CHAPTER

30

Imaging and Illuminating Fiber Optics

About This Chapter

Communications and sensing were latecomers in the world of fiber optics. The early developers of fiber optics were interested in transmitting images through bundles of fibers. Fibers developed for imaging differ greatly from those designed for communications because different considerations affect performance. This chapter is about fiber-optic imaging and the related field of illumination. Some fiber-optic illumination uses *bundles* of fibers to deliver light, but much illumination is with single fibers. This chapter covers these diverse noncommunication applications of fiber-optic devices in medicine, industry, and military systems.

Basics of Fiber Bundles

As you read in Chapter 1, optical fibers were invented for imaging and were soon applied to illumination as well. Imaging requires a bundle of fibers, one to carry each point on the image. For imaging, the bundle must be *coherent*, which in this case means that the ends of the fibers must be arranged in the same way on both ends of the bundle. Project an image onto one end of a coherent bundle, and the same image appears on the other end.

To visualize how a coherent bundle works, start with a handful of drinking straws all the same length. With a little care, you can hold the straws so they are aligned parallel to each other. Look through the straws at a printed page, and you'll see the words through the array of little pipes. The smaller the straws, the smaller the bit of the page you see through each one. Individual fibers are like individual straws, but they are much thinner and far more flexible. Fibers guide light by total internal reflection, but straws only transmit light straight along their axes.

Coherent bundles have the fibers in the same places on both ends.

There are two basic families of fiber bundles, each developed for distinct applications. Long, thin flexible bundles of loose fibers are used to examine or deliver light to otherwise inaccessible places. Important examples are the flexible endoscope threaded down a patient's throat to examine the stomach, and the flexible colonoscope used to examine the colon. Industrial counterparts are used to inspect the interiors of engines. Imaging requires coherent bundles, but illumination normally is done with bundles in which the fibers are randomly aligned. For most imaging and illumination applications, flexibility is important.

A second family is rigid fiber bundles in which the fibers have been fused together to make a solid block. Processing retains the light-guiding structure of the individual fibers that are aligned end to end in the bundle. Usually they are shorter and fatter than flexible bundles. These fused bundles can be used as optical devices for transmitting or magnifying images piece by piece, as well as for some types of inspection and for some other optical applications.

Both types of fiber bundles are based on step-index multimode fibers with thick cores and thin claddings. This structure means that light reaching the input face of the bundle is most likely to fall on a core, so it is transmitted to the other end of the bundle. Individual fibers may be drawn quite thin, but the ratio of core to cladding thickness remains unchanged. The difference between core and cladding index is larger than in communication fibers, so the cores can be drawn finer and still transmit multiple modes of light. Single-mode transmission is not desirable in imaging or illumination fibers because it limits how much light they can collect at the face of the bundle.

Making Fiber Bundles

Long, thin flexible bundles are made by winding a fiber around a spool and cutting through a glued region.

Figure 30.1 shows one way to make coherent fiber bundles. Start by looping a single long, thin fiber many times around a spool, glue the fibers together in one spot and remove them from the spool. Then cut through the glued region. This gives a flexible bundle, with fibers loose in the middle and fixed on both ends. Because the two ends were originally adjacent to each other, the fibers are all in the same positions.

This approach is simple in concept and dates back to the mid-1950s, when it was used to make the first flexible fiber bundle. However, it is a demanding process and is difficult when using very thin fibers, which are likely to break.

Fused imaging bundles are drawn jointly into solid rods.

An alternative approach is to draw many fibers simultaneously to finer and finer diameters in a series of stages. The first step is to draw a step-index fiber with a diameter about 2.5 mm. These fibers are easy to handle, and a group of them—typically 37 to 169—are grouped together, heated until they soften, and stretched out into a rigid *multifiber* about 2 mm in diameter, as shown in Figure 30.2. Then a number of multifibers (typically 61 to 271) are packed together, heated, and drawn again to produce a rigid fiber bundle, containing many thousands of fibers. Each fiber in the final bundle is about 3 to 20 μm in diameter. The number of fibers drawn together in each step is chosen to make patterns that pack together well.

