CHAPTER 13

Connectors and Splices

About This Chapter

Connectors and splices link the ends of two fibers both optically and mechanically. The two are not interchangeable. A *connector* is mounted on the end of a cable or optical device so it can be attached to other cables or devices. Like electrical connectors, fiber-optic connectors can be plugged and unplugged. In contrast, *splices* are permanent junctions between a pair of fiber ends. The cables attached to your television and stereo have connectors on the end so they can be plugged into other components. Splices are the optical equivalent of permanent solder joints.

This chapter starts by explaining their applications and their common operating principles, then describes connector properties and types, and splicing. Chapter 14 will cover couplers, which in fiber optics are quite different from connectors and splices.

Applications of Connectors and Splices

Connectors and splices both make optical and mechanical connections between a pair of fibers. Their job is to transfer light efficiently and hold the fibers together. They differ in how they do that job, and as a result they have different places in fiber-optic systems. You can think of connectors as being designed for connections that may have to change, while splices are used for permanent connections.

Electrical connectors are common in modular electronic, audio, or telephone equipment, although you may think of them as plugs and jacks. Their purpose is to connect two devices electrically and mechanically, such as a cable and a stereo receiver. A plug on the cable goes into a socket in the back of the receiver, making electrical contact and holding the cable in place. Both the electrical and mechanical junctions are important. If the cable falls out, it can't carry signals; if the electrical connection is bad, the mechanical connection doesn't do any good. (You'll understand the problem all too well if you've ever tried to find an intermittent fault in electronic connectors.)

Connectors make temporary connections among equipment that may need to be rearranged.

Fiber-optic connectors are intended to do the same job, but the signal being transmitted is light through an optical fiber, not electricity through a wire. That's an important difference because, as you learned earlier, the way light is guided through a fiber is fundamentally different from the way current travels in a wire. Electrons can follow a convoluted path through electrical conductors (wires) if the wires make good electric contact somewhere. However, fiber cores must be precisely aligned with each other and touch to transfer optical signals efficiently—just how precisely you'll see later.

Electrical connectors are used for audio equipment and telephones because the connections are not supposed to be permanent. You use fiber connectors for the same reason. For permanent connections, you splice or solder wires, and you splice optical fibers. Permanent connections have some advantages, including better mechanical stability and—especially for fiber optics—lower signal loss. However, those advantages come at a cost in flexibility; you don't want to cut apart a splice each time you move a computer terminal or telephone.

Splices and connectors are used in different places.

Fiber-optic connectors and splices are far from interchangeable. Connectors are normally used at the ends of systems to join cables to transmitters and receivers. Connectors are used in patch panels where outdoor cables enter a building and have their junctions with cables that distribute signals within the building. They are used where configurations may need to be changed, such as at telecommunication closets, equipment rooms, and telecommunication outlets. Examples include the following:

- Interfaces between devices and local area networks
- Connections with short intrabuilding data links
- Patch panels where signals are routed in a building
- The point where a telecommunication system enters a building
- Connections between networks and terminal equipment
- Temporary connections between remote mobile video cameras and recording equipment or temporary studios

Splices are used where junctions are permanent or where the lower loss of splices is critical. For example, long cable runs are spliced because the cable segments should never need to be disconnected. Splice loss is lower, and splices are smaller and fit into cables better. Splices generally are stronger, and with the right equipment are easier to install in the field.

In practice, this means that you usually put connectors on the ends of cables, and splices in the middle. Broken cables are repaired by splicing the fibers and mending the cable in the field. Connectors can be installed in the field or in the factory, but factory installation is easier. Sometimes the two techniques are used together to speed installations. For example, a cable may be connected to equipment in a building by splicing a fiber from the cable to a fiber pigtail attached to a factory-mounted connector.

The distinction between connectors and splices is not always a sharp one. Certain types of splices that hold fibers together mechanically can be taken apart and reused. However, you can't simply unsnap the end of the cable from the splice, as you can remove a phone cable from a wall jack. Rather it's more like opening up the wall jack and unscrewing the connections to the house wiring.

Fiber-to-Fiber Attenuation

The same basic considerations apply to transferring light between fibers in both connectors and splices. We will cover these first for connectors, then recall these principles when we discuss splices. To keep things simple, we will talk mostly about splices or connectors that transfer light between pairs of fibers, not between a fiber and a transmitter or receiver. However, the same principles apply whether light is being transferred from a light source into a fiber, or from a fiber into a detector.

The most important optical parameter of fiber connectors and splices is attenuation, the fraction of the signal power that is lost in passing through. *Loss* is measured in decibels for a mated pair of connectors or for a complete splice—that is, loss is the difference between the light entering the input fiber and the light exiting the output fiber. It isn't meaningful to talk about the loss of one connector or half a splice.

Typical attenuation is a fraction of a decibel for connectors and under 0.1 dB for splices. The loss depends on mechanical tolerances, and tends to be higher for small-core single-mode fibers than for larger-core multimode fibers. Generally loss is specified as a "typical" value rather than a maximum or minimum. Manufacturers specify attenuation for specific fiber types under the assumption that the same type of fiber is used on both sides of the splice or connector. As you will learn later in this chapter, mismatched fibers can have much higher loss.

Loss is the most important optical characteristic of connectors and splices.

The rest of this section is based on the assumption that a splice or connector joins the ends of two fibers. Connectors also can be mounted on transmitters, receivers, and other components, but although details differ, the principles are the same. This section concentrates on loss mechanisms that are important for connectors. The same principles apply to splices, but some effects are more important for one type of fiber connection than the other.

Connector and splice losses are caused by several factors, which are easier to isolate in theory than in practice. These factors stem from the way light is guided in fibers. The major ones are as follows:

- Overlap of fiber cores
- Alignment of fiber axes
- Fiber numerical aperture
- Fiber spacing
- Reflection at fiber ends

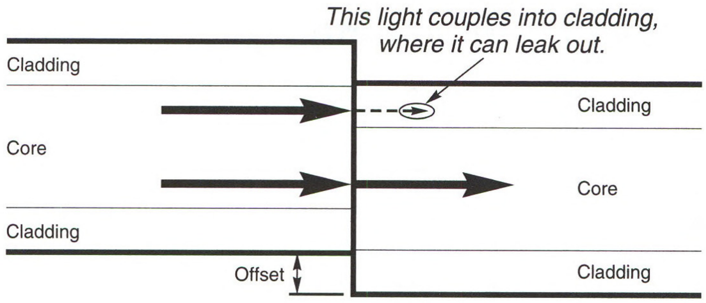
These factors interact to some degree. One—overlap of fiber cores—is really the sum of many different effects, including variation in core diameter, concentricity of the core within the cladding, eccentricity of the core, and lateral alignment of the two fibers.

Overlap of Fiber Cores

Offset of fiber cores by 10% of their diameter can cause a 0.6-dB loss.

To see how core overlap affects loss, look at Figure 13.1, where the end of one fiber is offset from the end of the other. For simplicity, assume that light is distributed uniformly in the cores of identical fibers and that the two fibers touch each other and are otherwise well

FIGURE 13.1
Offset fibers can cause loss.



aligned. The loss then equals the fraction of the input-fiber core area that does not overlap with that of the output fiber. If the offset is 10% of the core diameter, the extra loss is about 0.6 dB.

Mismatches of emitting and collecting areas also occur if core diameters differ. Suppose that the fibers were perfectly aligned but that the 50-μm nominal fiber core diameter varied within ±3 μm, a tolerance specified on a typical commercial graded-index fiber. With simple geometry, you can calculate the loss for going from a fiber with core diameter d_1 to one with core diameter d_2. (You also can use radius if you want—the factor of two differences from diameter cancels out—but usually core diameter is what's specified.) The relative difference in area is

$$\text{Loss} = \frac{(d_1^2 - d_2^2)}{d_1^2}$$

For the worst case, going from a fiber with a 53-μm core to one with a 47-μm core, the difference is a factor of 0.21. If light was distributed uniformly through the core, that fraction of the light, about 1 dB, would be lost. Fortunately things are rarely that bad, because light normally is concentrated toward the center of the core, and core diameter rarely varies as much as the maximum allowed by the specifications.

The same principles apply for single-mode fiber, but in that case the critical dimension is mode-field diameter, which is typically slightly larger than core diameter. The formula for relative loss is the same, but the tolerances are much tighter because single-mode fibers have much smaller cores. For example, a nonzero dispersion-shifted fiber has mode-field diameter of 8.4 ± 0.5 μm at 1550 nm. Although the diameter tolerance is very small, going from the largest fiber that meets these tolerances to the smallest can be costly in loss:

$$\text{Loss} = \frac{(8.9^2 - 7.9^2)}{(8.9)^2} = 0.21$$

The result is essentially the same as for the maximum variation in core diameter of 50-μm fiber, 0.21, or 1 dB. As with multimode fiber, things are rarely this bad in practice. A single-mode beam is most intense at the center of the core, and most specified single-mode connector losses are 0.1 to 0.5 dB.

