CHAPTER

6

Fiber Materials, Structure, and Manufacture

About This Chapter

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

Requirements for Making Optical Fibers

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

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

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

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

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

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

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

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

Glass Fibers

What Is Glass?

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

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

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

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

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

THINGS TO THINK ABOUT

Does Glass Flow?

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

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

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

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

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

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

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

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

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

Rod-in-Tube Glass Fibers

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

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

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

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

Limitations of Standard Glasses

Impurities limit transmission of standard glasses.

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

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

Fused-Silica Fibers

Fused silica is the basis for modern communication fibers.

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

Dopants, Cores, and Claddings

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

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

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

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

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

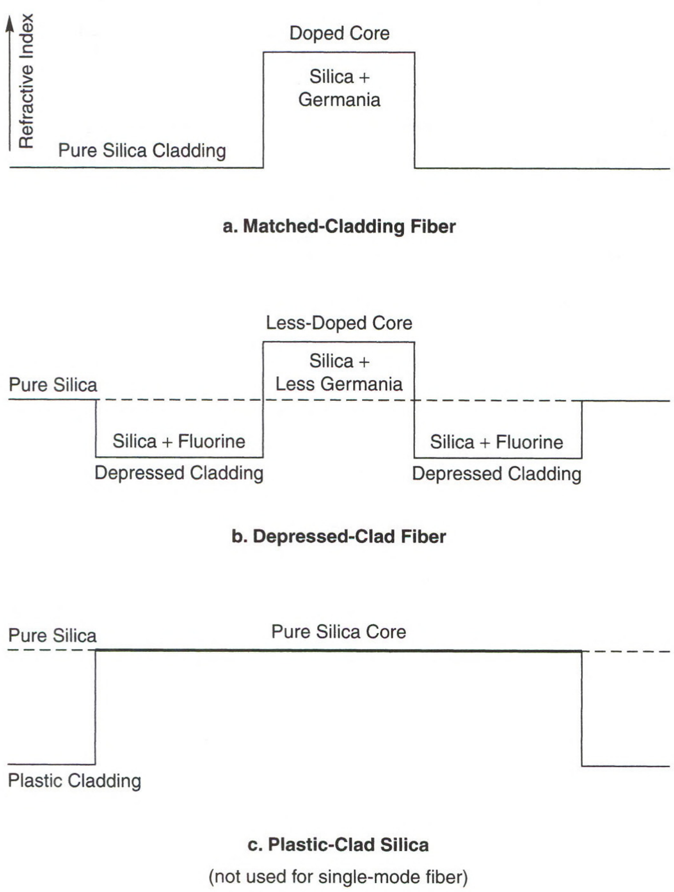


FIGURE 6.1
Refractive-index profiles of matched-clad and depressed-clad single-mode fibers and plastic-clad silica multimode fibers.

levels complicates processing, so manufacturers prefer to make as much as possible of the fiber from pure silica.) Both designs are used for single-mode fiber. An alternative used for multimode step-index fiber is a pure silica core clad with a lower index plastic.

As you learned in Chapter 4, the refractive-index profiles of dispersion-shifted fibers are considerably more complex, to provide the extra waveguide dispersion needed to shift the zero-dispersion point to longer wavelengths. So are the profiles of graded-index multimode fibers. The same dopants are used in these more complex fibers as in simple step-index fibers.

Silica Fiber Manufacture

The trickiest stage in the manufacture of fused-silica optical fibers is making the preform from which the fibers are drawn. Several processes have been developed; they share some common features but have important differences.

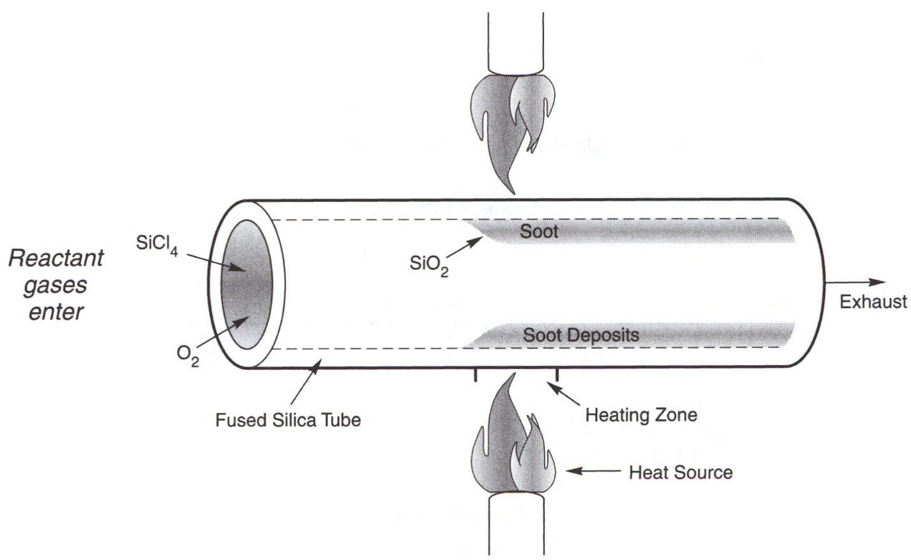
Fused-silica preforms can be made by depositing glass soot inside a tube of fused silica, which becomes the cladding.

The crucial common feature is the formation of fluffy fused-silica soot by reacting $SiCl_4$ (and $GeCl_4$, when it is used as a dopant) with oxygen to generate SiO_2 (and GeO_2 if the silica is doped). The crucial variations are in how the soot is deposited and melted into the final preform.

One approach is to deposit the soot on the inside wall of a fused-silica tube, as shown in Figure 6.2. Typically, the tube serves as the outer cladding, onto which an inner cladding layer and the core material are deposited. Variations on the approach are called inside vapor deposition, modified chemical vapor deposition, plasma chemical vapor deposition, and plasma-enhanced chemical vapor deposition. The major differences center on how the reaction zone is heated.

The chemicals react to deposit a fine glass soot, and the waste gas is pumped out to an exhaust. To spread soot along the length of the tube, the reaction zone is moved along the tube. Heating melts the soot, and it condenses into a glass.

FIGURE 6.2
Soot deposition inside a fused-silica tube.



The process can be repeated over and over to deposit many fine layers of slightly different composition, which are needed to grade the refractive index from core to cladding in graded-index fibers. The doping of input gases is changed slightly for each deposition step, producing a series of layers with small steps in the refractive index. Step-index profiles are easier to fabricate, because the whole core has the same doping. A final heating step collapses the tube into a preform.

Another important approach is the outside vapor-deposition process, which deposits soot on the outside of a rotating ceramic rod, as shown in Figure 6.3. The ceramic rod does not become part of the fiber; it is merely a substrate. The glass soot that will become the fiber core is deposited first, then the cladding layers are deposited on top of it. The ceramic core has a different thermal expansion coefficient than the glass layers deposited on top of it, so it slips out easily when the finished assembly is cooled before the glass is sintered to form a preform. The central hole is closed either in making the preform or drawing the fiber.

