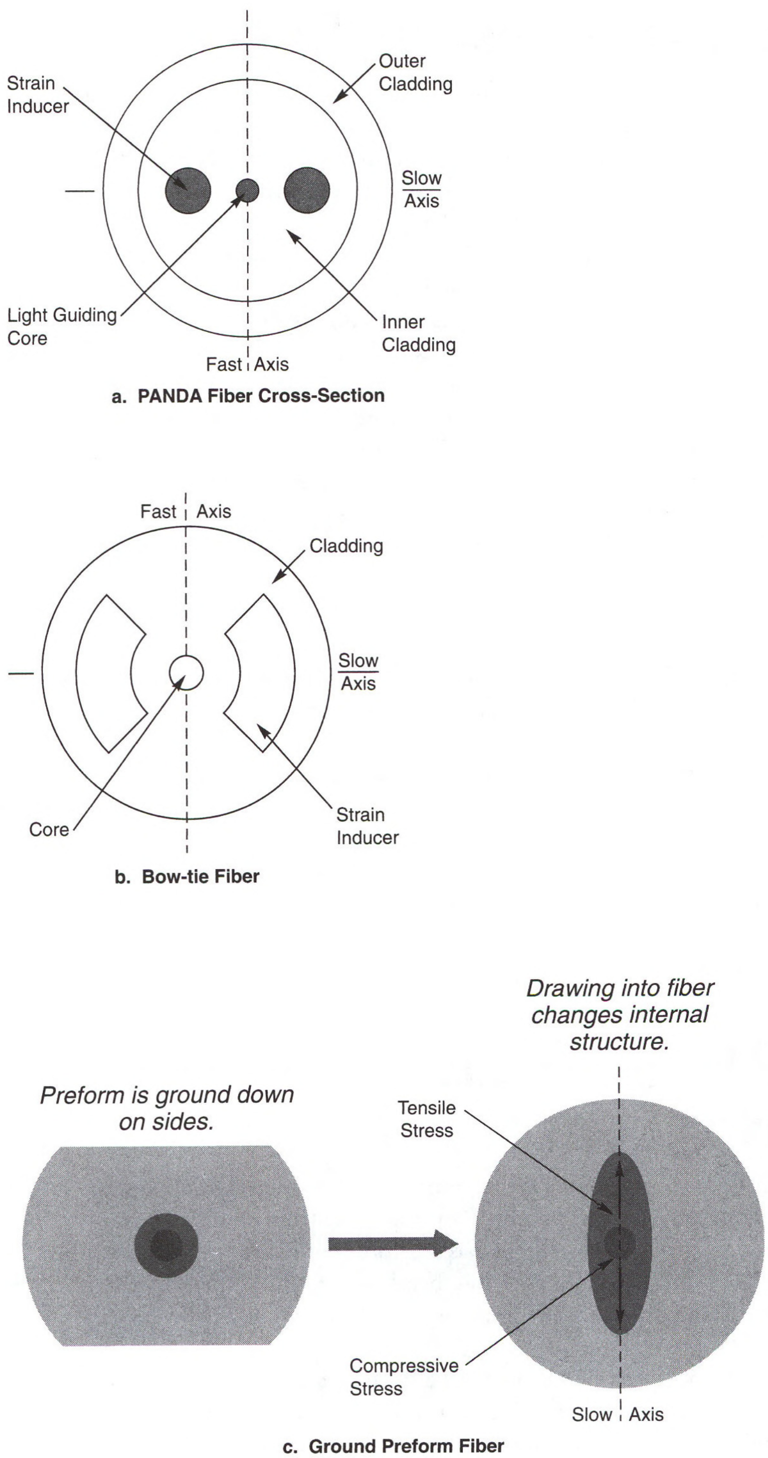
Polarizing fibers or *single-polarization fibers,* described earlier, guide light in one vertical polarization but not in the other. Polarizing fibers are similar in design to elliptical stress polarization-maintaining fibers, but their internal birefringence is much higher. This causes light in the fundamental mode to leak out of the core through the stressed region. Both polarizations leak out, but one escapes at a shorter wavelength than the other. Between those two wavelengths, the fiber transmits only one polarization and the perpendicular polarization leaks out.

Bend-Insensitive and Coupling Fibers

Standard transmission fibers are optimized for low transmission attenuation. However, the dominant losses in short lengths of fiber arise from coupling light into the core and from leakage at fiber bends. This has led to development of specialty fibers optimized for high coupling efficiency and low bend losses. These specialty fibers are more efficient than standard fibers in short lengths, such as pigtails linking light sources to a fiber.

Fibers can be made bend-insensitive by increasing the core refractive index so the core-cladding index difference is larger than in standard transmission fibers. Recall that the coupling efficiency depends on numerical aperture (NA), which increases with the

FIGURE 7.1
Three polarization-maintaining fibers: a) the PANDA fiber; b) the bow-tie fiber; c) drawing a ground preform into a fiber produces an elliptical stress layer.



core-cladding index difference. Increasing the core-cladding index difference also increases the confinement angle, which reduces light losses at bends in the fiber. Any increase in attenuation of the fiber is more than offset by the decrease in coupling and bending losses, which are far more important for short fiber segments than for transmission fibers.

Increasing core index reduces bend sensitivity and increases NA.

These characteristics make bend-insensitive fibers attractive for use in pigtails, or for short connections inside optical transmitters, receivers, and other devices. Internal space often is at a premium, so a fiber that can bend at a sharper angle increases design flexibility. These features also are useful in making the fused fiber couplers you will learn about in Chapter 14.

Bend-insensitive fibers can be designed for quite specific purposes. Some are metal-clad so they can be soldered into place in opto-electronic packages. Others have tapered cores so they can transfer light from a large-area source or large-core fiber into a smaller-core fiber. Others are made with a flattened core that can transfer light to or from planar optical waveguides more efficiently than standard fibers.

Reduced-Cladding Fibers

Reduced-cladding fibers have claddings with outer diameter of 80 μm rather than the usual 125 μm. These fibers have been introduced in the past few years to offer higher packing density and greater flexibility than standard fibers.

As mentioned in Chapter 4, the 125-μm cladding diameter of standard communication fibers was selected to deal with handling problems. Fibers that were much smaller than 125 μm clung to spools and were hard to handle; larger fibers tended to be too stiff and cracked when wound onto spools. The cladding diameter has little impact on the fiber's optical properties. As long as the cladding is at least 20 μm thick, the cladding diameter could be reduced considerably and still confine light in the core. Only single-mode fibers are offered with reduced cladding, so plenty of margin remains. As with standard fibers, a plastic coating is added to protect the outer glass surface and assist handling, which roughly doubles the outer diameter to 165 μm for reduced-cladding fibers.