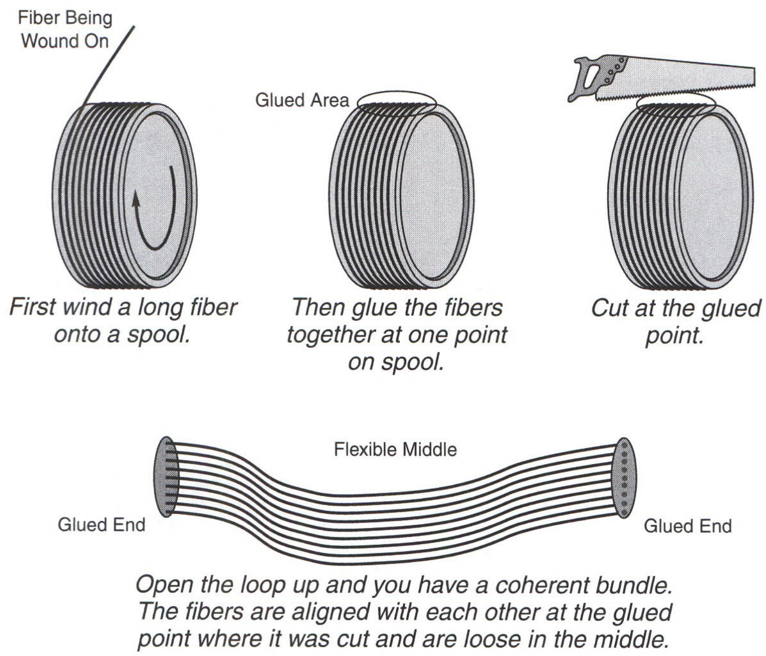


FIGURE 30.1
Flexible bundle made by winding fiber around a spool.

The *fused fiber* bundle process can be used to make flexible bundles, with a few important changes. Look carefully at Figure 30.2, and you will note that the large core is surrounded by two rings of cladding. One is the conventional low-index cladding that confines light to the core in all fibers. The composition of the other depends on the type of bundle being made.

For rigid bundles, that outer layer is a dark absorptive glass that keeps light from leaking between the cores in the bundle. A certain amount of light always leaks into the fiber cladding. Usually this stays in the inner part of the cladding, but for imaging bundles the cladding is quite thin. If the claddings were all fused together—as they would be without the dark glass—the light could freely disperse through the whole bundle within the fused cladding glass. Then it could leak back into the cores and degrade the image.

For flexible bundles, that outer layer is a glass that is soluble in acid. Manufacturers cover the ends of the rigid rod and then dip the whole fused bundle into an acid that dissolves away that leachable layer in the middle of the rod, leaving a flexible bundle of many thin fibers, which are arranged so their ends are aligned for imaging.

Individual fibers in a flexible coherent bundle can be small, but not quite as small as in a fused bundle. Some performance limits of flexible bundles are comparable to those of rigid bundles. When flexible bundles are used, an added concern is breakage of individual fibers, which does not occur in fused bundles. Each fiber break prevents light transmission from one spot on the input face. The loss of a single fiber is not critical, but as more fibers break, the transmitted light level drops and resolution can decline as well. Eventually breakage reaches a point where the image-transmitting bundle is no longer usable. Plastic fibers can reduce the breakage problem, but have other limitations.

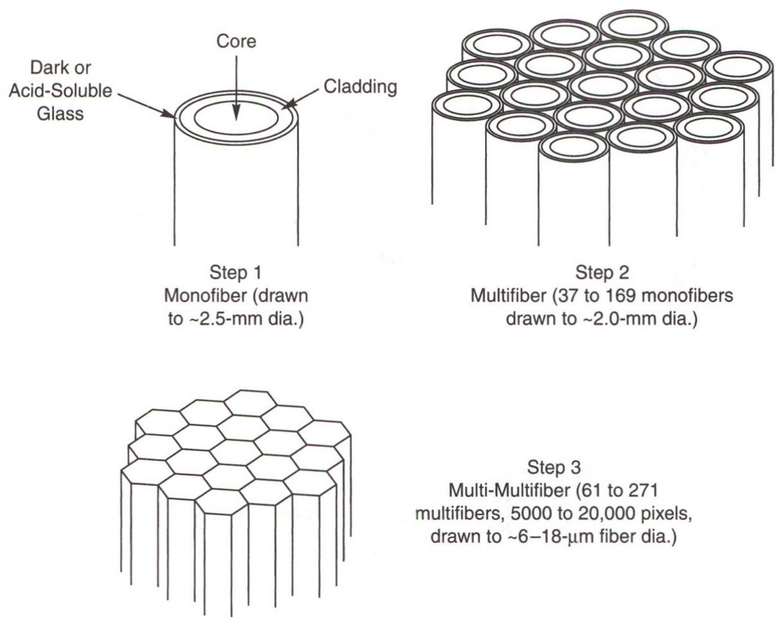


FIGURE 30.2
Stages in making a fiber bundle. (Courtesy of Schott Fiberoptics)

Randomly aligned bundles serve as "light pipes."

Randomly aligned bundles are made by collecting many fibers into a bundle, much like collecting strands of spaghetti. This would be very difficult if the fibers were as thin as those in imaging bundles, but such fine fibers are not needed because the resolution does not matter; random bundles serve purely as "light pipes." Typically, random bundles are made of fibers with diameters in the 100-μm range, which are flexible enough to bend freely with minimum fiber breakage.