Preforms also can be made by depositing soot on the outside or on the end of a rod.

The third main approach is vapor axial deposition, shown in Figure 6.4. In this case, a rod of pure silica serves as a "seed" for deposition of glass soot on its end rather than on its surface. The initial soot deposited becomes the core. Then more soot is deposited radially outward to become the cladding, and new core material is grown on the end of the preform. Vapor axial deposition does not involve a central hole.

All three processes yield long, glass cylinders or rods called *preforms.* They are essentially fat versions of fibers, composed of a high-index fiber covered with a lower-index cladding. They have the same refractive-index profile as the final fiber.

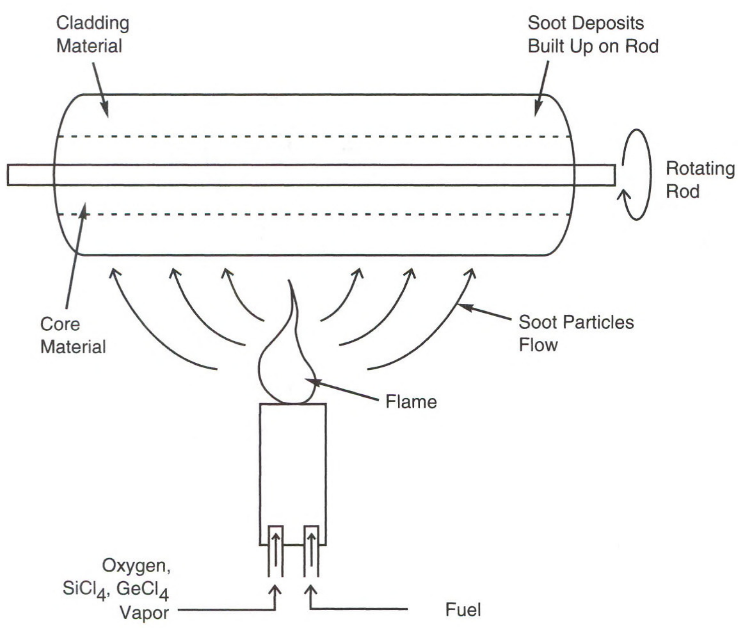
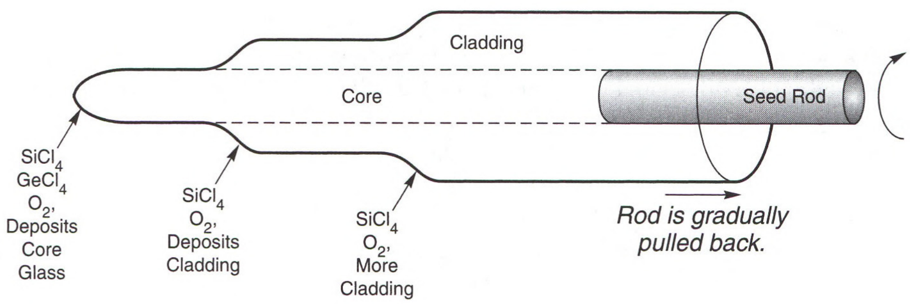


FIGURE 6.3
Outside vapor deposition to make a preform.

FIGURE 6.4
Vapor axial deposition to make a preform.



Drawing Fibers

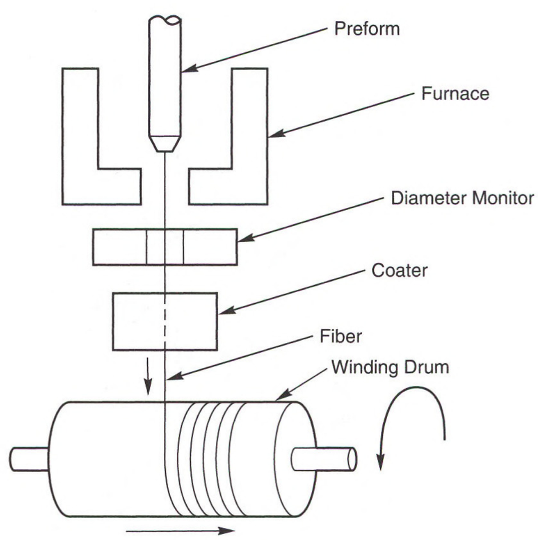
Fibers are drawn from the bottoms of hot preforms.

Optical fibers are *drawn* from preforms by heating the glass until it softens, then pulling the hot glass away from the preform. This is done in a machine called a *drawing tower.*

Drawing towers typically are a couple of stories high and loom above everything else on the floor of a fiber factory. The preform is mounted vertically at the top, with its bottom end in a furnace that heats the glass to its softening point. Initially a blob of hot glass is pulled from the bottom, stretching out to become the start of the fiber. (This starting segment of the fiber normally is discarded.)

The hot glass thread emerging from the furnace solidifies almost instantaneously as it cools in open air. As shown in Figure 6.5, the bare glass fiber passes through a device that monitors its diameter, then is covered with a protective plastic coating. The end is attached to a rotating drum or spool, which turns steadily, pulling hot glass fiber from the bottom of the preform and winding plastic-coated fiber onto the drum or spool. The actual length of the draw zone is longer than shown in the figure, to allow the fiber to cool and the plastic coating to cure properly.

FIGURE 6.5
Drawing glass fibers from preforms. (Courtesy of Corning Inc.)



Typically the fiber is drawn at speeds well over a meter per second. A single, large preform can yield over 20 kilometers of fiber; smaller preforms yield a few kilometers. After the fiber is drawn, it is proof tested and wound onto final reels for shipping.

Types of Silica Fibers

Silica is the standard material used for most communication fibers. Except for a few special cases, both core and cladding are made of silica, differentiated by different *doping* levels. Typically the cores contain dopants that increase refractive index above that of pure silica, while the cladding is either pure silica or doped with index-depressing materials such as fluorine, as shown in Figure 6.1 and discussed earlier.

All-silica fibers are used for communications.