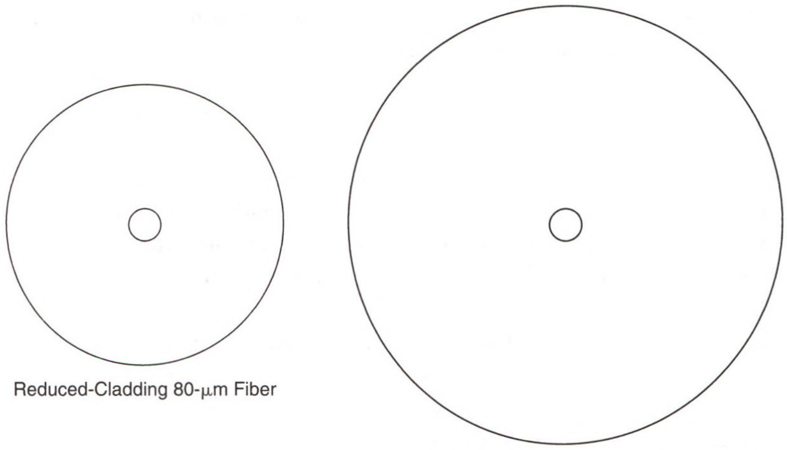
Fibers with 80-μm cladding diameter are more flexible and compact than standard 125-μm fibers.

A reduction in cladding can significantly reduce the volume occupied by a fiber. For example, if coatings are not considered, a fiber with 80-μm cladding has only 41% of the volume of a 125-μm fiber, as shown in Figure 7.2. With a 165-μm coating, the relative volume of a reduced-cladding fiber increases slightly to about 44%. Reduced cladding is not a major advantage for most transmission cables, but it would allow cables with high fiber counts to pack fibers more densely into the same volume. As you will learn in Chapter 8, this is most important for ribbon cables.

The reduction in cladding diameter can be quite important in coiled fiber devices such as fiber-optic gyroscopes and optical amplifiers, where the coil of fiber occupies a large fraction of the total device volume. The increased flexibility of the smaller fiber also allows tighter winding on a smaller spool.

The increased flexibility of reduced-cladding fiber allows it to be bent to a radius about 40% smaller than a conventional 125-μm fiber, or 3 centimeters compared to the usual 5 cm. In practice, the most important concern is avoiding extra attenuation from sharp bends.

FIGURE 7.2 *Reduced-cladding 80-μm fiber compared to standard 125-μm cladding fiber.*



Attenuation losses increase significantly at wavelengths longer than about 1580 nm, so the operating wavelength must also be considered. The tighter bend radius of reduced-cladding fiber can be important in short lengths of fiber used as pigtails or optical jumpers in packaged equipment. Thinner claddings also can be an advantage in fabricating couplers.

Fibers as small as 65-μm cladding and 125-μm coating are being tested to increase packing density and reduce bend diameter. This size is within the limit of cladding design for single-mode fibers, but pushes present fiber-coating technology. Thinner coatings offer less protection for the glass and increase the risk of the coating separating or delaminating from the cladding. This consideration is especially important for polarization-maintaining fiber because external stresses transmitted through the coating and cladding onto the core can affect polarization performance.

One trade-off inevitable with smaller claddings is difficulty in handling the fiber. Stiffness makes the fiber easier to handle, so the flexibility of reduced-cladding fiber increases difficulty of handling. Finer fibers also are harder to feel and to see.

Doped Fibers for Amplifiers and Lasers

Optical fiber amplifiers and fiber lasers are built around fibers in which the cores contain small amounts of elements that can be stimulated to emit light. You'll learn more about fiber lasers and the laser principle in Chapter 9, and more about optical amplifiers in Chapter 12. This section will introduce you to doped fibers and the basic concepts behind their use.

Stimulated Emission and Amplification

Both optical amplifiers and lasers are based on the concept of stimulated emission, a phenomenon in which an atom first absorbs energy, which excites it to an elevated energy level,

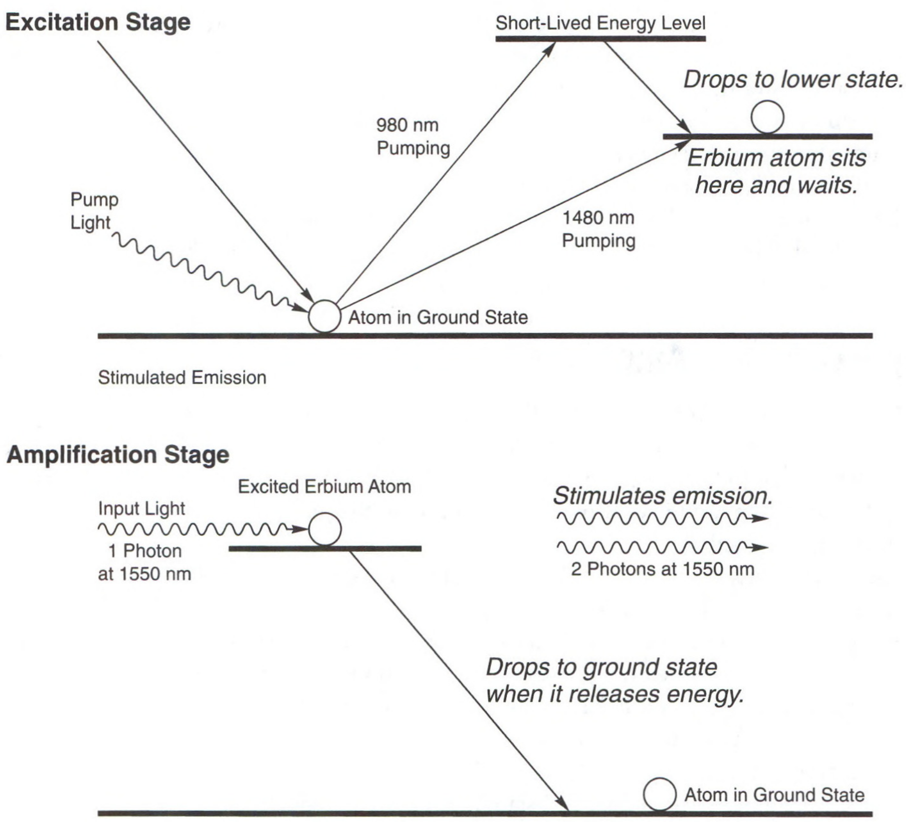


FIGURE 7.3
Excitation and amplification in erbium-doped fiber.

then is stimulated to emit some of that energy as light. The physics behind the process are complex, and light is emitted only at certain wavelengths for atoms that are excited in certain ways. For fiber optics, the most important type of optical amplifier is the erbium-doped fiber.