Imaging and Resolution

Resolution is a crucial issue in an imaging fiber bundle. Figure 30.3 shows how an image is carried from one end of the bundle to the other. Each fiber core carries its own segment of the image to the other end, maintaining its alignment.

Bundle resolution depends on the core sizes of the fibers it contains.

To visualize what happens, imagine that each fiber core captures a chunk of the image and delivers it to the other end of the bundle. This process averages out any details that fall within a single core. For example, if the input to a single core is half black and half white, the output will be gray. Thus, the fiber cores must be small to see much detail. For a stationary fiber bundle, the resolution is about half a line pair per fiber core, meaning two fiber core widths are needed to measure a line pair. Numerically, that means 10 μm fiber cores could resolve 50 line pairs per millimeter (1 line pair per 20 μm). Imaging bundles have fiber cores as small as 3 μm. Resolution is significantly higher—about 0.8 line pair per fiber core diameter—if the fiber bundle is moving with respect to the object.

Before you wonder too much about the quality of fiber-bundle images, you should realize that fiber cores typically are about 10 μm. If that was the case, the letter A in Figure 30.3 would be only 60 μm high, less than $\frac{1}{16}$ mm tall. That's many times smaller than the finest

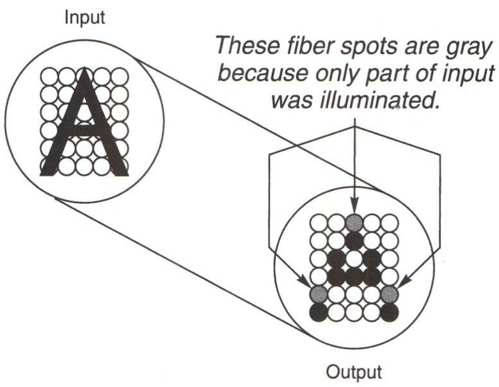


FIGURE 30.3
Image transmission through a fiber bundle.

of fine prints used in legal documents. You have to look very hard, and may need a strong magnifying lens to see the individual fiber spots on a good imaging bundle.

Cladding Effects

The cores conduct light in fiber bundles, but they are surrounded by cladding layers. Bundles are made with thin cladding layers, but some light must fall onto the cladding rather than the core. The fate of that light depends on the bundle design. Fibers in rigid bundles have a dark outer cladding layer that absorbs light so that little can pass between fiber cores. Light that leaks out of the cores of individual fibers in flexible bundles cannot easily enter other fibers. However, neither type can completely prevent light from leaking between fibers.

Light that falls into fiber claddings in bundles is lost, but typically 90% falls onto fiber cores.

Most light entering the cladding is lost, which can limit transmission efficiency. This makes the fraction of the surface made up by fiber cores an important factor in a bundle's light-collection efficiency. That is, the collection efficiency depends (in part) on the *packing fraction*, defined as

$$\text{Packing fraction} = \frac{\text{total core area}}{\text{total surface area}}$$

A typical value is around 90%.

Transmission Characteristics

Fiber bundles need to carry light only a few meters, so they do not have as low attenuation as communication fibers. Typical attenuation of bundled fiber is around 1 dB/m, thousands of times higher than that of communication fibers at 1550 nm.

Typical attenuation of bundled fiber is around 1 dB/m.

Likewise, operating wavelengths differ. Visible light is needed for imaging and illumination, and even for other applications the short distances make it unnecessary to operate at wavelengths where fibers are most transparent. Glass fiber bundles are typically usable at wavelengths of 400 to 2200 nm, and special types made from glass with good ultraviolet transmission are usable at somewhat shorter wavelengths. Plastic fibers are usable at visible wavelengths, 400 to 700 nm. Some special-purpose bundles are made of other materials, but they are not widely used.

Bundled fibers are step-index multimode types with large NA.

Bundled fibers generally have higher numerical apertures than communication fibers, because light-collection efficiency is critical and pulse dispersion is irrelevant. The relatively large difference between core and cladding index gives bundled fibers typical NAs of 0.35 to 1.1. The same holds true for large-core single fibers used in illumination; larger NAs are better because they boost light-collection efficiency.

Optics of Bundled Fibers

Some simplifications valid for communications are not valid for bundled fibers.

The underlying principles of fiber optics are the same if fibers are separate or bundled. However, earlier descriptions of communication fibers relied on some simplifications of optical principles. These simplifications don't always work for bundles or other noncommunication fibers. It's time to go back and face some complications that don't affect communications through single fibers.