It's vital to keep track of the fiber type. Serious problems result if the fiber types are mismatched, causing signals to go from a multimode fiber into a single-mode fiber. Going

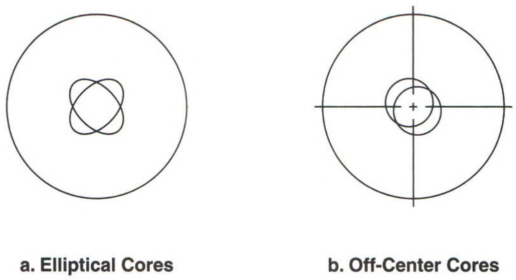


FIGURE 13.2
Losses arise when cores are elliptical or off center.

from a 62.5-µm graded-index fiber core to a single-mode fiber with 9-µm core results in a 97.9% drop in area, which produces a 17-dB loss if the light is distributed evenly. Even going from a 62.5-µm to a 50-µm core graded-index fiber reduces area 36%, corresponding to a 1.9-dB loss if the light is evenly distributed. As mentioned earlier, light is more concentrated at the center of the core, so losses usually aren't quite that bad, although still substantial.

Core mismatches also can arise from other factors. The core may be slightly elliptical or slightly off-center, as shown in exaggerated scale in Figure 13.2. Variations in the fiber cladding dimensions can lead to misalignment in aligning the core with other fibers.

Alignment of Fiber Axes

As you learned earlier, light must be directed straight along the fiber axis to be guided through a fiber. This is very different from electronic connections, which only need to make the attached wires touch each other for electrons to pass between them. This makes alignment of fiber axes critical to low optical connection loss.

Angular misalignment of fiber ends can cause significant losses.

Figure 13.3 shows how losses from fiber alignment increase with the angle between the two fibers. As the angle θ between the fibers increases, light from the first fiber enters the second fiber at a larger angle to the axis. Although a light ray passing directly along the axis may still fall within the fiber's acceptance angle, other rays can leak out. Losses are worst for fibers with small numerical apertures, while fibers with larger NAs can collect light entering over a wide range of angles. A good connection should align the two fibers very closely.

Fiber Numerical Aperture

Differences in NA between fibers also contribute to connection losses. If the fiber receiving the light has a smaller NA than the one delivering the light, some light will enter it in

Differences in NA can contribute to connection losses.

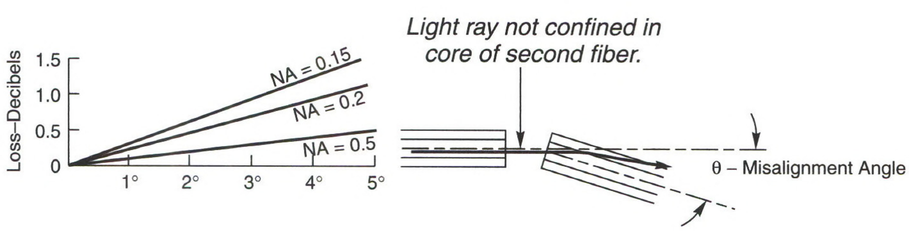


FIGURE 13.3
Misaligned fiber axes cause losses.

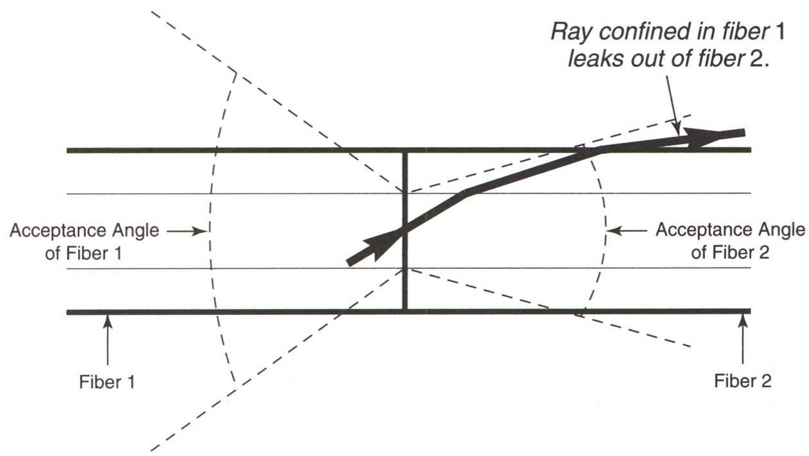


FIGURE 13.4
Mating fibers with different NAs can cause losses.

modes that are not confined in the core. That light will quickly leak out of the fiber, as shown in Figure 13.4. In this case, the loss can be defined with a simple formula:

$$\text{Loss (dB)} = 10 \log_{10}\left(\frac{\text{NA}_2}{\text{NA}_1}\right)^2$$

where NA_2 is the numerical aperture of the fiber receiving the signal and NA_1 is the NA of the fiber from which light is transmitted. The NA must be the measured value for the segment of fiber used (which for multimode fibers is a function of length, light sources, and other factors), rather than the theoretical NA. Note also that there is no NA-related loss if the fiber receiving the light has a larger NA than the transmitting fiber.

Spacing Between Fibers

Properly mated connectors leave no space between the fiber ends; the ends should touch each other. Two different mechanisms can cause loss if there is a gap between fibers—spreading of light emerging from the input fiber and reflection of light passing between air and glass. We'll talk about them separately, starting with the effect of light spreading.

Recall that light exits fiber in a cone, with the spreading angle—like the acceptance angle—dependent on the numerical aperture. The more the light cone spreads, the less light the other fiber can collect, as shown in Figure 13.5. The transfer losses increase as the NA of the input fiber increases because the higher NA causes the light to spread faster. The formula for the end-separation loss is rather involved, even when we assume the input and output fibers are identical.

$$Loss\,(dB) = 10\log_{10}\left(\frac{d/2}{d/2 + \left(S\tan\left(\arcsin\left(\frac{NA}{n_0}\right)\right)\right)}\right)$$

where d is core diameter, S is the fiber spacing, NA is the numerical aperture, and n_0 is the refractive index of the material between the two fibers. Figure 13.6 shows a plot of the loss for three different fibers, two with 50-μm cores and NAs of 0.2 and 0.4 and one single-

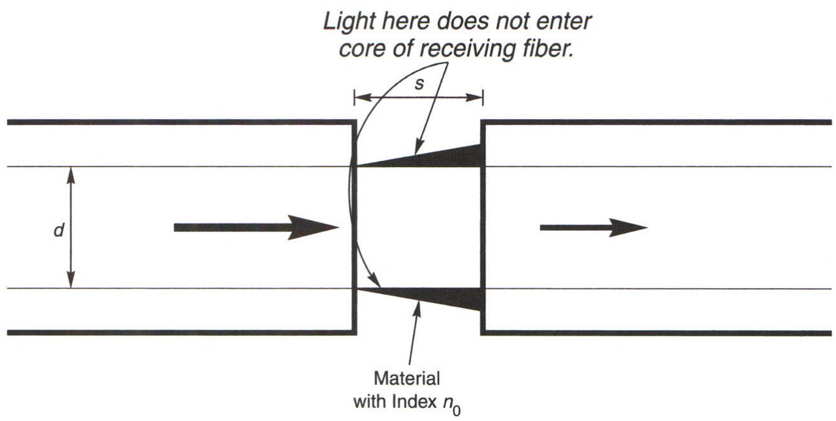


FIGURE 13.5
End-separation loss.

mode fiber with 0.15 NA; the material between the fibers is air, which has a refractive index almost equal to 1.

End-Reflection Loss

Leaving a space between fibers also causes end-reflection loss from a process called *Fresnel reflection,* which occurs whenever light passes between two materials with different refractive indexes. This loss occurs for all transparent optical materials, even ordinary window glass. If you look from a lighted room out into the dark, the reflections you see on the window come from Fresnel reflection. If you look carefully, you'll note they come from both the front and the back surfaces of the glass panes.

Fresnel reflection causes a 0.32 dB loss if there is a gap between fiber ends.

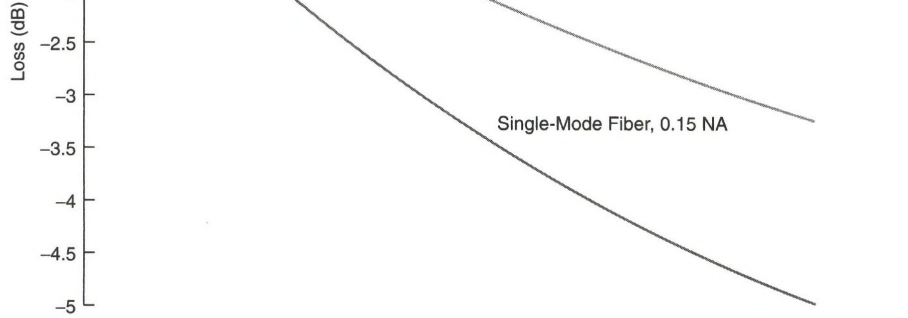


FIGURE 13.6
Loss caused by fiber spacing for three types of fiber, neglecting reflection loss.

Fresnel reflection loss depends on the difference in refractive index between the two materials. For light going from the core of a fiber with refractive index n_{fiber} into another material with refractive index n, this fraction of light reflected R is

$$R = \left(\frac{n_{\text{fiber}} - n}{n_{\text{fiber}} + n}\right)^2$$

This fraction increases with the index difference. For light going between glass and air, it is about 3.4% (0.15 dB) if the glass has a refractive index of 1.45 and 4% (0.18 dB) if the refractive index is 1.5. You can get the result directly in dB by using

$$\text{loss (dB)/surface} = -10 \log\left(1 - \left(\frac{n_{\text{fiber}} - n}{n_{\text{fiber}} + n}\right)^2\right)$$

These numbers give the loss per glass–air interface. The light suffers the same reflection in going from air back into glass, and there are two reflections in going through an interfiber gap from glass to air to glass. The total loss these two reflections cause as light goes through the gap is 0.30 to 0.36 dB, depending on the core index, with a typical value of about 0.32 dB.