This basic design is used for the single-mode and graded-index multimode fibers used for communications. Figure 6.6 shows typical attenuation curves for a high-quality nonzero dispersion-shifted (ITU G.655) single-mode fiber and a graded-index multimode

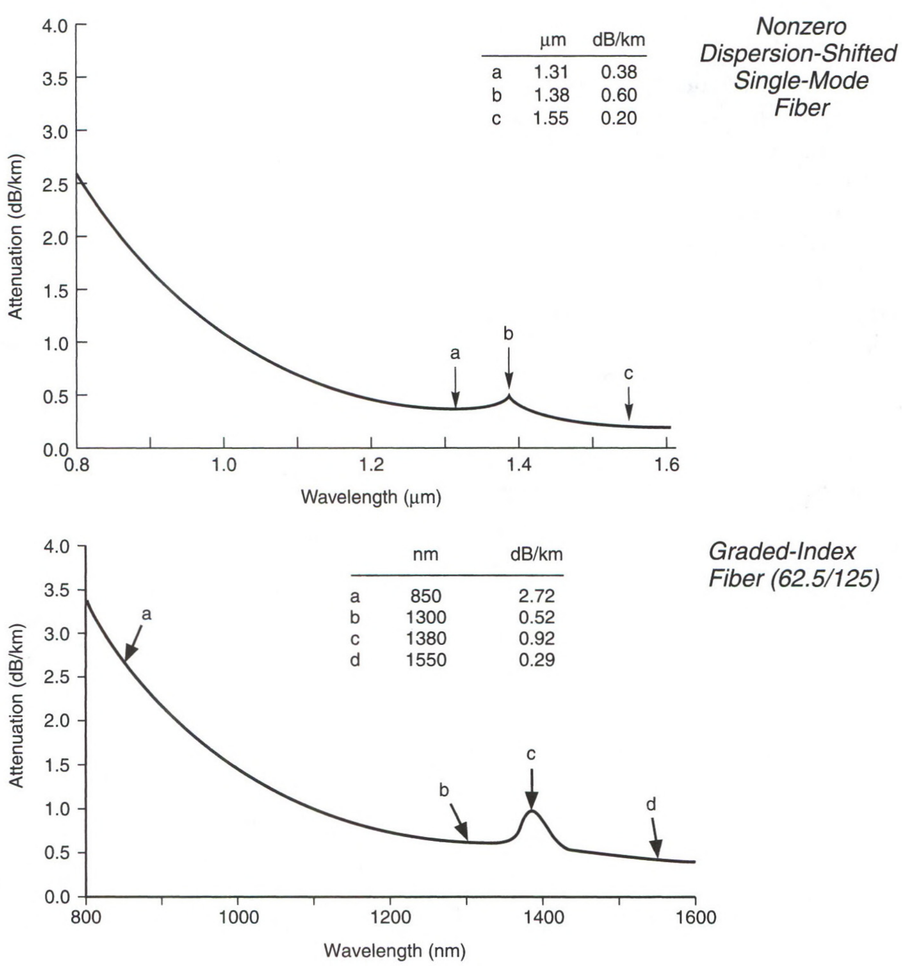


FIGURE 6.6 *Attenuation of non-zero dispersion-shifted ITU G.655 fiber (left) and graded-index multimode fiber (below). (Courtesy of Corning Inc.)*

fiber. Attenuation for step-index single-mode fiber is slightly lower than for the ITU G.655 fiber, but the difference is not significant and would not show on this scale. Low-water single-mode fibers lack the absorption peak near 1.38 μm. A quick comparison shows higher loss for the graded-index fiber, but this is not significant for the short-distance applications in which they are used.

Different designs are used for step-index multimode silica fibers. Typically these fibers have a pure silica core, which is clad either with silica doped to reduce its refractive index or with a plastic having lower refractive index than silica. This approach simplifies the manufacturing process and avoids the need for dopants in cores that are 100 μm or larger. Typically the claddings are thin—20 μm on a fiber with a 100-μm core and a 140-μm cladding diameter—with a protective plastic coating 50 to 100 μm thick applied over the cladding.

Large-core silica fibers are used for data transmission, laser beam delivery, or illumination.

Large-core step-index silica fibers come in a variety of configurations, and typically are used for data transmission, laser beam delivery, or illumination. The oldest type is *plastic-clad silica* (PCS), in which the cladding is a silicone plastic that is fairly easy to strip from the silica core. Easily removed cladding is good for some applications, but bad for others. *Hard-clad silica* (HCS) fibers have a tougher plastic cladding, which makes the fibers more durable. *Silica-clad fibers* can handle higher powers than either type of plastic-clad fiber, an important consideration for fibers delivering high laser powers.

Figure 6.7 shows attenuation for a selection of large-core silica fibers. The values vary depending on the type of cladding and the amount of moisture in the silica core. Fibers made in a low-water environment contain little OH and are more transparent in the near-infrared, while fibers that contain more OH are more transparent in the ultraviolet. (The fibers in Figure 6.7 all have low OH levels, and the plot does not show ultraviolet attenuation.)

Typical core diameters of large-core step-index fibers range from 100 to 1000 μm. The smaller fibers may be used for short-distance communication, but the larger fibers are used mostly for illumination. The largest-core fibers can carry considerable power, making them useful for laser-beam delivery, but they are significantly stiffer. For example, the rated continuous

FIGURE 6.7
Spectral attenuation of various large-core silica fibers. (Courtesy of 3M Specialty Optical Fibers.)

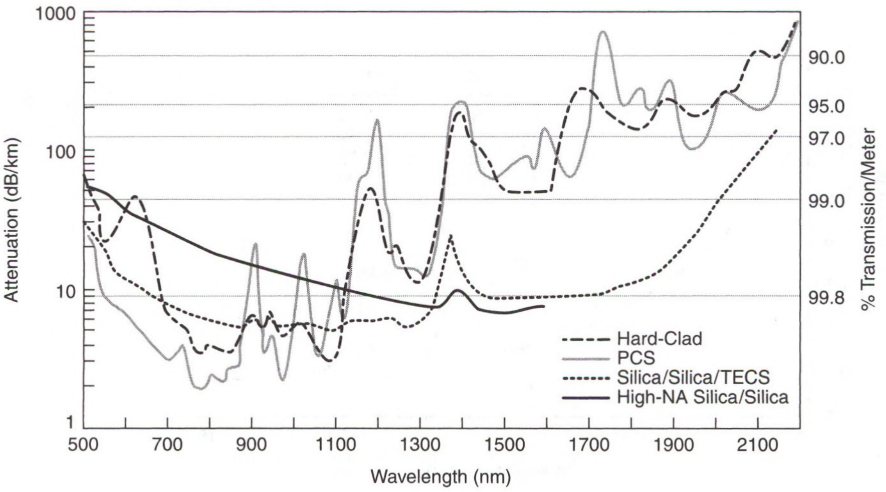


Table 6.1 Characteristics of large-core step-index silica fibers. Bandwidths of fibers with cores over 200 μm generally are unrated because they are very rarely used in communications

Fiber Type	Core/Clad Diameter (μm)	Attenuation at 0.82 μm	Bandwidth at 0.82 μm	NA
Silica clad	100/120	5 dB/km	20 MHz-km	0.22
Hard clad	125/140	20 dB/km	20 MHz-km	0.48
Plastic-clad, low OH	200/380	6 dB/km	20 MHz-km	0.40
Plastic-clad, high OH	200/380	12 dB/km	20 MHz-km	0.40
Silica clad	400/500	12 dB/km	—	0.16
Hard clad	550/600	12 dB/km	—	0.22
Silica clad	1000/1250	14 dB/km	—	0.16
Plastic-clad, low OH	1000/1400	8 dB/km	—	0.40

power capacity of one family of silica-clad fibers increases from 0.2 kW for 200-μm core fibers to 1.5 kW for 550-μm core fibers, and the rated minimum bend radius increases by a factor of 2.5. Table 6.1 summarizes important optical characteristics of selected fibers.