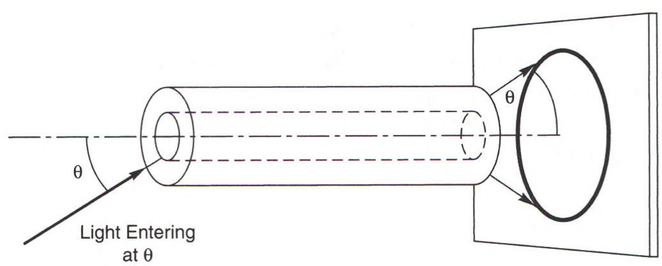
Light Rays in Optical Fibers

Light rays are an important concept in understanding how optical devices affect light. Earlier you learned how lenses worked, and saw a simple explanation of how total internal reflection of light rays guides light down a fiber. Those explanations are true as far as they go, but the behavior of light rays in a fiber is a bit more complicated.

As shown in Figure 30.4, a light ray that enters the fiber at an angle θ to the fiber axis will later emerge at roughly the same angle to the fiber axis, as long as the ray is within the fiber's acceptance angle. However, the ray may not emerge in the same direction; it will be part of a ring of light at roughly the original angle to the fiber axis. *Roughly* is the operative word, because imperfections in the fiber and other factors cause the light to emerge in a ring of angles centered on θ.

This does not conflict with what you learned about communication fibers. There the light ray was only an example of the path light could follow. In looking at multimode fibers, we considered the light rays and the modes collectively, never worrying about individual mode patterns. Generally there's no reason to worry about individual modes in multimode fibers.

FIGURE 30.4
Light rays emerge from a fiber in a diverging ring.



One other thing should be pointed out: step-index fibers with constant diameter cores do not focus light. (As you will see later, both tapered and graded-index fibers can focus light passing along their lengths.) All light emerges from a step-index multimode fiber at roughly the same angle that it entered, not at a changed angle, as would happen if it did focus light. As long as the fiber's sides and ends are straight and perpendicular to each other, a single step-index multimode fiber or a bundle of them—like a flat window pane—cannot focus light.

Step-index fibers with constant size cores do not focus light.

This has one important practical consequence that you'll discover the first time you look through an imaging bundle. You have to put the distant end up very close to what you want to see, or the image will become blurred. You see the image on the near end of the bundle because light travels straight through each fiber. For the light from the object to enter the right collecting fibers, it must either be focused onto the collecting end or the collecting end must be very close to the object, so light can't slip into other fibers.

If the fiber's output end is cut at an angle not perpendicular to its axis, light entering at an angle θ still emerges in a cone, but the center of the cone is at an angle to the fiber axis. If the slant angle (from the perpendicular) is a small value ϕ, the angle β by which the rays are offset is approximately

$$\beta = \phi(n - 1)$$

where n is the refractive index of the fiber core.

Tapered Fibers

I assumed earlier that fiber cores are straight and uniform, but they could also be tapered (although not over long distances). Figure 30.5 shows what happens to a light ray entering a tapered fiber at an angle θ_1. If the ray meets criteria for total internal reflection, it is confined in the core. However, it meets the core-cladding boundary at different angles on each bounce so each total internal reflection is at different angles from the axis. The result is that it emerges from the fiber at a different angle, θ_2. If input core diameter is d_1 and output core diameter is d_2, the relationship between input and output angles is

Tapered fibers magnify or demagnify objects seen through them. Tapered fibers are used in bundles.

$$d_1 \sin \theta_1 = d_2 \sin \theta_2$$

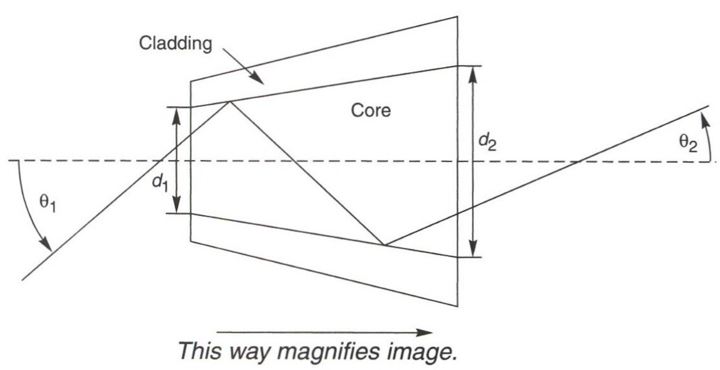


FIGURE 30.5
Light passing from the narrow to the broad end of a tapered fiber.

The same relationship holds for the fiber's outer diameter as long as core and outer diameter change by the same factor, d_2/d_1.

As a numerical example, suppose the input angle is 30° and the taper expands diameter by a factor of 2. The sine of the output angle θ_2 would be

$$\sin\theta_2 = \frac{d_1}{d_2}\sin\theta_1 = \frac{1}{2}(\sin 30°) = 0.25$$

Thus θ_2 would be about 14.5° and light exiting the broad end of a taper would emerge at a smaller angle to the fiber axis than it entered. Conversely, light going from the broad end to the narrow end would emerge at a broader angle.