This end-reflection loss is significant, generally greater than the end-separation loss. To avoid it, most connectors butt fiber ends together carefully to prevent damage to the fiber tips. In some older connectors, the space between fiber ends was filled with a transparent gel with refractive index close to that of the fiber.

Other End Losses

One dust particle can block most light transfer between a pair of single-mode fibers.

So far we have assumed that the fiber ends are cut and polished perfectly clean, and precisely perpendicular to the fiber axis. We all know things are never *that* good. The core of a single-mode fiber is less than 10 μm in diameter, so one dust particle could block virtually all light from the core. The fiber ends may not be perfect. Repeated mating and unmating of a connector can scratch the ends of fibers installed so they contact one another.

With all these loss mechanisms, it is no wonder why early developers were very worried about fiber-optic connections. (They developed multimode fiber because they did not think single-mode connections were feasible.) Tremendous progress has been made, but connection losses still can be significant in designing fiber-optic systems, as you will learn in Chapter 21. Typical losses of good single- or multimode connectors are 0.1 to 0.5 dB, while those of good splices typically are 0.1 dB or less.

The installation of a connector or splice is a critical variable, so mated fibers need to be tested. Repeated matings and unmatings can change attenuation by damaging fiber ends. Generally manufacturers specify a typical connector loss, along with changes they expect to be caused by mechanical and environmental factors during use.

Internal Reflections

Back-reflections from fiber ends can cause noise in lasers.

Back-reflections within connectors can cause problems that go beyond attenuation by affecting the performance of laser light sources. As you learned in Chapter 9, laser operation depends on reflection of light by mirrors on the two ends of the laser. Light reflected back into the laser cavity can also stimulate emission from the laser material, generating noise. Semiconductor lasers are especially sensitive to this problem, which can arise when light is reflected from an air-glass gap between two fiber ends in a connector. Analog systems used for cable-television transmission are the most vulnerable to noise produced by undesired reflection feedback into lasers.

The best way to prevent this noise is by blocking reflections. Most connectors butt the fiber ends together, which should minimize reflections by avoiding glass-air interfaces. An alternative is to fill any gap between fiber ends with a fluid or gel that has the same refractive index as the glass. "Wet" connectors are messy and rarely used, but gels may be used in mechanical splices. Fusion splices melt fiber ends together, which also fills any gap.

Reflection noise can be further reduced by cleaving and polishing the ends of the fiber so they are slanted. Thus any light reflected at the fiber junction is not directed down the fiber core. That is, the reflected light falls outside the fiber's acceptance angle and is lost. The big difficulty in this case is to make sure the slanted ends are aligned properly to avoid high losses; this requires rotating the fiber ends until they match.

Devices called *optical isolators* can suppress back-reflections in a different way: by transmitting light in only one direction. They are described in Chapter 15.

Mechanical Considerations in Connectors

So far we have concentrated on optical characteristics of fiber connections. Mechanical considerations also are important, and they differ markedly for connectors and splices. Thus we will shift from connections in general to connectors in particular. Important considerations range from size, shape, and ease of use to mechanical integrity.

Mechanical considerations are important for fiber connectors.

Virtually all fiber connectors are designed well enough to stay in place under normal conditions. Ideally they should withstand physical stress applied during their use, from the normal forces in mating and unmating to the sudden stress applied by a person tripping over a cable. Connectors also must prevent dirt and moisture from contaminating the optical interface.

Ease of Use and Size

The size and shape of a connector determine its ease of use and compatibility with communications equipment. Connector design has evolved greatly over the years, as engineers have refined requirements for usability. Many early connectors were screw-on designs, adapted from coaxial cable connectors. The industry has tended away from twist-on designs to connectors that snap into place, with a latch that holds them in place until released. Like the familiar snap-in jack on modern telephones, this design is very easy to use. It also is adaptable for duplex (two-fiber) connectors simply by clamping a pair of single-fiber connectors together. Many of these designs have structures that guide the connector into place only if it is inserted in the right orientation—vital in duplex connectors. They are called *polarized connectors,* but the polarization is mechanical, not optical. Some are designed to help technicians insert connectors "blindly" into sockets

Size and shape determine a connector's ease of use and compatibility with other equipment.

they can't see, like when you're reaching behind a cabinet and plugging a connector into its socket by feel.

Density of connections has become an important consideration. The first generation of connectors were comparable in size to coaxial cable connectors, about 9 to 10 mm (0.35 to 0.4 in.) wide. A new generation of small form-factor connectors are designed to fit two (or more) fiber connections into the same space as an older single-fiber connector. As you will learn later in this chapter, some are single-fiber connectors, and some hold two or more fibers. The newer designs also can snap into place in tight confines when connectors are closely packed on equipment.

Durability

Typical fiber connectors are specified for 500 to 1000 matings. Most can be torn from cable ends by a sharp tug.

Durability is a concern with any kind of connector. Repeated mating and unmating of fiber connectors can wear mechanical components, introduce dirt into the optics, strain the fiber and other cable components, and damage exposed fiber ends. Typical connectors for indoor use are specified for 500 to 1000 mating cycles, which should be adequate for most uses. Few types of equipment are connected and disconnected daily. Specifications typically call for attenuation to change no more than 0.2 dB over that lifetime.

Connectors are attached to cables by forming mechanical and/or epoxy bonds to the fiber, cable sheath, and strength members. (Usually the fiber is epoxied, and the other bonds are crimped.) That physical connection is adequate for normal wear and tear but not for sudden sharp forces, such as those produced when someone trips over an indoor cable. That sharp tug can detach a cable from a mounted connector, because the bond between connector and fiber is the weakest point. The same is true for electrical cords, and the best way to address the problem is to be careful with the cables.

Because sharp bends can increase losses and damage fibers, care should be taken to avoid sharp kinks in cables at the connector (e.g., where a cable mates with a connector on a patch panel). Fibers are particularly vulnerable if they have been nicked during connector installation. Care should also be taken to be certain that fiber ends do not protrude from the ends of connectors. If fiber ends hit each other or other objects, they can easily be damaged, increasing attenuation.

Environmental Considerations

Fiber ends must be kept free of contaminants to avoid excess losses.

Most fiber-optic connectors are designed for use indoors, protected from environmental extremes. Keeping them free from contaminants is even more important than it is for electrical connectors. Dirt or dust on fiber ends or within the connector can scatter or absorb light, causing excessive connector loss and poor system performance. This makes it unwise to leave fiber-optic connectors open to the air, even indoors. Many connectors and patch panels come with protective caps for use when they are not mated. These caps are the sort of things that are easily lost, but they should not be.

Special hermetically sealed connectors are required for outdoor use. As you might expect, those designed for military field use are by far the most durable. Military field connectors are bulky and expensive, but when sealed they can be left on the ground, exposed to mud and moisture. They are designed to operate even after having one end stuck in mud and wiped out with a rag! Normally, nonmilitary users will avoid outdoor connectors or house them in enclosures that are sealed against dirt and moisture.

Connector Structures

A wide variety of fiber-optic connectors have been developed, but the number of basic design approaches is more limited. The two most common approaches differ in how they align the fibers: One mounts the fibers in a cylindrical ferrule, the other aligns them in V-shaped grooves in a flat substrate. A third approach with limited applications expands the beam from the fiber to reduce sensitivity to mechanical tolerances.

Ferrule-Based Connectors

The common elements of ferrule-based connectors are shown in generic form in Figure 13.7. The fiber is mounted in a long, thin cylinder called a *ferrule*, with a hole sized to match the fiber cladding diameter. The ferrule centers and aligns the fiber and protects it from mechanical damage. The fiber end is at the end of the ferrule, where it can be polished smooth. The ferrule is mounted in a connector body, which is attached to the cable structure. A strain-relief boot protects the junction of the connector body and the cable.

Ferrules center and align the fiber in the connector.

Ferrules are typically made of metal or ceramic, but some are made of plastic. The protective plastic coating is stripped from the fiber before it is inserted in the ferrule. The hole through the ferrule must be large enough to fit the clad fiber and tight enough to hold it in a fixed position. Standard bore diameters are $126 + 1/-0$ μm for single-mode connectors and $127 + 2/-0$ μm for multimode connectors, but some manufacturers supply a range of sizes (e.g., 124, 125, 126, and 127 μm) to accommodate the natural variation in fiber diameter. Adhesive is typically put in the hole before the fiber is pushed in to hold the fiber in place. The fiber end may be pushed slightly past the end of the ferrule and then polished to a smooth face.

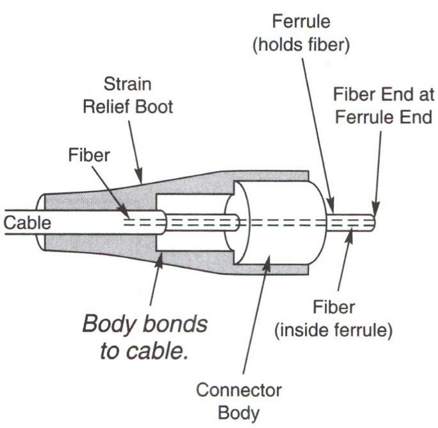


FIGURE 13.7
A simplified generic ferrule fiber connector.