Although most large-core silica fibers have step-index profiles, some are made with a graded-index core, surrounded by a thin silica cladding and typically a plastic coating and outer buffer layer. Their main application is in delivering high-power laser beams.

Plastic Fibers

Plastic optical fibers have long been a poor relation of glass. Traditionally regarded as inexpensive, flexible, lightweight, and easy to handle, plastic seems to offer some important attractions. These potential advantages can be hard to realize in practice, since silica fibers are reasonably priced and flexible in the small diameters used for telecommunications applications. However, the biggest problem of plastic fibers has been attenuation levels many times that of glass, making commercial types impractical for distances beyond 100 meters.

Multimode fibers made entirely of plastic have higher loss than silica fibers.

Years of research have reduced plastic loss considerably, but it still remains far higher than that of glass. The best laboratory plastic fibers have minimum loss around 50 dB/km. At the 650-nm wavelength preferred for communications using red LEDs, commercial plastic fibers have minimum attenuation as low as 150 dB/km. Unlike glass fibers, the loss of plastic fibers is somewhat lower at shorter wavelengths and much higher in the infrared, as shown in Figure 6.8.

For this reason, plastic optical fibers have found only limited applications. One is in flexible bundles for image transmission and illumination, where the light doesn't have to travel far and the flexibility and lower cost of plastic are important. Another application is in short data links, particularly within automobiles, where the ease of handling plastics is a major advantage and the required distances and data rates are small.

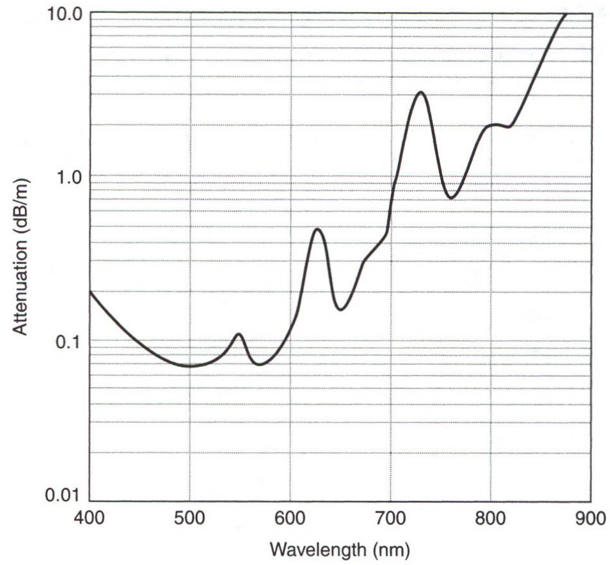


FIGURE 6.8
Attenuation versus wavelength for one commercial PMMA step-index fiber. (Courtesy of Toray Industries Ltd.)

Another important concern with plastic optical fibers is long-term degradation at high operating temperature. Typically plastic fibers cannot be used above 85°C (185°F). This may sound safely above normal room temperature, but it leaves little margin in many environments. The engine compartments of cars, for example, can get considerably hotter. Newer plastics can withstand temperatures to 125°C (257°F), but their optical properties are not as good.

Plastic fibers are made using the same principles as glass fibers. A low-index core surrounds a higher index cladding. The refractive-index difference can be large, so many plastic fibers have large numerical apertures. Commercial plastic fibers are multimode types with large cores. Most are step-index but a few are graded-index. There is little interest in single-mode plastic fibers because the material's high loss makes long-distance transmission impossible.

Step- and Graded-Index Plastic Fibers

Traditional plastic fibers are made of PMMA, with large step-index cores. They are used in bundles and for short data links.

Standard step-index plastic fibers have a core of polymethyl methacrylate (PMMA) and a cladding of a lower index polymer, which usually contains fluorine. The differences in refractive index typically are larger than in silica or glass fibers, leading to a large numerical aperture. For example, one commercial plastic fiber designed for short-distance communication has a PMMA core with refractive index of 1.492 and a cladding with index of 1.402, giving an NA of 0.47.

Plastic fibers typically have core diameters from about 85 μm to more than 3 mm (3000 μm). You can find larger light-guiding rods of flexible plastic, which sometimes are called fibers, but it's hard to think of something as thick as a pencil as a "fiber." The smallest fibers typically are used only in bundles, but larger fibers are used individually. Typically the claddings are thin, only a small fraction of overall fiber diameter. Large-core plastic fibers cannot carry optical powers as high as those carried by large-core silica fibers, but they are more flexible and less expensive. Plastic fibers with diameters up to around a millimeter are used for some short-distance communication because they are much easier to handle than glass fibers. For example, technicians can splice and connect plastic fibers on site with minimal equipment, instead of the expensive precision equipment required for glass fibers. Figure 6.8 plots attenuation of one PMMA fiber against wavelength, on a scale of decibels per *meter.* The minimum loss, near 500 nm, is equivalent to 70 dB/km, but for communications transmission normally is at the 650-nm wavelength of inexpensive red LEDs. The step-index profile also limits bandwidth, so signals normally are limited to traveling within a building or between adjacent structures.

Graded-index plastic fibers are a recent development because it had been difficult to produce good graded-index profiles in plastic. Typically a preform is heat-treated to make high-index materials diffuse from a fluorinated plastic core and raise the index of lower index plastics in the cladding. This plastic preform is then drawn into fiber, much like glass fibers but at much lower temperatures.

Graded-index profiles can be made in plastic fibers, increasing bandwidth.

As in silica fibers, the advantage of a graded-index profile is broader transmission bandwidth than step-index fibers. Graded-index plastic fibers with core diameters of 50 to 200 μm can transmit 2.5 Gbit/s over distances of 200 to 500 meters, making them attractive for high-speed local area networks. The fluorinated plastic fibers have attenuation around 60 dB/km over a broad range from about 800 to 1340 nm, allowing operation at the 850 and 1300 nm windows. However, attenuation through the entire range is tens of decibels per kilometer, limiting transmission to much shorter distances than with silica fibers, and the fibers are relatively expensive.