Tapered bundles of fused fibers can be used as magnifiers if the narrow end is placed on a page and you look at the top side. Each fiber expands or shrinks the spot of the image it transmits by the same amount. The eye sees this as each spot being spread over a larger area at the large end of the taper. This increases the size of the image, but not the clarity, because the transmitted image has only as many picture elements as the narrow end of the bundle.

Focusing with Graded-Index Fibers

Graded-index fibers can focus light in certain cases.

Unlike step-index fibers, graded-index fibers can focus light in certain cases. This does not make graded-index fibers useful for image transmission or other fiber-bundle applications, but short segments of graded-index fibers can function as focusing components in some optical systems.

In Chapter 4, you saw that light follows a sinusoidal path through graded-index fiber. When you looked at how a cone of light was transmitted through a long fiber, you saw output as a cone of the same angle. Now look instead at the path of an individual ray through a short segment of graded-index fiber, shown in Figure 30.6, and compare that with the path of a light ray in step-index fiber.

There is an important but subtle difference. Total internal reflection from a step-index boundary keeps light rays at the same angle to the fiber axis all along the fiber. However, graded-index fibers refract light rays, so the angle of the ray to the axis is constantly changing as the ray follows a sinusoidal path. If you cut the fiber after the light ray has gone

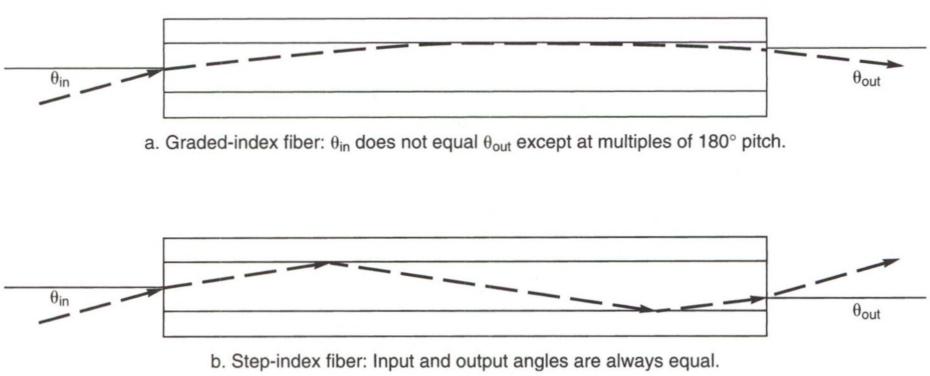


FIGURE 30.6 *Rays in graded-index and step-index fibers.*

through 180° or 360° of the sinusoid, the light emerges at the same angle to the axis that it entered. However, if the distance the light ray travels is not an integral multiple of 180° of the sinusoid, it emerges at a different angle. This property allows segments of graded-index fiber to focus light.

In the design of *graded-index fiber lenses* (usually sold under the trade name *Selfoc*), the key parameter is the fraction of a full sinusoidal cycle that light goes through before emerging. That fraction is called the *pitch.* A 0.23-pitch lens, for instance, has gone through 0.23 of a cycle, or $0.23 \times 360° = 82.8°$. The value of the pitch depends on various factors including refractive-index gradient, index of the fiber, core diameter, and wavelength of light.

Pitch is a critical parameter of graded-index lenses.

Although the lenses are segments of fiber, they are short by fiber-optic standards, just a few millimeters long. Thus, they can be considered as rod lenses as well as fiber lenses.

These tiny fiber lenses are used in a variety of applications. Some are used in fiber-optic transmitters to focus light from an LED or diode laser so that it can be coupled efficiently into a fiber. Others are used in optical systems such as fax machines and scanners. A linear array of fiber-optic microlenses can focus light reflected from a small area of a page onto a linear array of sensors that detect the light. Ideally each sensor collects light focused by one microlens.

Imaging Applications

Imaging covers a broad range of fiber-bundle applications. Most imaging systems use lenses and conventional optics, but fiber bundles do a better job in certain cases. Imaging bundles often are better for reaching into inaccessible places, from the inside of the human body to the interior of machines. Let's look briefly at these applications.

Medical Endoscopes

The most important use of imaging fiber bundles is to allow physicians to look inside the body without surgery. This is done with special-purpose coherent fiber bundles called *endoscopes*, which are up to a couple of meters long. Versions called *gastroscopes* are threaded down the throat to examine the stomach. *Colonoscopes* are versions designed to examine the colon. Short rigid bundles are used for some medical examinations because of their high resolution, but flexible types are preferred for most purposes because they are easier to insert and manipulate through body orifices.

Endoscopes allow physicians to look inside body cavities.