The ferrule may be slipped inside another hollow cylinder (also called a sleeve) before it is mounted in the connector body. The body, typically made of metal or plastic, includes one or more pieces that are assembled to hold the cable and fiber in place. Details of assembly vary among connectors; cable bonding is usually to strength members and the jacket. The end of the ferrule protrudes beyond the connector body to slip into the mating receptacle. A strain-relief boot is slipped over the cable end of the connector to protect the cable-connector junction.

Special ferrule connectors are used for operation at high powers. Heat from light absorption at the junction can damage standard epoxies and fiber coating materials, so the coatings must be removed (they often are anyway) and special high-temperature epoxies must be used. Quartz sleeves may be added to protect the fiber tip, especially at higher powers.

V-Groove Connectors

V-groove connectors can align fibers in connectors.

V-groove connectors avoid the need for a ferrule by aligning two fiber ends in a V-groove structure. One approach is by pressing a free fiber down into a groove and butting it up against another fiber already installed in the groove. An alternative is to align fibers in V grooves in a substrate, fix them in place, then mate two V-grooved elements together. If the grooves are accurately spaced, the fiber ends match accurately, just as ferrules do. In a sense, the grooved material serves the same function as a ferrule.

V-groove structures are easily adaptable for multifiber connectors by etching multiple grooves in each element to align them to mate the fibers they contain end-to-end. Guide pins can be added to the V-groove elements to mate them accurately.

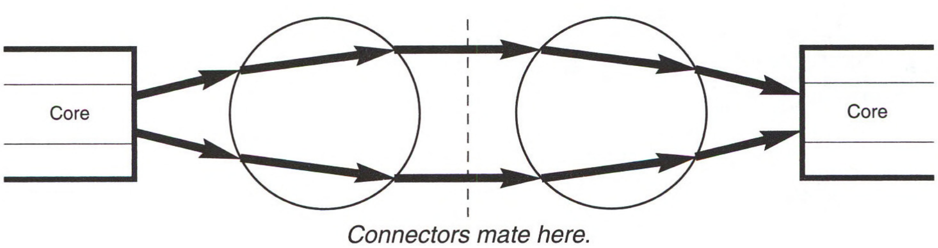
Expanded-Beam Connectors

Military field cables often use expanded-beam connectors.

Expanded-beam connectors are limited to applications where large tolerances are required, such as military field cables. As shown in Figure 13.8, light diverging as it exits the input fiber passes through a spherical lens, which collimates the light rays so they are parallel. Then a spherical lens attached to the output cable focuses the light rays into the output fiber.

This expands the beam diameter by a factor of 10 or more for multimode fiber, and by a larger factor for single-mode fiber, spreading the optical signal over a larger region. This design prevents dirt from blocking all or most of the beam, or small misalignments from causing high attenuation. In practice, expanded-beam connectors are mostly for cables used outdoors or in hostile environments where connectors can't be protected.

FIGURE 13.8
Operation of an expanded-beam connector.



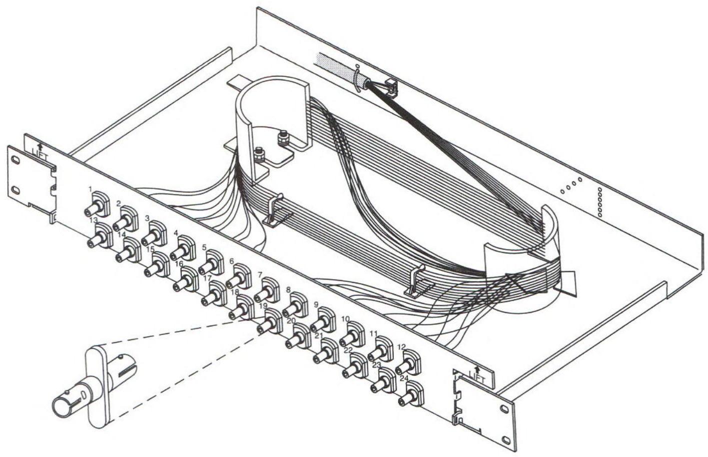


FIGURE 13.9
Connector panel. (Courtesy of Corning Cable Systems, Hickory, N.C.)

Mating Connectors

Most standard fiber connectors lack the male-female polarity often seen in electronic connectors. Instead, the fiber connector is plugged into an adapter, which serves as an interface to another connector, or is mounted on a transmitter, receiver, or service box. This arrangement is similar to that of standard American telephone wiring, where cables are terminated with standard jacks that fit into any telephone or wall socket. Two cables can be connected by plugging jacks into both sides of an adapter.

Most fiber connectors plug into adapter interfaces.

In fiber systems, connectorized cables normally plug into adapters mounted on transmitters, receivers, junction boxes, or other devices. Transmitters and receivers are often packaged with internal fiber links between the adapter on the outside of the box and the laser or detector on the inside. In a junction box or patch panel, a cable may be divided into individual fibers that run to an array of connector adapters, ready to take single-fiber connectors, as shown in Figure 13.9. Remember that the adapters are what you see on the outside of the box.

Adapters offer the advantage of flexibility in cabling because they can accept one type of connector on one side and a different type on the other.

Connector Installation

Users face trade-offs when deciding whether to install connectors in the field or in a factory. Tight tolerances are easier to reproduce in a factory, but field installation gives more flexibility in meeting system requirements and performing on-the-spot repairs. Manufacturers have developed connectors optimized for each environment.

Fiber connectors can be installed in the field or in the factory.

Factory installation employs trained technicians working in a controlled environment with all the specialized equipment needed to do the job right, so you can buy ready-to-use cables. That works well for standard lengths of connectorized jumper cables, but not for longer cables of varied lengths needed for intrabuilding or interbuilding use.

One alternative is to supply cable segments with factory-mounted connectors on one end and fiber pigtails on the other. Splicing in the field is generally easier than installing connectors, but it does require special equipment. This approach works best for loose-tube cables containing many fibers.

Field installation of a complete connector enhances flexibility, but results depend on both the skill of the technician and the connector design. Installing a connector in the field generally requires more time, tools, and skill than splicing a premounted connector. It works best for tight-buffered cables. Some manufacturers supply field connectorization kits with the most sensitive internal alignments already done.

Multifiber Connectors

Multifiber cables may be broken out to individual fibers, each with its own connector.

Most cables contain multiple fibers, and the complexity of installing connectors increases with the number of fibers involved. The cable may be broken out into individual fibers, with connectors on the end of each fiber, or two or more fibers may terminate in the same connector. Breakout cables often terminate in a patch panel, as shown in Figure 13.9.

The simplest case is the *duplex* connector, which links cables that contain a pair of fibers, one transmitting in each direction. Duplex connectors may consist of two single-fiber connectors side by side in a single housing, or a single connector that mounts two fibers. In practice, duplex connectors are *polarized* so they can be mated in only one way, with the two fibers connected to their counterparts transmitting in the same direction. Attach a duplex connector the wrong way, and you have the transmitters sending signals to each other while the two receivers stare at each other through a dark fiber, each waiting in vain for the other to send a signal.

Multifiber connectors simultaneously connect many fibers, greatly simplifying installation and reducing space requirements. This approach requires arranging the fibers in a fixed format in the cable and mating them to corresponding fibers in another cable that uses the same format. Loss in multifiber connectors tends to be higher than for single-fiber connectors, but the space and labor savings can be worthwhile. Generally multifiber connectors are used with ribbon cables.

Polarization-Maintaining Connectors

The concept of connector polarity can be confusing in optics, where light is also polarized. You may encounter two variations on the concept in fiber connectors.

You are most likely to encounter polarity when dealing with duplex connectors, which require you to know which fiber is transmitting in which direction. You need to keep track of this polarity in order to connect fibers so they always send signals from the transmitter to the receiver.

Polarization-maintaining connectors are rare, but important when they are used. They connect polarization-maintaining fibers, which transmit light in a way that maintains the optical polarization of the light waves. Polarization-maintaining connectors align fibers so that they retain the polarization orientation of the light.

Standard Connector Types

Many connector designs have been standardized by the IEC and other organizations.

During the 1980s, almost every manufacturer of fiber-optic connectors seemed to have its own design. Some remain in production, but much of the industry has shifted to standardized connector types, with details specified by standards organizations such as the

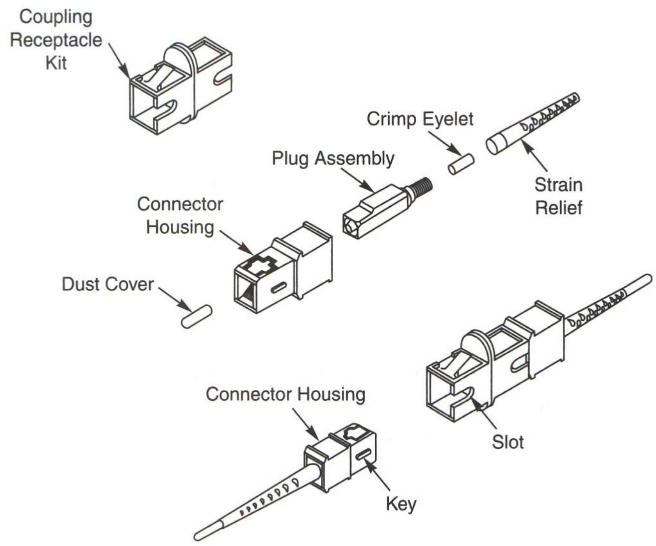


FIGURE 13.10
SC connector, expanded and assembled. (Courtesy of AMP Inc.)