Figure 7.3 shows the process involved. First, the erbium atom absorbs pump energy from a photon at a wavelength of either 980 or 1480 nm, which raises it to a higher energy level. If it absorbs the shorter wavelength, it quickly drops to a lower state, the same one the 1480-nm photon excites it to. The atom sits there with the extra energy for a long time by atomic standards. If nothing happens, it eventually releases the energy as light. However, light of the right wavelength—between 1530 and 1620 nm—can stimulate the erbium atom to release the energy. Critically, the photon released is at exactly the same wavelength, and going in exactly the same direction, as the photon that stimulated the emission. If the input light is an optical signal, the process produces a second photon exactly in phase with the input photon, which amplifies the signal.

Erbium atoms are added to the fiber core to amplify the 1550-nm band.

To make an optical amplifier, erbium atoms are added to the glass in the core of a simple single-mode optical fiber. For the fiber to amplify light, the core must be illuminated by a laser emitting light at 980 or 1480 nm. The erbium atoms, which absorb this light, are raised to a higher energy level where an optical signal can stimulate them to emit energy. The input light has to be continuous to keep exciting the erbium atoms back to that higher energy level after they release their energy by stimulated emission and drop back down to the ground state. The pump light also should be intense enough to keep most of the erbium atoms in the excited state.

If the pump laser is off, an erbium amplifier absorbs rather than amplifies the signal. The erbium atoms that amplify light in the upper energy level instead absorb light in the lower energy level. Thus an optical amplifier without a pump laser actually blocks the signal rather than transmitting it unamplified.

Types of Fiber Amplifiers

The *erbium-doped fiber amplifier* (EDFA) described so far is the most common type of optical amplifier. The level of erbium doping in the fiber depends on the type of amplifier. It differs for amplifiers working in the C-band at 1530 to 1565 nm, and the L-band at 1570 to 1625 nm, and may also vary depending on the power level and number of channels being amplified.

Thulium and praseodymium also are used in fiber amplifiers for other wavelengths.

Other elements chemically similar to erbium are used to make fiber amplifiers for different wavelengths. The processes of pumping and stimulated emission are the same as for erbium, but the pump and amplification wavelengths are different. Praseodymium-doped fibers have been developed for amplification at 1310 nm, but have found few applications. Thulium-doped fibers have been developed for amplification at 1450 to 1500 nm, but also have found few applications. Ytterbium and neodymium have been doped into fiber cores for use in fiber lasers.

Most fiber amplifiers are made of standard silica glass. However, the gain of the amplifier and its strength at various wavelengths depend on the interaction between the light-emitting atoms and the host material, so amplifiers also have used other types of fibers. The fluoride fibers described in Chapter 6 have been used in some fiber amplifiers. Tellurite glasses, based on compounds of tellurium, also can be doped with erbium for amplifiers. Tellurite fibers offer higher gain at the longer-wavelength end of the erbium spectrum, but are not as easy to use as silica fibers.

Dual-Core Fiber for High-Power Lasers

Dual-core fibers are used in high-power lasers.

A dual-core structure is used to make fiber lasers that generate a watt or more of continuous optical power. These are high-power lasers, and some versions can reach a kilowatt, an amazing feat for light generated in the core of an optical fiber.

A fiber laser resembles a fiber amplifier, but has mirrors on both ends and has no input signal. The fiber laser is an *oscillator,* in which stimulated emission amplifies light generated internally when some of the excited atoms spontaneously release their energy. The mirrors reflect the light back and forth through the fiber core, with one mirror transmitting a fraction of the light to form a beam. (You'll learn more about lasers in Chapter 9.)

Lasers can be built around single-core fibers, but the dual-core design shown in Figure 7.4 transfers power more efficiently. The inner core has a higher refractive index than the outer

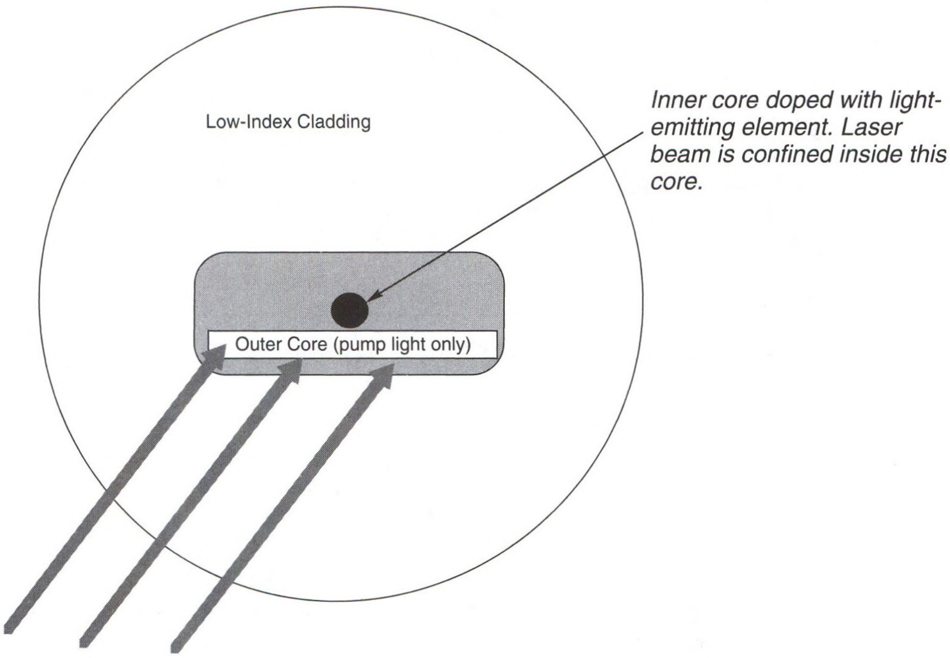


FIGURE 7.4
Dual-core fiber for high-power fiber lasers. The outer core guides the pump light so it passes through the inner core, which is doped with light-emitting atoms. Different shapes such as octagons can be used for the outer core.

core, and the outer core, in turn, has a higher index than the cladding. The cladding may be glass or a polymer, as long as its index is lower than that of the outer core. Only the high-index inner core is doped with a light-emitting element. Light from the pump laser is coupled into the large outer core, which is designed to collect light efficiently. The shape of the outer core is not radially symmetric, so total internal reflection sends the pump light on an irregular path. This path takes the pump light through the inner core many times, so it can excite light-emitting atoms efficiently. The highest powers obtained so far have been from fibers doped with ytterbium, which emits at 1120 nm.