Issues in Developing Plastic Fibers

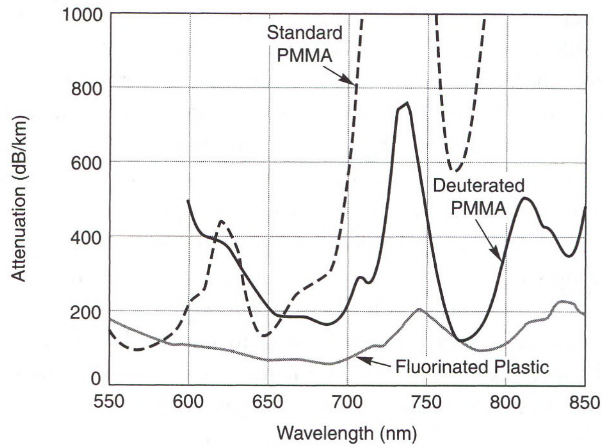
High attenuation has been a stubborn problem in plastic optical fibers. Bonds between atoms found in plastics—notably carbon-hydrogen and carbon-oxygen bonds—absorb light at visible and near-infrared wavelengths, even in plastics that look transparent to the eye. Fused silica is much more transparent because these bonds are not present in it.

Attenuation is a key issue in plastic fibers.

Efforts to reduce loss have concentrated on changing the chemical composition of the plastics. One step is to replace normal hydrogen with the heavier (stable) isotope deuterium, which shifts the absorption peaks of carbon-hydrogen bonds to longer wavelengths. Another step is to use fluorinated plastics instead of standard hydrocarbon plastics, because carbon-fluorine bonds have lower attenuation. Figure 6.9 compares attenuation curves for fibers made of standard hydrogen-based PMMA, deuterated PMMA, and one type of fluorinated plastic between 550 and 850 nm. Loss of the fluorinated plastic remains relatively low at wavelengths to 1.3 μm. However, changing composition raises other issues, including the need for more expensive materials.

Another important issue, mentioned earlier, is the durability of plastics, both over time and under extreme conditions. Plastic fibers generally are more flexible than glass, and are easier to cut and install. They generally work fine in a controlled environment such as an office. However, plastics are not as resistant to heat and sunlight as glass. Temperature limitations have proved a particular problem in areas such as the automotive industry, where equipment installed in the engine compartment must withstand frequent temperature cycling and extremes.

FIGURE 6.9
Attenuation spectra of graded-index plastic fibers made with regular PMMA, a fluorinated plastic, and deuterated PMMA. (Courtesy of Takaaki Ishigure.)



Exotic Fibers and Light Guides

From time to time, you may encounter some unusual optical fibers, light guides, or optical waveguides based on novel materials. They presently play little role in communications, but have other applications.

Liquid-Core Fibers (or Light Guides)

In the very early days of fiber-optic communications, developers desperately seeking low-loss materials turned to liquids. They filled thin silica tubes with tetrachloroethylene, a dry-cleaning fluid that is extremely clear and has a refractive index higher than fused silica. The index difference was adequate to guide light, and developers eventually reduced loss to several decibels per kilometer, very good for the time, and better than current plastics.

Liquid-core fibers were far from a practical communications technology. Filling the tiny capillary tubes took a very long time, but the real problem was thermal expansion. The liquid expanded at a different rate than the tube that held it, so the liquid-core fiber acted like a thermometer, with liquid rising and falling with temperature. If you weren't careful, the liquid could squirt out the ends.

A liquid in a plastic or glass tube can act like a fiber core if its refractive index is higher than the tube.

Now larger diameter liquid-core light guides are finding a new life transmitting visible light short distances for illumination. Single liquid-core light guides 2 to 10 mm thick are an alternative to standard illuminating bundles. Using suitable fluids, they have lower attenuation than standard bundle fibers, particularly at green and blue wavelengths. The liquid is housed in a plastic tube rather than glass, so the liquid waveguide is more flexible than a large solid fiber. Because lengths are modest—at most 20 m and typically only a few meters—thermal expansion poses little problem.

Midinfrared Fibers

The extremely low scattering losses expected at wavelengths longer than 1.55 μm prompted interest in those wavelengths for long-distance communications in the 1980s. The absorption of silica rises rapidly at longer wavelengths, so developers looked to other materials that are transparent in that region. Theorists hoped that extremely low-loss glass fibers could be made from some of those materials. (Recall that glass is a disordered material, not necessarily made from silica.) If other losses could be avoided, the floor set by scattering loss suggested attenuation might be as low as 0.001 dB/km. Such incredibly low loss would allow extremely long transmission distances without amplifiers or repeaters.

Fibers made of nonsilica glasses transmit infrared wavelengths, which silica absorbs.

Unfortunately, very low-loss *infrared fibers* have proven exceedingly difficult to make. Purification of the materials is difficult. The raw materials are far more expensive than those for silica fibers. (Despite occasional jokes about desert nations concerning the market on raw materials, silica fibers can't be made from raw sand, as can many glass products.) Infrared materials are harder to pull into fibers because they are much less viscous than silicate glass when molten. The fibers that can be produced are weaker mechanically than silica and suffer other environmental limitations. In short, infrared fibers have been a bust for ultra-long-distance communications.

On the other hand, fibers made from nonsilicate glasses can transmit infrared wavelengths that do not pass through silica fibers. This makes them useful in specialized applications such as infrared instrumentation, although their losses are much larger than the minimum loss of silica fibers at shorter wavelengths.

Fluorozirconate fibers transmit light between 0.4 and 5 μm. Often simply called fluoride fibers, they are made primarily of zirconium fluoride (ZrF_4) and barium fluoride (BaF_2), with some other components added to form a glass compound. The lowest losses for commercial fluorozirconate fibers are about 25 dB/km at 2.6 μm, but loss as low as about 1 dB/km has been reported in the laboratory. A typical transmission curve is shown in Figure 6.10, along with other infrared fibers. Fluoride fibers are vulnerable to excess humidity, so they should be stored and used in low-humidity environments. Fluoride