Telecommunications Industry Association, the International Electrotechnical Commission, and the Electronic Industries Association. Standards groups, in turn, have developed standards for more than two dozen connector types, most of them widely used types and some of them new types developed for emerging needs.

I can't hope to cover the whole variety of connectors in any detail; that's best done by consulting catalogs and product specifications. However, I will discuss a few examples of important types used for single- and multimode glass fibers. Other types of connectors may be used for plastic fibers and large-core fibers. I divide them loosely into families, which sometimes overlap: single-fiber connectors that snap or twist in place, polarizing connectors, multifiber connectors, and small form-factor connectors.

Snap-in Single-Fiber Connectors (SC)

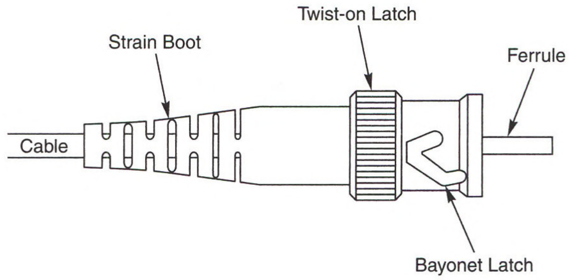
Figure 13.10 shows a widely used snap-in connector, the SC connector developed by Nippon Telegraph and Telephone of Japan. It is built around a cylindrical 2.5-mm ferrule that holds the fiber, and it mates with an interconnection adapter or coupling receptacle. Pushing the connector latches it into place, without any need to turn it in a tight space, so a simple tug will not unplug it. It has a rectangular 9-by-7.9 mm cross section that allows high packing density on patch panels and makes it easy to package in a polarized duplex form that assures the fibers are matched to the proper fibers in the mated connector.

The SC is a widely used snap-in single-fiber connector.

Twist-on Single-Fiber Connectors (ST and FC)

Figure 13.11 shows a widely used twist-on connector, the ST connector long used in data communications. It may look familiar because it is one of several fiber connectors that evolved from designs originally used for copper coaxial cables. Like the SC, it is built

FIGURE 13.11
ST connector.



around a 2.5-mm cylindrical ferrule and mates with an interconnection adapter or coupling receptacle. However, it has a round cross section and is latched into place by twisting it to engage a spring-loaded bayonet socket.

Another design for a twist-on connector is the FC (sometimes called FC-PC). Its structure is similar to that of the ST, but it is threaded and screws in place rather than twisting to latch. One drawback of such twist-on connectors is that they generally cannot be mounted in pairs as a duplex connector.

Duplex Connectors

Duplex connectors are keyed to mate in only one orientation.

Standard plug-in connectors like the SC can be mounted side by side to make duplex connectors. Some of the small form-factor connectors described later also come in duplex versions, notably the MT-RJ.

Other duplex connectors have been developed for specific types of networks as part of the network standards. One example is the *fixed shroud duplex* (FSD) connector specified by the Fiber Distributed Data Interface (FDDI) standard, as shown in Figure 13.12. Another is the *retractable shroud duplex* (RSD) connector developed by IBM for local-area networks.

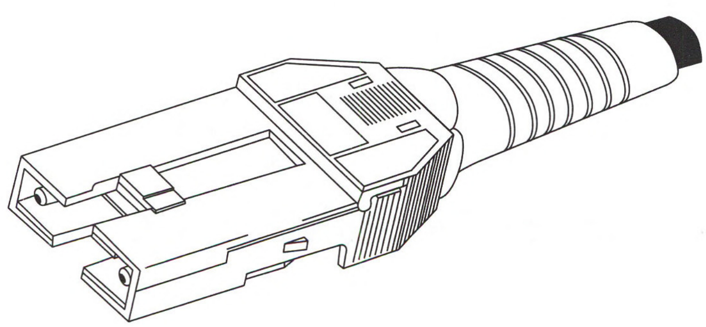
Some network standards specify duplex connectors as integral parts of transmitters and receivers (or combined transceivers).

MT Multifiber Connectors

MT connectors align fibers in V grooves.

An important family of multifiber connectors is built up around the MT V-groove element (a noncylindrical ferrule), which aligns many fibers parallel to each other, as shown in

FIGURE 13.12
Fixed shroud duplex (FSD) connector for FDDI network. (Courtesy of Corning Cable Systems, Hickory, N.C.)



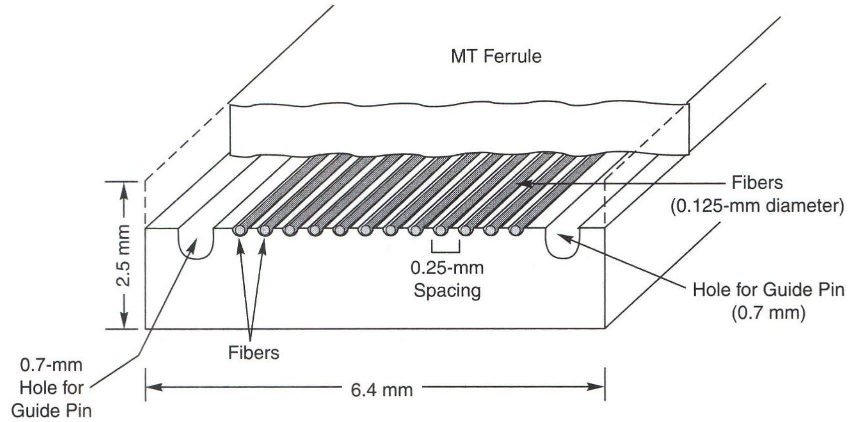


FIGURE 13.13
MT ferrule holds a dozen fibers in parallel grooves.

Figure 13.13. As you may suspect from the arrangement, the MT connector was developed for multifiber ribbon cable. Coatings are removed before the fibers are mounted in the grooves, leaving 125-μm fibers mounted on 250-μm centers. The ferrules include a pair of 0.7-mm holes, parallel to the fibers on the other edges of the structure. These holes accommodate precision metal guide pins, which align the mated elements with tight tolerances to match up the fibers.

Pairs of MT ferrules can be mated together with guide pins and held in place with metal clips. Alternatively, the MT ferrules can be mounted within connector bodies, which mate together, usually with an adapter, while the guide pins align the ferrules precisely with each other. Many of these designs have male–female polarity.

Depending on details of the design, the guide pins may be supplied separately for insertion when the connectors are mated or may be installed permanently in one ferrule (typically one that is permanently mounted in a case rather than on a cable). It is the guide pins that assure the precise alignment of fiber ends. The connector bodies provide the mechanical force holding the ferrules in place; typically they are spring-loaded and snap into position, like SC connectors. There are a variety of connectors built around MT ferrules, including the small form-factor duplex MT-RJ.

One such design is the rectangular-format MPO connector, shown in Figure 13.14. A pair of connectors mate in an adapter. The male connector (shown in the figure) has the guide pins; the female connector does not. Some companies have modified designs with minor differences, such as allowing two plugs to mate with each other without an adapter between them. These connectors are intended for installations that require many fiber connections. Some versions include up to 72 fibers. The MPO must be factory-installed.

Trying to align many fibers at once stresses mechanical tolerances, so typical losses of multifiber connectors can be higher than those of single-fiber connectors, up to about 1 dB. (Duplex connectors typically have about the same loss as single-fiber connectors.) However, multifiber connectors greatly reduce installation costs for multifiber systems.

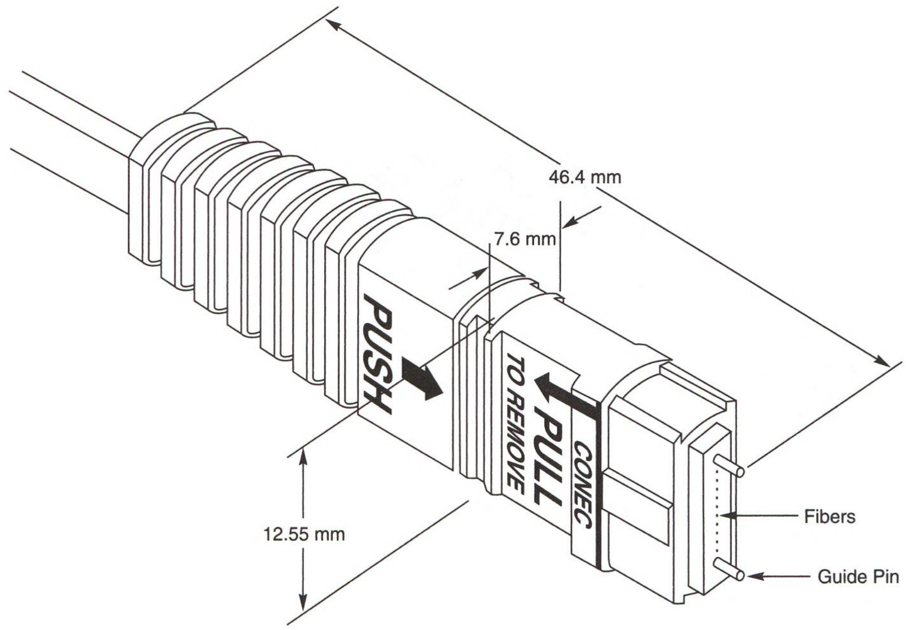


FIGURE 13.14
Male MPO connector assembly (Courtesy of US Conec.)