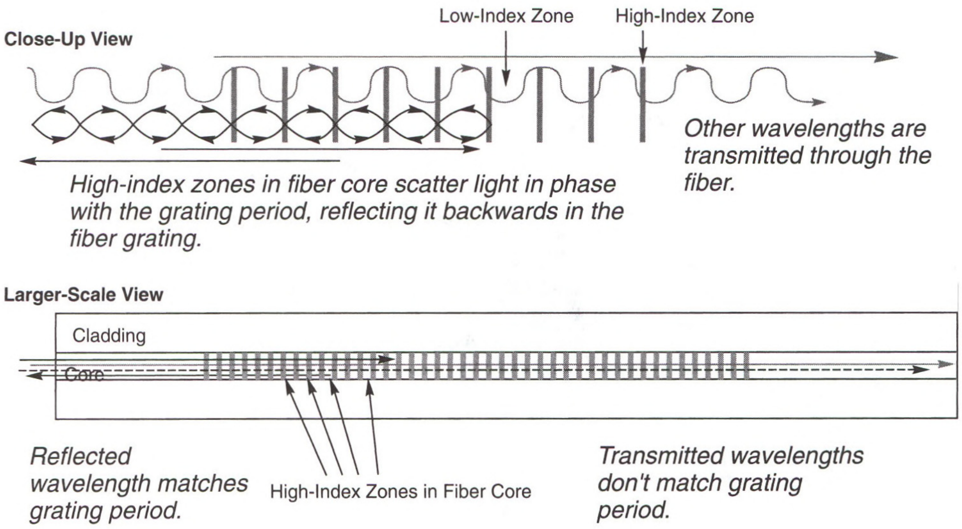
Fiber Gratings and Photosensitive Fibers

Refractive index varies periodically along a fiber grating.

Fiber gratings and photosensitive fibers might initially seem to be two separate classes of specialty fibers but are actually different aspects of the same thing. Photosensitive fibers are used to make fiber Bragg gratings. Thus the two are treated together here, with the emphasis on what users see, the fiber Bragg grating (which gets its name from the periodic variation of refractive index along its length).

Standard optical fibers have the same refractive index along their entire length, so a slice taken from one part of the fiber looks just like one taken from any other part of the fiber, apart from small imperfections. In a *fiber Bragg grating,* the refractive index rises and falls along its length periodically in a pattern that would look like a uniform wave if you plotted the index variation with distance. (The distance between index peaks is called the

FIGURE 7.5
Fiber Bragg grating reflects light at wavelengths that match the grating period and transmits other wavelengths.



grating period.) These refractive-index variations scatter light back into the fiber at any point where light encounters a refractive index variation.

The grating period selectively reflects one wavelength.

All wavelengths are scattered by the regularly spaced index variations, which causes the waves to interfere with each other in the fiber. Light at the wavelength that hits each index peak at the same phase experiences constructive interference and is selectively reflected back into the fiber, as shown in Figure 7.5. Light scattered at other wavelengths by the grating elements is out of phase and cancels out by destructive interference.

Fabrication of Fiber Gratings

Ultraviolet illumination changes refractive index in the fiber core.

Fiber Bragg gratings are made by illuminating photosensitive fibers with intense ultraviolet light. The ultraviolet photons break atomic bonds in the germania-doped silica core of a fiber with a composition that makes it particularly sensitive to the light. The fibers may be treated with hydrogen to enhance their response, although manufacturers say that specialty photosensitive fibers do not require hydrogen treatment.

The grating pattern can be created by illuminating the fiber with an ultraviolet laser through a *phase mask,* a thin flat slab of silica with a pattern of fine parallel troughs etched on its bottom, as shown in Figure 7.6. The phase mask diffracts most of the light in two directions, and the light waves interfere to form a pattern of alternating light and dark zones along the length of the fiber. The ultraviolet light breaks bonds in the lighted regions but not in the dark zones. Because of the geometry, the lines in the fiber grating are half as far apart as the lines in the phase mask. The laser wavelength does not affect the line spacing.

Another approach is to split the incoming ultraviolet light into two beams, then recombine them to form an interference pattern that exposes the side of the photosensitive fiber. Like the phase mask, this approach can create short gratings. It also can write gratings

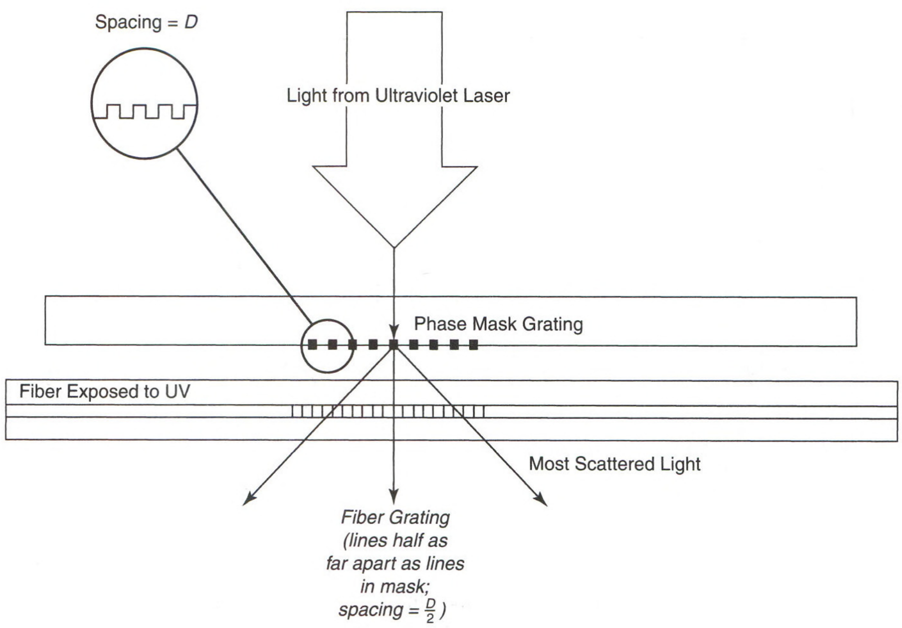


FIGURE 7.6 *Ultraviolet light forms grating in photosensitive fiber core.*

meters long by modulating the ultraviolet light as the fiber is moved relative to the interference pattern.

The amount of change in the refractive index depends on the extent of ultraviolet irradiation, the laser wavelength, the glass composition, and the processing before treatment. Typically, pulsed ultraviolet lasers illuminate the fiber with high intensity for a few minutes, increasing the refractive index of germania-doped silica by a factor of 0.00001 to 0.001. Hydrogen treatment or special processing can increase the sensitivity of the fiber so the index change reaches 1% (0.01), a value larger than the difference between core and cladding index in standard single-mode fibers.