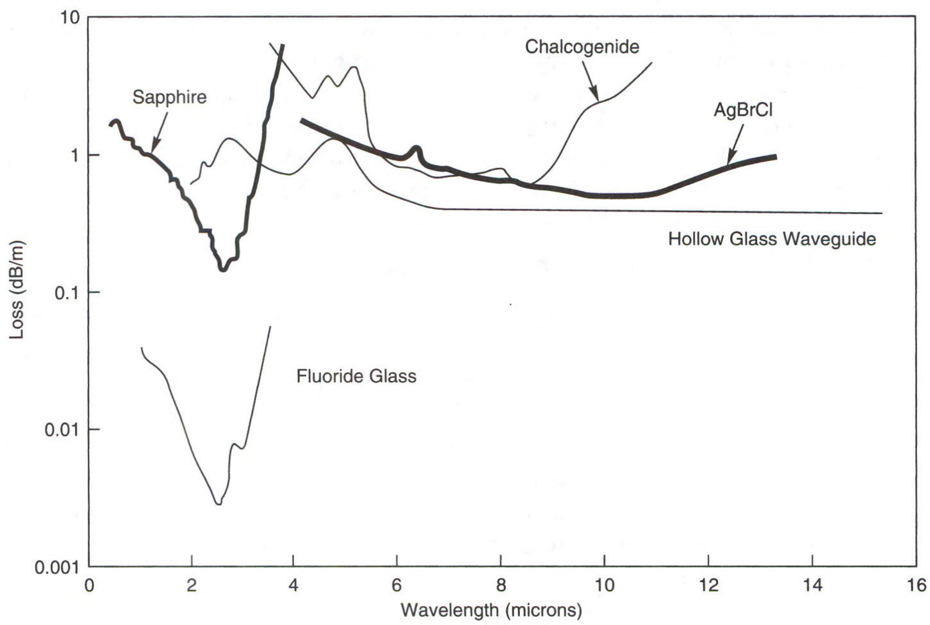


FIGURE 6.10
Attenuation of infrared optical fibers. (Courtesy of James Harrington, Rutgers University)

fibers are used in some fiber amplifiers because of desirable optical characteristics. However, they have a refractive index higher than 2, so they have high reflection from their ends.

Fibers made from silver halide compounds (AgBrCl in Figure 6.10) have useful transmission between about 3 and 16 μm in the infrared. They are not a true glass, but a solid made of many small crystals.

Synthetic crystalline sapphire (Al_2O_3) can be drawn into single-crystal fibers that transmit between 0.5 and 3.1 μm. As Figure 6.10 shows, their loss is higher than fluoride fibers, but the material is much more durable.

Hollow Optical Waveguides

Hollow waveguides can transmit longer infrared wavelengths.

Hollow *optical waveguides* were first developed in the 1960s, after the laser stimulated interest in optical communications. Work on hollow waveguides for the visible and near-infrared stopped shortly after the first low-loss glass fibers were made in the 1970s. However, new types of hollow optical waveguides are being developed for infrared wavelengths longer than a few micrometers. I mention them here because they serve the same purpose as infrared fibers, and compete successfully for some infrared applications. There are two basic types of hollow infrared waveguides, metal and hollow glass.

Hollow metal waveguides are coated inside with a nonconductive dielectric material to make them more reflective. The infrared light bounces along the shiny walls, with high reflectivity limiting loss to about 500 dB/km. That isn't bad considering how many reflections the light undergoes. Many hollow glass waveguides work on the same principle; they have the advantage of very smooth surfaces that give loss as low as 0.5 dB/m with suitable coatings, as shown in Figure 6.10.

Other hollow glass waveguides work on a different principle. At certain wavelengths, some materials have an effective refractive index less than 1. Functionally, that means they absorb those wavelengths strongly, but it also means they can serve as a low-index cladding surrounding a hollow core of air, which at that wavelength has a higher refractive index. Silica glass meets those conditions at wavelengths of 7 to 9.4 μm, and sapphire at 10 to 17 μm. These waveguides are called *attenuating total internal reflection* guides because the fraction of the wave in the cladding is absorbed, so loss is over 1 dB/m. However, hollow sapphire guides can be used at the important 10.6-μm wavelength of carbon dioxide lasers.

Photonic or Microstructured Fibers

Microstructured photonic materials confine light.

A new family of optical fibers, largely in the research stage, relies on internal microstructures to control the propagation of light in ways impossible with conventional fibers. These are often called *photonic fibers,* but also have been called "microstructured" or "holey" fibers because their internal structures typically have holes running along their length.

Figure 6.11 shows how microstructured fibers are made. Hollow glass tubes and solid rods are stacked together with the desired proportions and enclosed in an outer tube. In the design shown, a single solid rod is at the center of the array. Then the glass is fused together and drawn into a fiber. Careful processing produces finished fiber with fine holes running along its length.

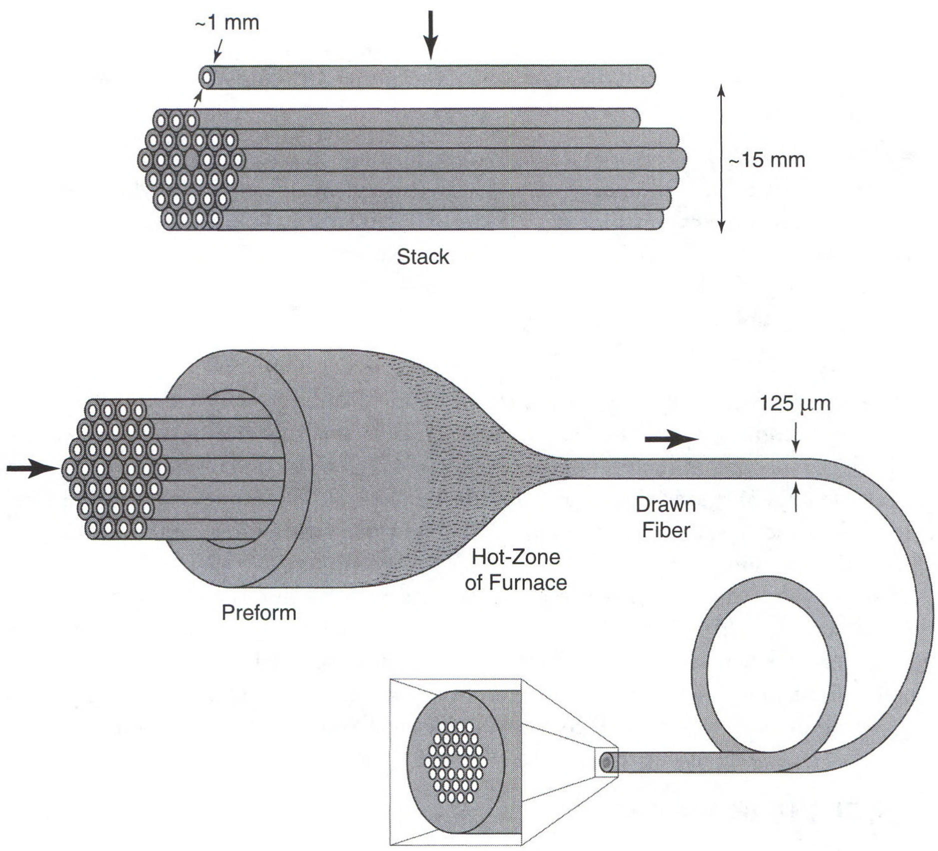


FIGURE 6.11
Structure and fabrication of photonic crystal fiber with solid core. (Courtesy of Tim Birks, University of Bath)

Microstructured fibers developed from the phenomenon of the *photonic bandgap*, which arises in materials with internal structures that make it impossible for light to propagate at certain wavelengths. In that sense, the photonic bandgap is analogous to the electronic bandgap, a range of energy levels that electrons can't occupy in semiconductors. Semiconductor bandgaps are used to confine electrons; photonic bandgaps are used to confine the path of light.