Small Form-Factor Connectors

Small form-factor connectors fit into tighter spaces.

A number of small form-factor connectors have been developed in recent years to fill the demand for devices that can fit into tight spaces and allow denser packing of connections. Some are miniaturized versions of older connectors, built around a 1.25-mm ferrule rather than the 2.5-mm ferrule used in SC-type connectors. Others are based on smaller versions of MT-type ferrules, or other designs. Most have a push-and-latch design that adapts easily to duplex connectors and feels like a phone jack. Figure 13.15 shows a sampling. Typical dimensions are 5-mm square for the plug end of the connector, with ferrule in the middle, and 10-by-13 mm for a duplex adapter.

The MT-RJ duplex connector shown in Figure 13.15(a) is derived from the MT design and used for intrabuilding communications. The two fibers (not shown in the drawing) are held in a miniature two-fiber ferrule, and the connector's overall size is about the same as the standard RJ45 jack used on home telephone cables. These two fibers are hard-to-see dots on the front of the ferrule, between the two larger holes used for the alignment pins. A spring pushes the guide pins through the ferrule and the whole assembly into the housing. MT-RJ connectors are designed as plugs and jacks, like RJ45 phone connectors, and can sit in the same slot in a wall plate as the phone connector. Adapters can be used for mating the MT-RJ, but are not required.

The LC connector in Figure 13.15(b) borrows features from both electronic telephone jacks and the SC fiber connectors. Externally it resembles a standard RJ45 phone jack. Internally, it's a miniature version of the SC, with its plastic case holding a 1.25-mm ceramic ferrule that mates in an adapter. The LX.5 connector also uses a 1.25-mm ferrule in a miniature SC-like plastic case, but has an integral end cap that automatically

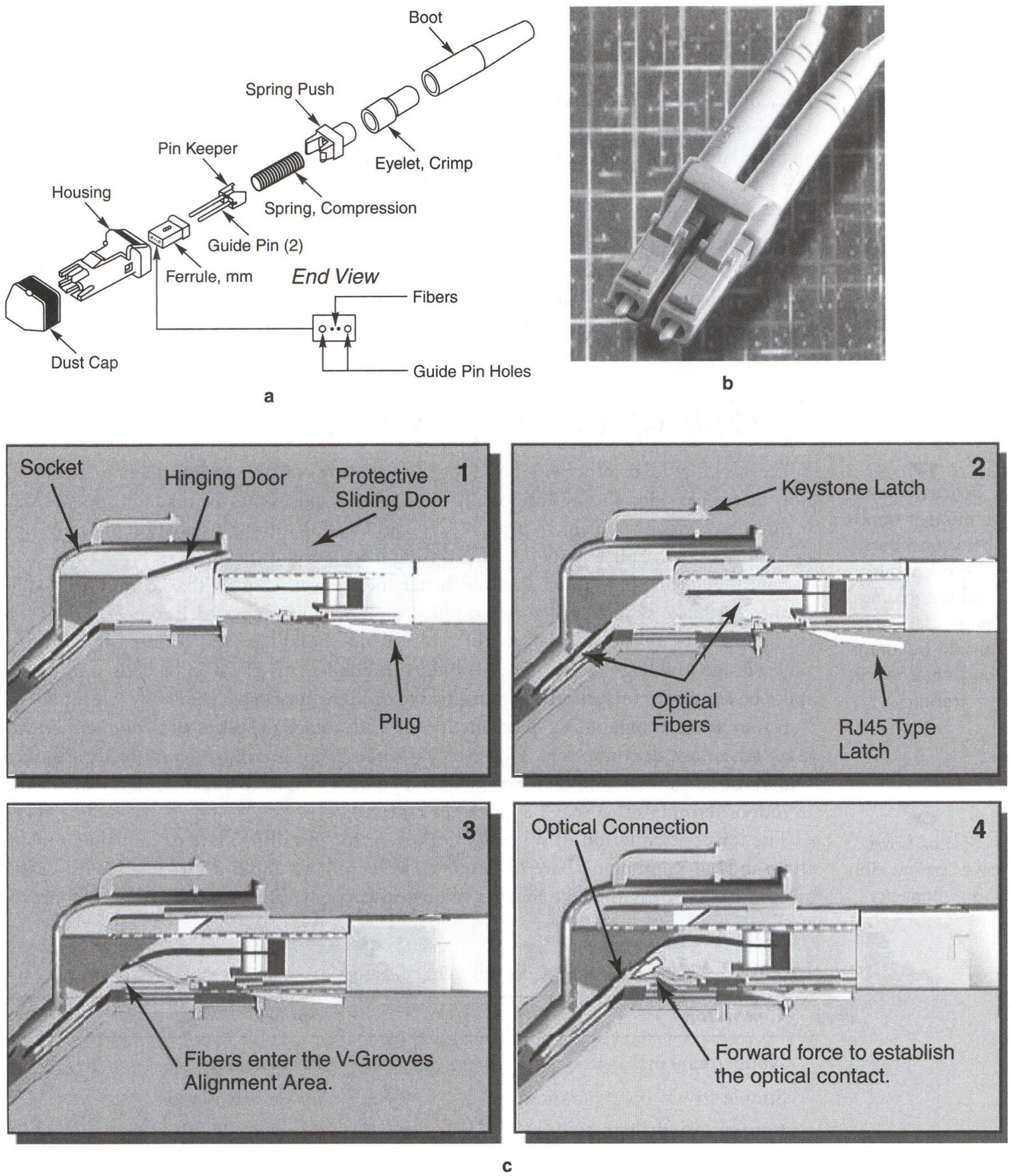


FIGURE 13.15

Small form-factor connectors. (a) MT-RJ connector. (Courtesy of Tyco Electronics) (b) Duplex LC connector. (Courtesy of Agere Systems) (c) VF-45 connector. (Courtesy of 3M Telecom Systems Division) slides out of the way when plugged into an adapter, then slips back to cover the ferrule when removed.

The MU connector is another miniature version of the SC built around a 1.25-mm ferrule, but unlike the LC retains the push–pull external latching mechanism of the SC. Other small form-factor connectors, also built around 1.25-mm ferrules, differ in details such as latching mechanism and assembly procedures. One small form-factor connector, the Fiber-Jack, is based on a 2.5-mm ferrule.

V-groove connectors have also been developed as small form factors. The VF-45 connector shown in Figure 13.15(c) has covers that slide away when the plug and socket are mated. The fibers in the socket are mounted in V grooves in a substrate that is at a 45° angle to the fibers on the plug. The mating process slides the fibers in the plug into the V grooves, where pressure holds them in place, avoiding the need for precision ferrules.

Splicing and Its Applications

Splices make permanent bonds between fibers. Applications include joining lengths of cable outside buildings and emergency repairs.

Splices weld, glue, or otherwise bond together the ends of two optical fibers in a connection that is intended to stay connected. "Temporary" splices may be made in special cases, including emergency repairs to broken cables and testing during installation or renovation of a cable system. Splices may be made during installation or repair.

Splices generally have lower loss and better mechanical integrity than connectors, while connectors make system configuration much more flexible. Table 13.1 compares their features. Typically, splices join lengths of cable outside buildings, and connectors terminate cables inside buildings. Splices may be hidden inside lengths of cable, or housed in special splice boxes; connectors are typically attached to equipment or patch panels at cable interfaces.

It may seem strange to list "permanent" as an advantage of splices and "nonpermanent" as an advantage of connectors. However, each has its advantages. A splice to fix a broken underground cable should be permanent, but you don't want to attach cables permanently to indoor terminals that may be moved or replaced.

Splices have lower attenuation than connectors.

The lower attenuation of splices is important for installing systems that span tens to thousands of kilometers. Bare fiber comes in lengths to about 25 km, but most cables are too bulky to fit that much on a manageable spool. In practice, outdoor cables are

Table 13.1 Comparison of connector and splice advantages

Connectors	*Splices*
Nonpermanent	Permanent
Simple to use once mounted	Lower attenuation
Factory installable on cables	Lower back-reflection
Allow easy reconfiguration	Easier to seal hermetically
Provide standard interfaces	Usually less expensive per splice
	More compact

spliced in the field at least every several kilometers, or more often depending on the configuration.

The physical characteristics of splices are important in many outdoor applications. The spliced cables must withstand hostile outdoor environments, so the splices are housed in protective enclosures. (Fibers spliced during cable manufacture are protected by the cable structure that surrounds them.) Generally outdoor enclosures are sealed to protect against moisture and temperature extremes, but can be re-opened if repairs or changes are needed—like their electronic counterparts on copper cables.

Splicing Issues and Performance

Three main concerns in splicing are the optical characteristics of the finished splice, its physical durability, and the ease of splicing.