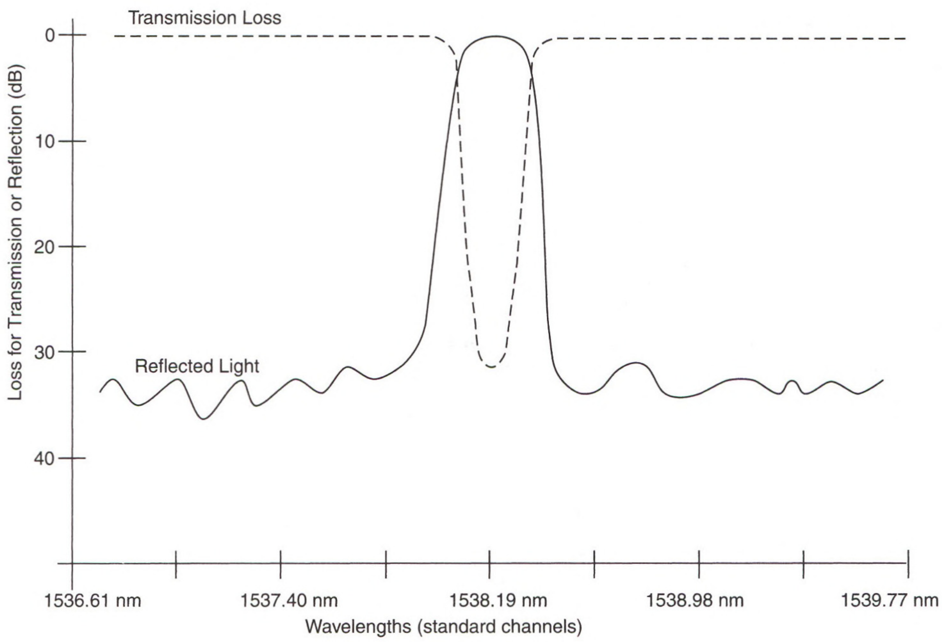
Reflection and Transmission in Fiber Gratings

The wavelength selectively reflected by the grating is twice the period of the grating because the light must go between the grating lines twice: once when it enters, and once when it's reflected. The wavelength in the glass is what counts, which is shorter than the wavelength in air by a factor of the refractive index n. The wavelength λ is normally defined in air, so this means that for a grating spacing of D, the reflected wavelength (measured in air) is

$$\lambda_{\text{reflected}} = 2nD$$

For example, if the grating spacing is 0.500 μm and the refractive index is 1.47, the selected wavelength is 1.47 μm. You also can flip the equation to calculate the grating spacing needed to reflect a particular wavelength if you know the refractive index.

FIGURE 7.7
Reflection and transmission by a fiber grating.



The light reflected back into the fiber at other wavelengths averages out to zero, so the grating transmits it essentially unaffected. This makes a fiber Bragg grating function as a line-reflection filter, selecting a wavelength it reflects while transmitting other wavelengths. Fiber Bragg gratings can be made with peak reflection across a narrow band and very sharp cutoffs on both sides, as shown in Figure 7.7 for peak reflectivity centered at 1538.19 μm. The sharpness of the reflective peak depends on the strength, length, and regularity of the grating. The plot in Figure 7.7, a composite based on typical products, shows how much lower the reflected and transmitted signals are than the input, measured in decibels. The reflected light is 30 dB below the input intensity at wavelengths outside the selected band, which is 100 GHz (0.8 nm) wide. Conversely, virtually all the light at the selected wavelength is reflected, while transmission is 30 dB below the input power.

The variation in reflectivity with wavelength depends on the quality of the grating. Fine, thin, evenly spaced grating lines concentrate reflection at a narrow range of wavelengths. Higher-contrast gratings increase reflectivity and broaden the range of reflected wavelengths. Gratings have been produced that select bands as narrow as 12.5 GHz, about 0.1 nm in the 1550-nm band, with much broader bands also possible.

The grating period can be chirped along the fiber length.

Chirped Gratings and Dispersion Compensation

To select a single wavelength, a fiber grating should have a uniform spacing along its entire length. However, the grating spacing doesn't have to be uniform. It can be "chirped," with

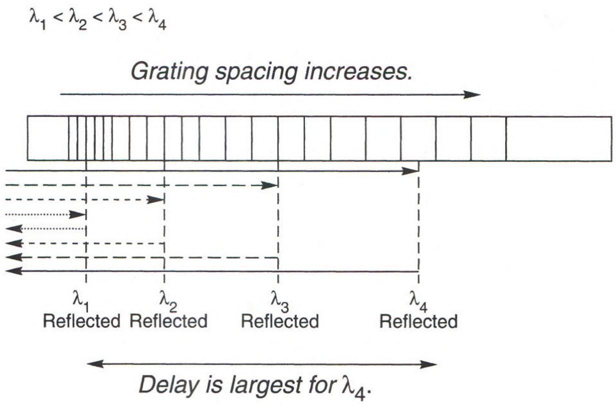


FIGURE 7.8
Fiber grating works as a delay line.

spacing changing along the length of the fiber, or with a series of zones of discretely different spacing in successive regions. Such a grating can serve as a wavelength-selective optical delay line, with the wavelengths reflected further along the grating delayed relative to those reflected first. Such a delay line can be used to compensate for chromatic dispersion along the length of a fiber.

Suppose, for example, that the longest wavelengths in a pulse arrived first and the shorter wavelengths arrived last. As shown in Figure 7.8, the grating can be made so segments that reflect different wavelengths are spaced along the fiber. In this case, the longest wavelength, λ_4, arrives first and is transmitted to the last part of the grating. Thus it has to travel farther than the shortest wavelengths, which arrive last and are reflected by the first part of the grating. Delaying the longest wavelength lets the shortest wavelength catch up, compensating for dispersion.

Fiber gratings don't have to be long to compensate for dispersion. If the average refractive index of the grating was 1.5, it would take only about 10 mm of grating to compensate for 100 ps of dispersion.

Other Fiber-Grating Filters

Spacing and strength of fiber gratings can be adjusted to reflect a broader range of wavelengths, or to reflect a controlled fraction of input light to attenuate certain wavelengths. Some fiber gratings have been designed specifically for sensing.

Important applications of fiber gratings include:

- Mirrors that reflect a narrow range of wavelengths to stabilize a fiber laser that emits at those wavelengths. You'll learn in Chapter 9 how such lasers work.
- Fibers that attenuate light intensity by varying amounts across a range of wavelengths to offset for uneven attenuation or amplification by other components. These fibers are usually called *equalization* filters because they make optical devices perform equivalently across a range of wavelengths.