The two basic components of a microstructured fiber are a glass matrix and holes containing air (or some other gas or liquid). The relative packing and size of the holes and glass can range from nearly solid glass with a few tiny holes that act as flaws to a thin lattice of glass spread through a volume that is largely air. Specialists divide microstructured fibers into two broad classes, depending on whether the light is confined in a central solid area or within a central hole.

- *Photonic crystal fibers,* like the one shown in Figure 6.11, have a solid core surrounded by a layer containing holes running the length of the fiber. The central solid region is a defect in a sense, because it lacks the holes present in the surrounding microstructure. The microstructured zone is a photonic bandgap material with an average refractive index lower than that of the solid core. That makes photonic crystal fibers act somewhat like a conventional solid fiber, with a high-index core surrounded by a lower index cladding. However, the light guiding of the structure depends on the size and spacing of the holes, which determine the effective refractive index of the holey cladding layer.

Photonic bandgap fibers confine light in a hollow core.

Photonic bandgap fibers have a hollow core surrounded by a photonic bandgap cladding, which reflects all light at certain wavelengths. In this way, it guides light through the air-filled core, which has a lower refractive index than the surrounding material. Such light guiding is impossible in conventional fibers because the refractive index of air is lower than that of any conventional solid, so these fibers can only be described in terms of photonic bandgaps.

These types of fibers can be designed to have properties impossible in standard fibers. Photonic crystal fibers with a large fraction of the cladding filled with air and small features can confine light in effective mode areas as small as one square micrometer, which is useful for producing nonlinear effects. Large-holed microstructures also can produce high waveguide dispersion for use in dispersion compensation or shifting. Other photonic crystal structures can confine light in a larger core than otherwise possible, reducing nonlinear effects.

Photonic bandgap fibers have received less attention because they are a more recent development, but they offer other possibilities. Guiding light in air should allow very low attenuation and reduce nonlinear effects. It also could allow light transmission at wavelengths where no usable transparent solids are available. Because the photonic bandgap effect is wavelength-dependent, such fibers would guide some wavelengths but not others.

Planar Waveguides

Planar waveguides are thin strips on flat substrates that guide light by total internal reflection.

Planar waveguides work on the same principle of total internal reflection as optical fibers, but they come in a different form. A planar waveguide is a thin layer on the surface of a flat material, which has higher refractive index than the bulk material. Typically the high refractive index is produced by doping the substrate material with something that increases its refractive index. Figure 6.12 shows the basic idea. The boundaries of the doped area form an interface that guides light, like the core-cladding interface in optical fibers. In Figure 6.12, the substrate provides the low-index materials on the sides and bottom, while air is the low-index medium on the top.

An alternative approach is to deposit a layer of high-index material on a lower index substrate. In this case, the waveguide is a raised stripe on the substrate, surrounded by air on top and on the sides, and contacting the substrate only on the bottom. As with the doped waveguide, total internal reflection confines light in the waveguide layer.

From a theoretical standpoint, both types of planar waveguides are *dielectric slab waveguides.* That means they are made of nonconducting (dielectric) materials, and are rectangular in cross section, rather than round like a fiber. The theory of such waveguides is quite well developed.

Planar waveguides are used in couplers, lasers, modulators, and switches.

From a practical standpoint, planar waveguides also have some attractions. The technology for making thin stripes of material on flat substrates has been well developed by the semiconductor electronics industry. The technology can be used with a wide variety

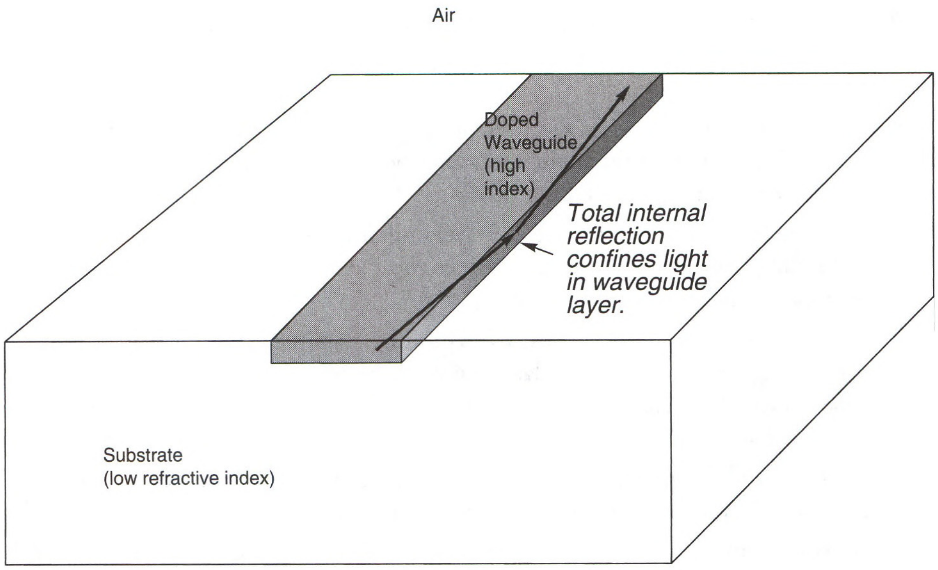


FIGURE 6.12
Planar waveguide.

of materials, including silica glass and other compounds as well as semiconductors. Active optical components such as lasers and photodetectors can be made on the semiconductor materials. So can a wide variety of passive optical components, such as demultiplexers and couplers that divide and combine optical signals. That opens the possibility of integrating optical components on a chip.

On the other hand, planar waveguides also suffer serious practical drawbacks. Their attenuation is much higher than optical fibers, so they can't send signals very far. Their flat, wide geometry differs greatly from the round cores of optical fibers, so light is inevitably lost in transferring from a fiber to a waveguide. Such problems limit the uses of planar waveguides.

Nonetheless, planar waveguide devices can manipulate light in many useful ways. Many semiconductor lasers are planar waveguide devices; you'll learn about them in Chapter 9. Other important planar waveguide devices include couplers, modulators, switches, and wavelength division-multiplexing components; you'll learn about them in Chapters 14, 15, and 16.

For now, what's important is to remember what planar waveguides are, that they can guide light like optical fibers, and that they can serve as the basis for a variety of important components.

What Have You Learned?

1. Fiber-optic materials must be transparent and drawable into thin fibers.
2. Glass is a noncrystalline solid. Most glasses are compounds of silica and other oxides. A wide variety of compositions have been developed for various uses.
3. Silica-based glasses have refractive indexes of 1.44 to 1.8, with pure silica among the lowest.