Traditional fiber-optic endoscopes use one set of fibers to transmit light inside the body and a separate set to collect and view the reflected light. Lenses on the end of the instrument focus light onto the fiber bundle, so it does not have to be pressed against tissue. Endoscopes may include surgical tools to treat lesions in the stomach or colon. Some newer endoscopes use fibers to transmit light into the body, but collect light with a miniature CCD (charge-coupled device) imaging camera that is inserted into the body.

Some endoscopes include fibers capable of transmitting high laser powers as well as illuminating light, so physicians can perform laser surgery. For example, a surgeon performing microsurgery on the knee could make an incision to insert an endoscope. After viewing the area to be treated, the surgeon could look through the viewing fibers to align the instrument, look away, then fire laser pulses to treat the lesion. (Surgeons avoid watching during laser pulses to protect their eyes.) After each set of laser pulses, the surgeon looks back to check progress.

Industrial Inspection Instruments

Fiber-optic imaging instruments also are used in industry to inspect dangerous or otherwise inaccessible areas. Lenses on the end of the instrument focus light onto the end of the bundle. Flexible fiber bundles could be used in this way to examine the inside of a storage tank that has only one small opening. Fiberscopes also could examine the interiors of machinery.

Faceplates

Image transmission does not have to be over a long distance. Another common application of fiber-optic image transmission is the fiber-optic *faceplate*, a thin slice of a coherent bundle in which individual fibers are only a fraction of an inch long. Faceplates are cut from longer, fused coherent bundles like slices of salami, although generally one or both surfaces are not flat.

Fiber-optic faceplates transfer light between surfaces of different shapes.

The job of a faceplate is to transmit an image between two stages of an imaging system that must amplify weak input light to generate a clearly visible image. It is typically used in military systems where faint light is amplified so soldiers can see an image of the scene. Image amplifiers may go through multiple stages, each amplifying the input light by a certain factor. Infrared light is used to generate a visible image. The output stages often are strongly curved screens that can't be focused onto flat input devices without distortion. A faceplate can convert the curved output screen to a flat surface, as shown in Figure 30.7. If the input of the next stage works best with a curved screen, the other side of the faceplate can be curved to match.

The big advantage of the faceplate is that it transfers light very efficiently between two surfaces that otherwise can't be butted face to face. Suppose, for example, you're trying to

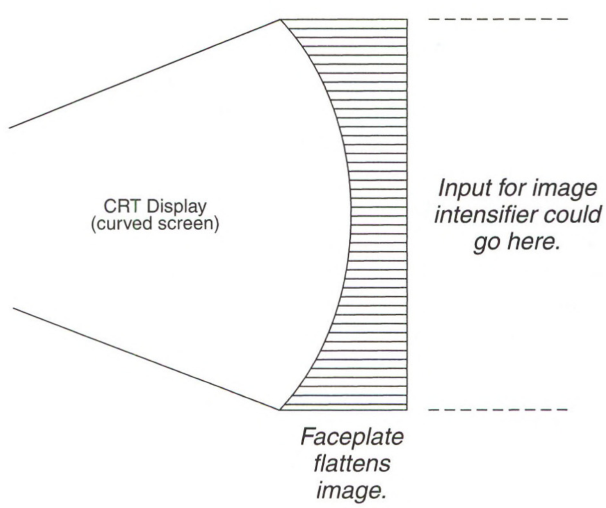


FIGURE 30.7
A fiber-optic faceplate transfers light from a curved display tube.

detect some very weak light from a scene illuminated only by starlight. A single-stage image-intensifier camera makes the image brighter, but not bright enough to see clearly. You want to add a second stage, but the output of the first stage is on a curved screen. Put a fiber faceplate between that output and the input of the second-stage tube and you lose very little light. An imaging lens would lose much more light. The first fiber-optic faceplates were developed for such military imaging tubes, and they remain in use for newer equipment.

Faceplates also can help flatten the curved image generated by some display screens, correct for distortion, and make the display appear brighter by concentrating light toward the viewer.

Image Manipulation, Splitting, and Combining

Coherent fiber bundles can manipulate images.

Coherent fiber bundles can do more than just transmit images; they can also manipulate them. Twisting a coherent bundle by 180° inverts the image. You can do the same with lenses, but a fiber-optic image inverter does not require as long a working distance, which is of critical importance in some military systems. (Some image inverters are less than 1 in. long.)

Another type of image manipulation possible with fused fiber optics is the image combiner and splitter shown in Figure 30.8. This is made by laying down a series of fiber-optic ribbons, alternating them as if shuffling a deck of cards. One ribbon goes from the single input to output 1, the next from the input to output 2, the next to output 1, and so on. Put a single image into the input, and you get two identical (but fainter) output images. Put separate images into the two outputs, and you get one combined image.