THINGS TO THINK ABOUT

Separating Wavelengths with Fiber Bragg Gratings

Fiber Bragg gratings separate signals at one wavelength from those at other wavelengths. Yet you've just seen that the fiber grating reflects the wavelength it selects back in the direction it came. The reflected light travels out the input fiber and back toward the light source. You can separate reflected light easily if it goes in some other direction; but how can you separate it if it goes back through the input fiber?

The answer is that you need another device, called an *optical circulator,* described in Chapter 15 and shown in Figure 7.9. An optical circulator acts like a one-way valve that sends light travelling in one direction one way, and light travelling in the opposite direction a different way. It's an ingenious and complex device, and is essential to the practical use of fiber Bragg gratings. Its critical importance is worth pondering. When fiber Bragg gratings were first introduced for wavelength selection, the people touting them didn't make it clear that they wouldn't work without optical circulators: There was no way you could separate the wavelength you wanted from all the other light going in the other direction. This example is a reminder that you need to check new ideas to make sure people are telling you everything you need to know.

Circulators are not needed for fiber gratings that are used for sensing applications because the system that probes the sensor's response contains a tunable laser source and a wideband spectrum analyzer. This equipment scans the laser wavelength across the spectrum, then records the reflected wavelength for each Bragg grating in the fiber assembly. The system then compares the response to the gratings' reference wavelength to determine the change in temperature or strain in each grating due to the wavelength shift.

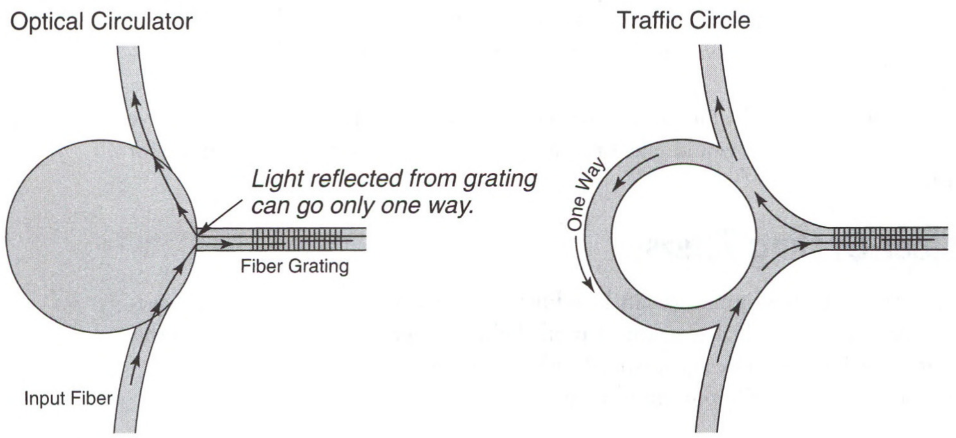


FIGURE 7.9
An optical circulator works like a traffic rotary, preventing light reflected from the fiber grating from going the "wrong way."

Photonic or "Holey" Fibers

Chapter 6 described the fabrication of photonic fibers in which light guiding depends on internal microstructures. This gives fiber designers more degrees of freedom than are available for conventional fibers, allowing them to make fibers with features that are otherwise impossible. The technology is still evolving, so we will concentrate on key concepts.

Photonic crystal fibers are fibers that guide light in a central solid core surrounded by microstructured material with internal holes, as shown in Figure 7.10. Although the cladding design is based on the photonic bandgap concept, the light guiding also can be viewed in conventional terms; the cladding has a lower refractive index than the solid core, so the guiding mechanism can be interpreted as total internal reflection. The microstructure does allow the core to maintain single-mode transmission at larger diameters than otherwise possible, reducing the fiber's nonlinearity. Conversely, the same principles can be used to make small-core fibers with high nonlinearity. Adjusting cladding properties also can affect chromatic dispersion in the fiber.

Photonic crystal fibers guide light in a central solid core.

Photonic bandgap fibers are similar to photonic crystal fibers, but have a hollow core with lower refractive index than the surrounding cladding. Their operation depends entirely on the presence of a photonic bandgap layer, which cannot transmit light trapped in the hollow core. Because the photonic bandgap material blocks light only at certain wavelengths, a photonic bandgap fiber guides only those wavelengths, not the whole spectrum.

Photonic bandgap fibers guide light in air, not a solid, so they have lower nonlinearity and different dispersion properties than standard fibers. Those properties can be changed by filling the central holes with other gases. The hollow cores can be large or small, and some versions resemble waveguides. Hollow-core waveguides potentially can transmit any wavelength, depending on the design of the photonic bandgap layer.

Properties of photonic fibers can be varied over a wide range.

Photonic fibers are likely to find their first applications as specialty fibers for applications that require high nonlinearity in a fiber. At this writing, photonic fibers are still in development.

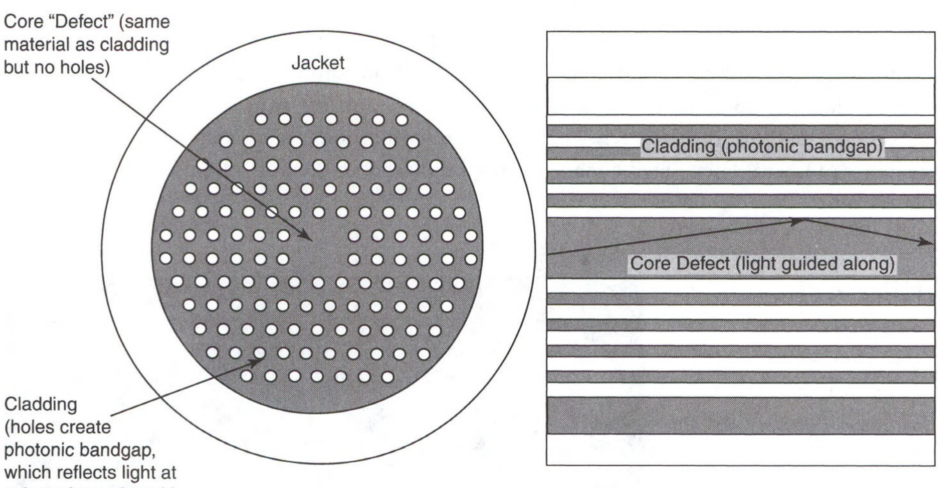


FIGURE 7.10
A photonic crystal fiber guides light in the solid core, which lacks the holes present in the cladding.