4. Simple glass-clad fibers are made by collapsing a low-index tube onto a high-index rod, called a preform, heating the tip, and drawing fiber from the soft, hot end.
5. Impurities are the main cause of attenuation in standard silica glasses. Synthetic fused silica is the base for communication fibers; it is very clear because impurities are reduced to a part per billion or less.
6. Silica must be doped to form either a high-index core or a low-index cladding for an all-glass fiber. Fluorine can reduce the index of silica; germanium can increase its index.
7. Fused silica preforms are formed by depositing glass soot inside a fused silica tube, on a ceramic rod that is later removed, or on the end of a preform. This soot is melted to make the preform. Fiber is drawn from the bottom of a preform mounted in a drawing tower.
8. Large-core silica fibers are used for illumination and laser beam delivery. They may be clad with doped silica, hard plastic, or soft plastic.
9. All-plastic fibers have attenuation much higher than silica fibers. They are used for image transmission or short-distance communications.
10. Standard plastic fibers are made from PMMA and have step-index profiles. Graded-index plastic fibers are available but are not widely used. Lower-loss plastics are in development, but there are no prospects for reaching the low losses of silica fibers.
11. Silica does not transmit at wavelengths longer than 2 μm, so other materials are used in fibers transmitting at longer wavelengths. None of these are as transparent as silica fibers. Hollow waveguides also are used in the infrared.
12. Photonic bandgap materials permit new types of fibers.
13. Planar waveguides are thin layers on flat substrates, which guide light by total internal reflection, like optical fibers.

What's Next?

In Chapter 7, you will learn about special types of fibers including fiber Bragg gratings, fibers used in optical amplifiers, and photonic bandgap fibers.

Further Reading

James Harrington, "Infrared Fiber Review," available at *http://irfibers.rutgers.edu/ir_rev_glass.html*

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

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Yasuhiro Koike and Takaaki Ishigure, "Bandwidth and Transmission Distance Achieved by POF," *IECE Transactions Electronics,* Vol. E82-D, No. 98, August 1999, available on the Web at *http://www.ieice.org/eng/index.html*

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

Questions to Think About

1. Window glass looks very clear when you look straight through a pane, but when you look into the edge it looks green. What causes this color?
2. Why is it easy to make fibers from glass but impossible to make them from ice, even in Antarctica?
3. What are the main trade-offs in picking dopants for the core and cladding of fused-silica fibers?
4. The large-core step-index fibers listed in Table 6.1 have cores that are nominally pure silica and generally carry higher laser powers than telecommunication fibers. Yet their attenuation is higher than for single-mode telecommunication fibers at the same wavelengths. Why should this happen?
5. How would you compare the advantages of plastic and glass fibers? What are the best features of each? Where might plastic have an advantage?
6. Roughly how many times higher is the minimum loss of plastic fibers than that of glass fibers, measured in dB/km?
7. If you aimed a 1.55-μm laser beam straight up through clear air, about 90% of the light would escape into space, with 10% scattered or absorbed. The atmosphere becomes more tenuous at higher altitudes, so assume that sending a beam into space is equivalent to transmitting it through 10 km of air. What is the equivalent attenuation in dB/km? How does this compare with the best optical fibers at that wavelength? Does that imply a limit on the transparency of hollow photonic bandgap fibers?

Chapter Quiz

1. What is the most essential property of all glass?
   a. It is a noncrystalline solid.
   b. It is a crystalline solid.
   c. It must be transparent.
   d. It must be made of pure silica.
   e. It must have a refractive index of 1.5.

2. What type of fiber is drawn from a preform made by fusing a low-index tube onto a higher-index rod?

a. step-index single-mode
b. graded-index multimode
c. dispersion-shifted
d. short-distance imaging and illumination
e. all of the above

3. What impurity levels are required in fused silica for communications fibers?

a. less than 0.1%
b. less than 0.001%
c. one part per million
d. ten parts per billion
e. one part per billion

4. What is done to make a depressed-clad fiber?

a. The fiber is flattened by rollers to depress it before the cladding is applied.
b. The refractive index in the core is depressed by adding germanium.
c. The refractive index in the inner part of the cladding is depressed by adding fluorine.
d. The fiber is clad with a low-index plastic.
e. The entire fiber is made of pure silica because it has the lowest refractive index of any glass.

5. How are preforms for communications fibers made?

a. by the rod-in-tube method
b. by soot deposition in a fused silica tube
c. by soot deposition on the outside of a ceramic rod
d. by vapor axial deposition on the end of a rod
e. by methods b, c, and d

6. What is *not* used as a cladding for silica fiber?

a. silica with refractive index depressed by adding fluorine
b. silica with refractive index increased by adding germanium
c. hard plastic
d. soft plastic
e. pure silica cladding on a core doped to have higher refractive index

7. What type of fiber could transmit the highest laser power?

a. step-index silica fiber with a 550-μm core
b. hard-clad silica fiber with a 100-μm core
c. all-plastic fiber with a 1000-μm core

d. single-mode fiber
e. plastic-clad silica fiber with a 200-μm core

8. What is the lowest loss of laboratory all-plastic fibers?
a. 1 dB/km
b. 50 dB/km
c. 150 dB/km
d. 500 dB/km
e. 1 dB/m

9. At what wavelength does PMMA plastic fiber have the lowest loss?
a. 500 nm
b. 650 nm
c. 850 nm
d. 1.3 μm
e. 1.55 μm

10. Why would you use fluorozirconate fibers?
a. because you couldn't find any other fibers
b. because their attenuation is 0.001 dB/km
c. to transmit near-infrared wavelengths of 2–5 μm where silica fibers have high loss
d. to transmit infrared wavelengths near 10 μm
e. to compensate for losses in plastic fibers

11. What types of fibers can be used at wavelengths longer than 2 μm?
a. fused silica, fluoride, and silver halide
b. plastic, fused silica, and fluoride
c. fluoride, chalcogenide, and silver halide
d. plastic, fused silica, and chalcogenide
e. only plastic-clad silica

12. What is the main advantage of graded-index plastic fiber over other plastic fibers?
a. higher bandwidth
b. uses less plastic
c. more flexible
d. as clear as graded-index glass fiber
e. larger core diameters

13. What is a holey fiber?
a. a fiber made from a flawed preform that contains tiny air bubbles, which scatter light from the sides
b. a fiber that guides light through holes in a plastic with a very low refractive index

c. a photonic fiber in which the glass contains tiny holes that block light transmission at certain wavelengths

d. a theoretical proposal, which has yet to be demonstrated

e. another name for a hollow optical waveguide used to transmit the 10.6-μm wavelength of carbon-dioxide lasers

14. In what way is a planar waveguide like an optical fiber?

a. It guides light through a region of high refractive index by total internal reflection.

b. It has attenuation below 0.5 dB/km at 1.3 to 1.6 μm.

c. It is a flexible structure.

d. It has a plastic coating to protect it from scratches.