Similar ideas could be used in other image manipulators or in devices to perform operations on optical signals. However, before you rush out for a patent application on your

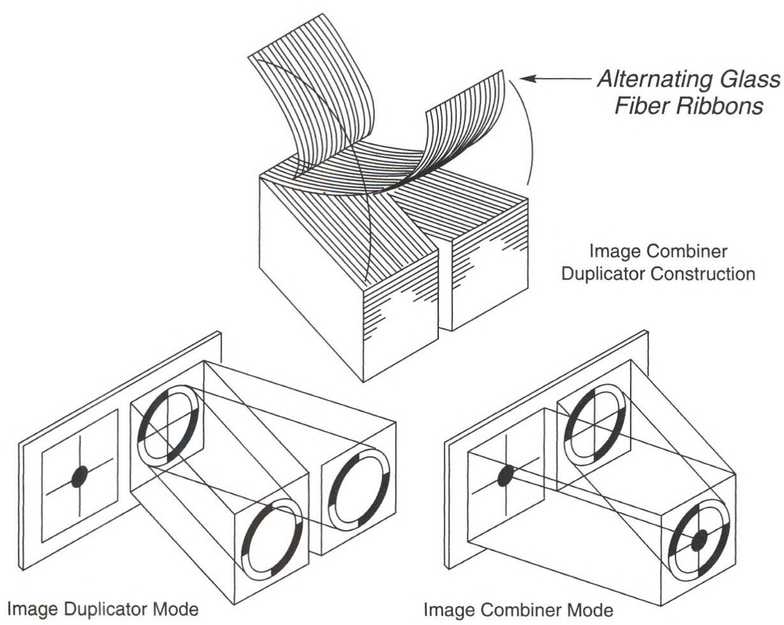


FIGURE 30.8
A fiber-optic image combiner and duplicator. (Courtesy of Galileo Electro-Optics Corp.)

own bright idea, you must face the ugly reality of cost. Manufacture of the fiber-optic image combiner in Figure 30.8 requires time and exacting precision, making it too expensive for most uses. Image inverters are used in some systems, but only where less costly lens systems won't do the job.

Light Piping and Illumination

Light piping delivers light through optical fibers.

Illumination and light piping are the simplest applications of optical fibers. *Light piping* is simply the transfer of light from one place to another by guiding it through one or more optical fibers. It doesn't matter how the fibers are arranged, as long as they deliver the light to the desired place. Thus fibers need not be arranged in the same way at both ends of an illuminating bundle. A single fiber may suffice for many applications.

Light piping for illumination is merely the delivery of light to a desired location. Why bother with optical fibers to do a lightbulb's job? A flexible bundle of optical fibers can efficiently concentrate light in a small area, or deliver light around corners to places it otherwise could not reach, such as inside machinery. A fiber bundle also can deliver light without the heat generated by incandescent bulbs, and without bringing electric current near the illuminated spot. This can be important in locations where bulbs and current can't be used because of explosive vapors or heat-sensitive materials. Fiber bundles also can be divided to deliver light from one bulb to many separate places. Light-piping fibers also can serve as indicators, to verify that an important bulb is operating.

Another important application of light piping is *optical power delivery*, transmitting laser beams for medical treatment or industrial material working. Conventional laser systems use lenses or mirrors to focus beams onto the desired spots. These systems use large optics, making them bulky, which is cumbersome for fine tasks such as delicate surgery. Optical-fiber beam delivery systems are much easier to manipulate. Some are designed for surgeons to use with their hands; others are built for robotic control in factories.

Single large-core fibers can deliver powerful laser beams.

Single large-core step-index fibers are best for many power delivery applications as long as the input light can be concentrated into a single core. Low-loss, large-core silica fibers have surprisingly high power transmission capabilities, and can easily carry tens of watts over a few meters. Illuminating bundles transmitting lower powers can use smaller-core, step-index fibers of glass or plastic, as long as light intensities and heat levels are low.

If all fibers in an illuminating bundle go to the same place, they illuminate a single area. If they are directed to different places, they can form a patterned image, such as the fiber-optic sign shown in Figure 30.9. All the fibers collect input light from one bulb, then are splayed out to show the desired pattern. Diffusing lenses at the fiber ends can spread light to make large, easily visible spots. (The WALK sign makes a good example, but it's not widely used.)

A bundle of fibers spreading out from a single illuminating bulb can make a sparkling display, like the one that introduced me to fiber optics 30 years ago. Then they were a rarity, but today they're commonplace. At Christmas, you can buy little fiber splays to attach to Christmas tree lights, and at a recent trade show one company was handing out little plastic flashlights with a splay of plastic fibers that sparkled with colors at their tips. I couldn't resist and picked one up.

FIGURE 30.9
A fiber-optic sign.

What Have You Learned?