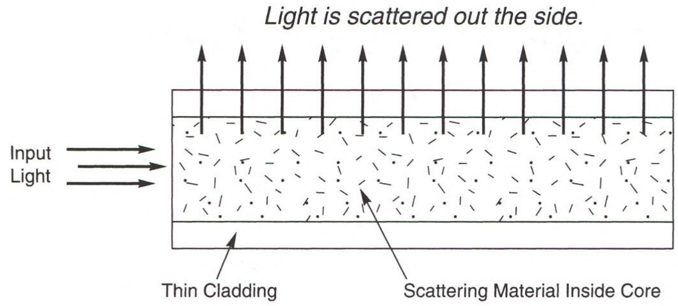


FIGURE 7.11
Side-glowing fiber contains material in the core that scatters light out the side, so the fiber glows along its length like a neon tube.

Special Noncommunications Fibers

Side-Glowing Decorative Fibers

Light-scattering material can be added to the cores of optical fibers to create interesting effects for decoration, fabrics, and illumination.

A small amount of scattering is inevitable in all optical fibers that guide light from end to end, but normally it is undetectable. Essentially all the light emerges from the end of the fiber. In decorative objects using standard fibers, such as lamps for Christmas trees, this creates glittering points of light at the fiber tips, with the rest of the fiber emitting no light.

Materials added to the core can scatter light from the sides of decorative fibers.

Side-glowing fibers are produced by adding finely divided light-scattering materials to the core of a fiber, as shown in Figure 7.11. Light passing through the core bounces off the material and out the sides, making the length of the fiber glow. The illuminating light, the fiber, or the scattering particles may be colored, and fluorescent materials can be used. In some cases, a side-glowing fiber can look like a neon tube. The cladding normally is thin, and light is scattered so widely that the cladding's presence is not obvious. The length of fiber illuminated depends on the brightness of the source and the degree of scattering.

Side-glowing fibers can be made as thread-like filaments for use in decorative fabrics. These fine fibers can be woven into fabrics, and some artists use them to create fascinating objects, like "The River," by Laurie Carlson, shown in Figure 7.12.

Side-glowing fibers made for architectural decoration are much thicker, sometimes a centimeter or more in diameter. These fibers resemble rods, but retain the core-cladding structure of fibers. They may be made from solid plastic, or contain a liquid core in a hollow plastic tube.

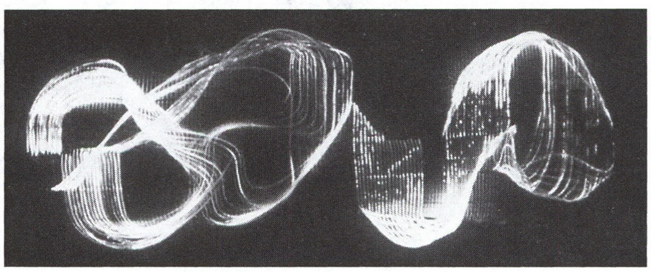


FIGURE 7.12
"The River," fabric fiber-optic art by Laurie Carlson. (Courtesy of Laurie Carlson)

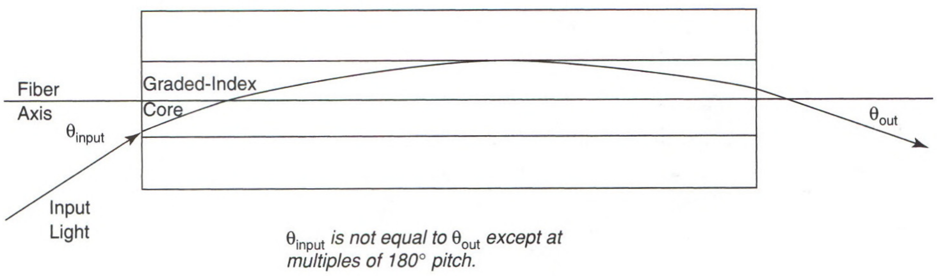


FIGURE 7.13 *Graded-index fiber lens.*

Graded-Index Fiber Lenses

Graded-index fibers can focus light and act as lenses.

Short lengths of graded-index fibers can act as tiny lenses to focus light. These fiber-optic microlenses have limited uses in fiber-optic systems, but have found applications in other systems that manipulate images point by point, such as photocopiers, scanners, and facsimile machines. (These are different from the fiber-optic imaging bundles described in Chapter 30.)

In Chapter 4, you learned that light follows a sinusoidal path through graded-index fiber. In that chapter, you saw a cone of light entering a long graded-index fiber, and light spreading from the end of the fiber in a cone of the same size. Now consider instead the path of an individual light ray through a short segment of graded-index fiber, shown in Figure 7.13.

In a step-index fiber, total internal reflection from the step-index boundary keeps light rays at the same angle to the fiber axis all along the fiber; so the output angle equals the input angle. Graded-index fibers refract light rays, so the angle between the ray and the fiber axis changes constantly as the light bends back and forth following a sinusoidal path. If you cut a graded-index fiber at a point where the light ray has gone through 180° or 360° of the sinusoidal curve, the light emerges at the same angle that it entered. If you cut the fiber at some other point, the light emerges at a different angle, as shown in Figure 7.13. Making light rays emerge at a different angle is equivalent to focusing them with a lens, so a segment of graded-index fiber can serve as a lens.

The key parameter for graded-index fiber lenses (usually sold under the trade name Selfoc™) is the fraction of a full sinusoidal cycle the light has completed before leaving the fiber. That fraction is called the *pitch*. A 0.23-pitch lens, for instance, has gone through 0.23 of a cycle, or 82.8°. The value of the pitch depends on various factors including the refractive-index gradient in the fiber, its core diameter, and the wavelength of the light. Typical graded-index fiber lenses are a few millimeters long, very short by fiber standards.

What Have You Learned?

1. Specialty fibers have properties that differ significantly from those of standard transmission fibers and are fine-tuned for specific applications.
2. Dispersion-compensating fibers are made with high waveguide dispersion to give them high negative chromatic dispersion.
3. Polarization-maintaining fibers are made with internal stress that helps them separate the two polarizations of light. They are used in fiber gyroscopes, some components, and some special transmission systems.