Attenuation and Optical Characteristics

The same factors that contribute to loss in connectors can cause splice loss, although differences between the two processes mean that some mechanisms are less important for splices than for connectors.

Splices align fibers more accurately than connectors, so they have lower attenuation.

Splices bond the two fiber ends together by melting (fusing) them, gluing them, or mechanically holding them in a tight structure. This tends to align the fibers with tighter tolerance than in a connector, giving lower attenuation. As long as these processes bond the two fiber ends together with no intervening air space, they largely eliminate fiber-spacing loss and minimize back-reflection.

Differences between the fibers being spliced cause *intrinsic losses.* Mechanisms include variations in the size and shape of the fiber core, core eccentricity or offset, and differences in refractive-index profile. The inevitable manufacturing tolerances cause slight variations even in nominally identical fibers. These mechanisms are the same as those affecting connector loss, which you learned earlier.

Good splices can have loss near 0.05 dB.

Extrinsic losses arise from the nature of the splice itself. They depend on alignment of the fiber ends, quality of end preparation, refractive-index matching between ends, contamination, end spacing, waveguide imperfections at the junction, and angular misalignment of bonded fibers. Again, the same mechanisms affect connector loss, although their impacts may differ.

Typically intrinsic and extrinsic losses are comparable in magnitude for well-made splices. Fortunately, the total splice loss often is less than the arithmetic sum of the two types. Total loss can be very low, near 0.05 dB, in properly made splices, but imperfect junctions can suffer from high loss. A single 10-μm dust particle in the wrong place can block the core of a single-mode fiber. With proper tools and procedures, attenuation is comparable for splices of single- and multimode fibers. (Measurement anomalies can make some splices seem to be "gainers," but this effect is not real.)

Back-reflection normally is very low in good splices. High back-reflection or attenuation is a sign of a defective splice.

Specified values for splice loss assume the fibers are correctly matched. As in connectors, mismatched fibers can cause significant losses. For single-mode fibers, the most important mismatches are in mode-field diameter. This may be inevitable when different fibers are being spliced together for dispersion management. Natural variations in fiber characteristics can raise loss above the average values of 0.05 to 0.1 dB. The worst type of mismatch is splicing multimode fiber to single-mode with light going into the single-mode fiber, which can cause attenuation of nearly 20 dB. Such mistakes can happen because virtually all telecommunication fibers have the same 125-μm core diameter. Color-coding in cables identifies individual fibers, but does not distinguish different types.

Strength

Fibers are more vulnerable to damage at splices. Stripping the plastic coating can damage the fiber surface.

If you pull a spliced copper wire, you expect the splice to fail long before the wire itself fails. Optical fibers likewise are more vulnerable at splices, with the specific mechanisms depending on the splice type.

Stripping coatings from fibers can damage them before splicing, causing microcracks that later become points of failure. This is particularly likely for mechanical stripping. In fusion splicing, contaminants can weaken the melted zone, while thermal cycling from heating and cooling can weaken adjacent parts of the fiber. In practice, fusion splices tend to fail near the splice interface, but not exactly at the junction point.

Typically both mechanical and fusion splices are protected by coatings, claddings, and/or jackets that bond to the fibers and protect them from mechanical and environmental stresses.

Ease of Splicing

Splices often are made in the field, making the ease of splicing a critical concern. This has led to the development of special equipment, which I'll describe in more detail below.

Types of Splicing

There are two basic approaches to fiber splicing: *fusion* and *mechanical*. Fusion splicing melts the ends of two fibers together so they fuse, like welding metal. Mechanical splicing holds two fiber ends together without welding them, using a mechanical clamp and/or glue. Each approach has its distinct advantages. Fusion splicers are expensive, but they require almost no consumable costs, and fusion splices have better optical characteristics. Mechanical splicing requires less equipment (and no costly fusion splicer), but consumable costs per splice are much higher.

Fusion Splicing

Fusion splicing welds fiber ends together.

Fusion splicing is performed by butting the tips of two fibers together and heating them so they melt together. This is normally done with a fusion splicer, which mechanically aligns the two fiber ends, then applies a spark across the tips to fuse them together. Typical splicers also include instruments to test splice quality and optics to help the technician align the

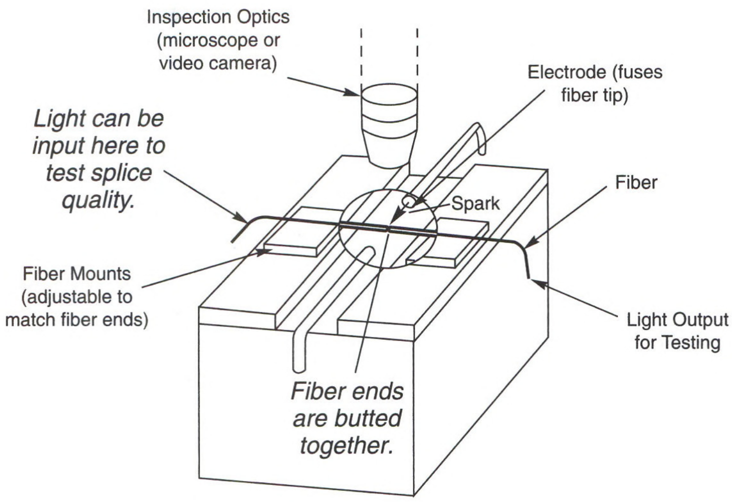


FIGURE 13.16
Key components of a fiber splicer.

fibers for splicing. Typical splice losses are 0.05 to 0.2 dB, with more than half below 0.1 dB. The basic arrangement of a fiber splicer is shown in Figure 13.16.

Individual fiber splicers are designed differently, but all have the common goal of producing good splices reliably. Many are automated to assist the operator. They are expensive instruments, with prices starting at thousands of dollars and reaching tens of thousands of dollars for the most sophisticated models. Major differences center on the degree of automation and the amount of instrumentation included. Most models share the following key elements and functions:

- A fusion welder, typically an electric arc, with electrode spacing and timing of the arc adjustable by the user. The discharge heats the fiber junction. Portable versions are operated by batteries that carry enough charge for a few hundred splices before recharging. Factory versions operate from power lines or batteries.
- Mechanisms for mechanically aligning fibers with respect to the arc and each other. These include mounts that hold the fibers in place, as well as adjust their position. More expensive splicers automate alignment and measurement functions.
- A video camera or microscope (generally a binocular model) with magnification of 50 power or more so the operator can see the fibers while aligning them.
- Instruments to check optical power transmitted through the fibers both before and after splicing. Typically, light is coupled into a bent portion of the fiber on one side of the splice and coupled out of a bent portion on the other side. With proper calibration, this can measure the excess loss caused by the splice. (This may be missing from inexpensive field splicers.)

Before fusion splicing, plastic coatings must be removed from the fiber, and the end must be cleaved perpendicular to the fiber axis.

Fusion splicing involves a series of steps. First, the fiber must be exposed by cutting open the cable. Then the protective plastic coating or jacket must be stripped from a few millimeters to a few centimeters of fiber at the ends to be spliced. The fiber ends must be cleaved to produce faces that are within 1° to 3° of being perpendicular to the fiber axis. The ends must be kept clean until they are fused.

The next step is alignment of the fibers, which may be done manually or automatically. After preliminary alignment, the ends may be "prefused" for about a second with a moderate arc that cleans their ends and rounds their edges. These ends are then pushed together, allowing power transmission to be tested to see how accurately they are aligned. After results are satisfactory, the arc is fired to weld the two fiber ends together. Care must be taken to ensure proper timing of the arc so the fiber ends are heated to the right temperature. After the joint cools, it can be recoated with a plastic material to protect against environmental degradation. The spliced area can also be enclosed in a plastic jacket. The entire splice assembly is then enclosed mechanically for protection, which in turn is mounted in a splice enclosure. The case around the individual splice provides strain relief.

Mechanical Splicing

Mechanical splicing gives higher losses but requires simpler equipment than fusion splicing.

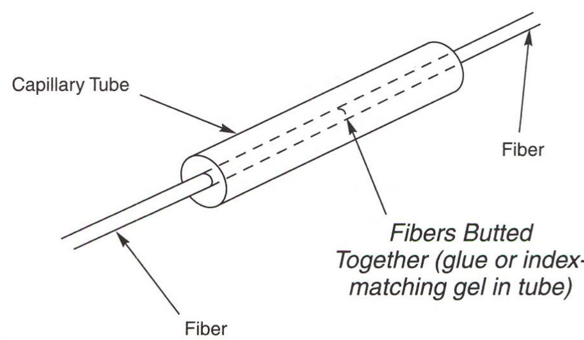
Mechanical splices join two fiber ends either by clamping them within a structure or by gluing them together. A variety of approaches have been used in the past, and many are still in use. The extremely tight tolerances in splicing single-mode fiber often require special equipment not needed for splicing multimode fiber. Those extra requirements typically make single-mode splicing more expensive.

In general, mechanical splicing requires less costly capital equipment but has higher consumable costs than fusion splicing. This can tilt the balance toward mechanical splicing for organizations that don't perform much splicing, or for emergency on-site repair kits. Mechanical splices tend to have slightly higher loss than fusion splices, but the difference is not dramatic. Back-reflections can occur in mechanical splices, but they can be reduced by using epoxy to connect the fibers, or by inserting into the splice a fluid or gel with a refractive index close to that of glass. This index-matching gel suppresses the reflections that can occur at a glass–air interface. There are several types.