1. Rigid or flexible bundles of optical fibers can transmit images if the fibers that make them up are properly aligned at the ends (coherent). Rigid bundles are made of fibers fused together; flexible bundles contain separate fibers bonded at the ends. Resolution is limited by the size of the fiber cores, typically around 10 μm.
2. Bundles of fibers in which the ends are not aligned with one another serve as "light pipes" to illuminate hard-to-reach places. The bundle can be broken up on one end to form an image or display (e.g., a WALK sign).
3. Light that falls into fiber claddings in bundles is lost, but typically 90% falls onto fiber cores.
4. Imaging and other short-distance fibers generally have much higher attenuation than communication fibers. Bundled fibers are step-index multimode types with large NA.
5. Step-index multimode fibers do not focus light, but segments of graded-index fiber do focus light and can serve as lenses. Tapered fibers magnify or demagnify objects seen through them; they are used in bundles.
6. Thin fiber-optic faceplates are used to concentrate light from certain displays in a particular direction. They are used with certain high-performance imaging tubes, but not for ordinary cathode-ray tubes.

7. Coherent fiber bundles can invert, split, and combine images.
8. Endoscopy is the use of coherent fiber bundles to view inside the body without surgery.
9. Large-core fibers can deliver laser power for medicine or materials-working.

Further Reading

Schott Fiberoptics, "Introduction to Fiber Optic Imaging," *http://www.schottfiberoptics.com/introfiber.html*

Walter Siegmund, "Fiber Optics," Chapter 13 in Walter G. Driscoll, ed., *Handbook of Optics* (McGraw-Hill, 1978)

Questions to Think About

1. Many laser printers have resolution of 600 dots per inch. Could you spot those dots with a bundle of 10-μm fibers? (Assume that resolution in line pairs is equivalent to dots per inch.)
2. Using the criterion that the finest possible resolution corresponds to half a line pair per fiber core diameter, what is the largest core fiber that could resolve 300 line pairs per inch?
3. A typical packing fraction for bundled fiber is 90%. Assuming that the fiber cores are 10 μm and you can neglect space between fibers (not a good assumption, but it makes the math manageable), what is the outer diameter of each fiber and how thick is the cladding?
4. Given the same assumption about neglecting the spacing between fibers, what would be the packing fraction for a bundle assembled from 100/140 step-index multimode fibers?
5. You are trying to deliver a 50-W laser beam through a 3-m length of fiber with attenuation of 10 dB/km. How much power is lost in the fiber?
6. If you put a fiber-optic image inverter flat on a printed sheet of paper, you can read the inverted letters through the taper. You're seeing reflected light. How did it reach the paper?

Chapter Quiz

1. Which of the following statements is false?
   a. Coherent fiber bundles can transmit images.
   b. Coherent fiber bundles can focus light.

c. Graded-index fiber segments can focus light.

d. Imaging fiber bundles contain step-index multimode fibers.

2. A graded-index fiber lens has a pitch of 0.45. How much of a sinusoidal oscillation cycle do light rays experience in passing through it?

a. 27°

b. 45°

c. 81°

d. 162°

e. 180°

3. What does it mean to say that a fiber bundle has a packing fraction of 90%?

a. 90% of the fibers are intact.

b. 90% of the input surface is made up of optical fibers.

c. 90% of the input surface is made up of fiber core.

d. 90% of the input surface is made up of fiber cladding.

e. The bundle transmits 90% of the incident light through its entire length.

4. You want to resolve an image with 8 line pairs per millimeter. In theory, what is the largest fiber core size that you could use in a stationary coherent bundle?

a. 8 μm

b. 50 μm

c. 62.5 μm

d. 100 μm

e. 125 μm

5. Endoscopes used in medicine to view inside the body

a. usually are flexible fiber bundles.

b. sometimes transmit laser beams to treat disease.

c. can examine the stomach or colon.

d. all of the above

e. none of the above

6. Fiber-optic faceplates are

a. specialized sensors that detect temperature variations across a surface.

b. thin, rigid fiber bundles used to transfer light efficiently in image intensifiers.

c. assemblies of graded-index fiber lenses that focus light in photocopiers.

d. used on most television sets.

7. Average attenuation of bundled fibers is

a. 0.5 dB/km.

b. 1 to 5 dB/km.

   c. 10 to 100 dB/km.
   d. around 1 dB/m.

8. What types of fibers are used in imaging bundles?
   a. step-index multimode
   b. graded-index multimode
   c. step-index single-mode
   d. all of the above

9. The practical use of fiber-optic bundles to manipulate images is limited by what?
   a. poor resolution
   b. high attenuation
   c. fragility
   d. high cost

10. Which of the following is the most important advantage of random fiber bundles over coherent bundles for illumination?
   a. flexibility
   b. low cost
   c. size
   d. durability