4. Fibers made for use in pigtails, couplers, and short connections inside devices have a core with a high refractive index to reduce their sensitivity to bend losses.
5. A high-index core increases numerical aperture, reducing coupling losses.
6. Reduced-cladding fibers have 80-μm cladding diameter, which makes them more flexible and compact than standard 125-μm fibers. The reduced cladding does not affect the optical properties of single-mode fibers.
7. Reduced-cladding fibers are used in fiber gyroscopes and fiber amplifiers, but rarely in cables.
8. Optical amplifiers are built around fibers with single-mode cores that are doped with rare-earth elements such as erbium. These elements produce stimulated emission, which amplifies a weak optical signal.
9. Erbium-doped fiber amplifiers are the most widely used; they amplify in the 1550-nm band. Thulium and praseodymium fiber amplifiers are used for other wavelengths.
10. Dual-core fibers are used to make high-power fiber lasers.
11. Fiber Bragg gratings are periodic variations in refractive index along the length of a fiber that are produced by illuminating a photosensitive fiber with intense ultraviolet light.
12. The refractive-index variations in fiber Bragg gratings scatter light. Interference among the scattered light waves reflects one wavelength while transmitting others through the grating.
13. The wavelength reflected by a fiber grating equals twice the grating spacing multiplied by the refractive index of the fiber.
14. The period of a fiber Bragg grating can be chirped along its length.
15. Photonic fibers can guide light in a solid or a hollow core. Their properties can be adjusted over a wide range, giving high or low nonlinearity and changing chromatic dispersion.
16. Materials added to the core scatter light from the sides of decorative fibers.
17. Short lengths of graded-index fibers can focus light and act as lenses.

What's Next?

In Chapter 8, we move on to learn about the cables that contain optical fibers in communication systems.

Further Reading

University of Bath, "Photonic Crystal Fibre," *http://www.bath.ac.uk/physics/groups/opto/pcf.html*

P. C. Becker et al., *Erbium Fiber Amplifiers: Fundamentals and Technology* (Academic Press, 1999)

John A. Buck, "Optical Fiber Amplifiers," in Michael Bass, ed., *Handbook of Optics Vol. 4: Fiber Optics and Nonlinear Optics* (McGraw-Hill, 2001)

Kenneth O. Hill, "Fiber Bragg Gratings," in Michael Bass, ed., *Handbook of Optics Vol. 4: Fiber Optics and Nonlinear Optics* (McGraw-Hill, 2001)

K. O. Hill and G. Meltz, "Fiber Bragg grating technology fundamentals and overview," *Journal of Lightwave Technology V.15,* 1263–1276 (August 1997)

Raman Kashyap, *Fiber Bragg Gratings* (Academic Press, 1999)

Gerd Keiser, *Optical Fiber Communications* (McGraw-Hill, 2000). See Chapter 11 on optical amplifiers.

J. C. Knight et al., "Photonic crystal fibers: New solutions in fiber optics," *Optics and Photonics News 13,* pp. 26–30 (March 2002)

Questions to Think About

1. Reduced-cladding fibers have outer diameters of 80 μm, but developers have proposed 60-μm claddings. That should not affect optical performance because the claddings would be only about 25 μm thick. What problems might be expected from the smaller diameter?
2. A fiber grating reflects light waves that are in phase with the grating with a wavelength $\lambda = 2nD$, where D is the spacing between the grating lines. This wavelength is the longest that would make exactly one round trip between a pair of grating lines. A wavelength exactly half that value also would be resonant with that grating spacing because exactly two waves would make one round trip. Why isn't this light also reflected?
3. Why is refractive index always measured in air rather than in glass?
4. What's the advantage of doping erbium only in the fiber core?
5. The gain of an erbium-doped fiber varies as a function of wavelength. It is highest from about 1530 to 1565 nm, and lower at longer wavelengths. Recalling how gain is defined, how can you make an erbium-doped fiber amplifier with a high amplification factor at longer wavelengths?
6. Think of a way to demonstrate light scattering from the side of a fiber designed for decorative lighting. Start with a laser pointer.
7. A high-power erbium-doped fiber amplifier has saturated its output at 10 mW/channel for 20 optical channels with 100-GHz spacing. You add 20 more channels at intermediate wavelengths. Assuming the amplifier is so saturated it can't generate any more total output, what is the new output per channel?

Chapter Quiz

1. What creates the grating effect in a fiber grating?
   a. lines etched on the fiber surface by high-power ultraviolet pulses
   b. changes in the refractive index of the fiber core induced by ultraviolet light

c. interference among several modes in a multimode fiber
d. variations in glass composition caused by changes in doping during preform fabrication
e. optical white magic

2. A grating with period of 0.5 μm is made in a glass fiber with core refractive index of 1.5. What wavelength of light is reflected most strongly?

a. 1300 nm
b. 1500 nm
c. 1550 nm
d. 1600 nm
e. none of the above

3. Which wavelengths are transmitted by the grating in Problem 2?

a. None; all light is reflected or scattered from the fiber.
b. 1300 and 1600 nm only
c. 1300, 1500, and 1600 nm
d. 1300, 1550, and 1600 nm
e. 1300, 1500, and 1550 nm

4. What causes a fiber to maintain the polarization of light transmitted through it?

a. tension applied along the length of the fiber
b. doping of the core with germanium
c. stress applied by structures in the fiber cladding
d. stress applied by structures inside the fiber core
e. Polarization cannot be maintained because the fiber is radially symmetric.

5. How does increasing the refractive index of the core of a fiber make it better for coupling light into fibers?

a. It reduces attenuation of the glass.
b. It increases NA and reduces attenuation of the glass.
c. It increases NA and reduces bend sensitivity.
d. It decreases NA, bend sensitivity, and attenuation.
e. It reduces bend sensitivity and glass attenuation.

6. What determines which wavelengths can be amplified in a fiber amplifier?

a. the number of modes guided in the fiber
b. attenuation of the fiber
c. properties of the light-emitting ion doped into the core
d. the wavelengths of the pump lasers
e. dispersion of the fiber

7. What wavelengths are amplified by an erbium-doped fiber amplifier?

a. 980–1480 nm

b. 1250–1350 nm

c. 1300–1700 nm

d. 1470–1530 nm

e. 1530–1620 nm

8. Which type of fiber cannot be made in reduced-cladding form?

a. graded-index fiber with a 62.5-μm core

b. polarization-maintaining fiber

c. erbium-doped fiber for amplifiers

d. short fiber lengths for pigtails

e. standard single-mode fiber

9. Neglecting the weight of the spool and the plastic coating on the fiber, how much can you reduce the weight of a fiber-optic gyroscope by switching from a standard 125-μm fiber to a reduced-cladding fiber?

a. 10%

b. 35%

c. 50%

d. 60%

e. 90%

10. What can you do with a photonic bandgap fiber that you cannot do with any conventional fiber?

a. guide light in a hollow core

b. guide light in a solid core

c. maintain polarization of the input light

d. dope the core with erbium for use in an optical amplifier

e. fabricate a fiber grating in the core