A capillary splice holds two fiber ends in a thin tube.

The *capillary splice* relies on inserting two fiber ends into a thin capillary tube, as shown in Figure 13.17. The plastic coating is stripped from the fiber to expose the cladding, which is inserted into a tube with an inner diameter that matches the outer diameter of the clad

FIGURE 13.17
Capillary splice joins two fibers.



fiber. The two fiber ends are then pushed into the capillary until they meet (often with index-matching gel inserted to reduce reflections). Compression or friction usually holds the fiber in place, although epoxy may also be used.

Alignment of the fiber ends depends on mechanical alignment of the outside of the fibers. The result is a simple splice that is easy to install and can compensate for differences in the outer diameters of fibers. However, it is not designed to compensate for other differences between the fibers being joined.

The *rotary* or *polished-ferrule* splice is a more elaborate type that can compensate for subtle differences in the fibers being spliced. As with other splices, the plastic coating is first removed from the fiber. Then each fiber end is inserted into a separate ferrule, and its end is cleaved and polished to a smooth surface. The two polished ferrules then are mated within a jacket or tube, and rotated relative to each other while splice loss is monitored. The ferrules are fixed in place at the angle where splice loss is at a minimum. Although this technique is more complex and time-consuming than capillary splicing, it offers a more precise way of mating fibers. Its sensitivity to rotation of the fiber around its axis makes it suitable for splicing polarization-sensitive fibers.

V-groove splices are valuable for multifiber ribbon cables.

Fibers also can be spliced by butting them together in V-shaped grooves, as shown for fiber ribbons in Figure 13.18. (Recall that MT-family connectors and the VF-45 connector also butt fibers together in V grooves.) The fibers are placed in opposite ends of the same groove, and are pushed together until they contact. Then a separate matching plate is applied on top. The fiber ends can be inserted into separate grooved plates, which can have covers applied and the ends polished before they are mated with another plate, as in MT-family connectors. The *V-groove splice* is particularly useful in multifiber splicing of ribbon cables, where each parallel fiber slips into a separate groove. Special splicers are sold for this purpose.

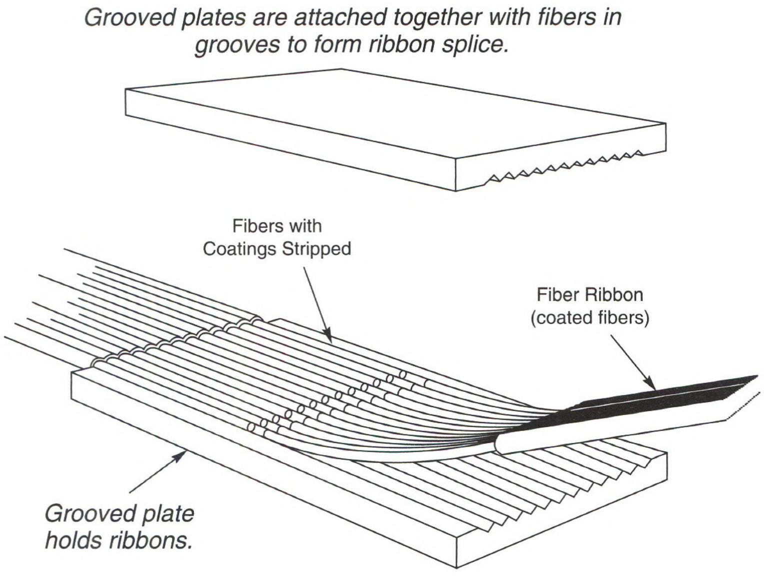


FIGURE 13.18
Mass-splicing of 12-fiber ribbon in V-grooved plate.

The *elastomeric splice* has an internal structure similar to that of a single-fiber V-groove splice, but the plates are made of a flexible plastic held in a sleeve, and the groove is tapered toward the center. The plates are assembled in a sleeve before the fibers are installed. First an *index-matching gel* or epoxy is inserted into the hole, then one fiber is inserted until it reaches about halfway through the splice. Then the second fiber is inserted from the other end until it pushes against the first. This type of splice is useful in field kits for emergency fiber repairs by technicians with little fiber experience, giving typical loss of 0.25 dB, adequate for such repairs.

A *reusable splice* is a mechanical splice in which the fibers are clamped in place but not glued. The V-groove splice in Figure 13.18 is one example. The plates may be held together by screws or clamps, which can be released to remove one fiber and replace it with another. Although reusable splices are not truly permanent, they are used in places where change is unlikely. Their installation requires a technician with special tools, not just an ordinary user who wants to plug in a different telephone or computer.

Splicing Requirements

Commercial splicing equipment is designed to serve a variety of needs and be used in a variety of environments. Fusion splicing normally is done by technicians who work primarily with fiber, whether installing new cables or repairing existing ones. Telephone companies may have vans equipped with specialized fiber equipment for these purposes. Fusion splices tend to be used mostly for cables with long outdoor runs, where loss is a major concern.

Mechanical splices are more likely to be used by nonspecialists to repair shorter cables indoors, where final loss of the cable is less important than fixing it promptly. For example, the technician responsible for maintaining a corporate local-area network may use mechanical splices to patch a damaged indoor cable, or to make a few splices needed to reconfigure the system. The cost per splice is higher than fusion splicing, but the overall cost is much lower because of the high cost of a fusion splicer.

Splice Housings

Fiber-optic splices require protection from the environment, whether they are indoors or outdoors. Splice enclosures help organize spliced fibers in multifiber cables, and also protect splices from strain and contamination.

Splice housings organize splices in multifiber cables.

Splice housings typically contain a rack such as the one shown in Figure 13.19, which contains an array of individual splices. This rack is mounted inside a case that provides environmental protection. Individual fibers broken out from a cable lead to and from the splices. To provide a safety margin in case further splices are needed, an excess length of fiber is left in the splice case. Like splice enclosures for telephone wires, fiber-optic splice cases are placed in strategic locations where splices are necessary (e.g., in manholes, on utility poles, or at points where fiber cables enter buildings).

Fiber splice enclosures should be designed to

- Hold cable strength member tightly
- Block entrance of water

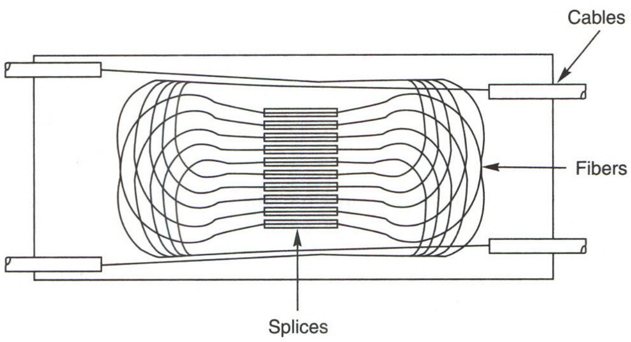


FIGURE 13.19
Splices arrayed inside housing.

- Provide redundant seals in case one level fails
- Electrically bond and ground any metal elements in the cable (e.g., strength members and armor)
- Be re-enterable if the splice must be changed or repaired
- Organize splices and fibers so they can be readily identified
- Provide room for initial splicing and future modifications
- Leave large enough bend radii for fibers and cables to avoid losses and physical damage

What Have You Learned?

1. Connectors hold fiber ends together in a temporary connection. They are used where equipment may need to be rearranged.
2. Splices permanently attach and align fiber ends. They are used for permanent junctions while installing or repairing fiber.
3. The most important optical specification of connectors and splices is attenuation, the loss in transferring a signal between fibers.
4. Causes of loss include mismatch of fiber cores, misalignment of fiber axes, differences in numerical aperture, spacing between fibers, reflection at fiber ends, and dirt in fiber junctions. Alignment tolerances are tighter for small-core single-mode fibers than for larger-core multimode fibers.
5. Fresnel reflection causes a 0.32-dB loss if there is an air gap between fiber ends. To avoid this, fibers are butted together in connectors or spliced together mechanically.
6. Back-reflection is an important parameter because it can cause noise if the light returns to laser transmitters. Butting fiber ends together, fusion splicing, or filling the junction between fibers can reduce this reflection. So can angled connectors.

7. Mechanical properties of connectors are important. They should withstand hundreds of matings, keep fiber ends clean, and hold cables in place.
8. Most connectors contain cylindrical ferrules that hold the fiber inside a connector body. Most fiber-optic connectors lack male–female polarity and mate through interconnection adapters or coupling receptacles.
9. Many types of connectors have been marketed and remain available, but only a few are in wide use.
10. Duplex connectors are used for pairs of fibers, one carrying signals each way. Multifiber cables may be attached to multifiber connectors or broken out to individual connectors.
11. Standard-form connectors include the snap-in SC and the twist-on ST and FC.
12. Small form-factor connectors are about half the size of standard-form connectors. They include the LC, MT-RJ, MU, Fiber-Jack, and VF-45.
13. Splices are normally made in the field; connectors usually are installed in the factory.
14. Splices have lower attenuation than connectors.
15. Fusion splices melt two fiber ends together; they are made with expensive fusion splicers. Typical loss of a fusion splice is less than 0.1 dB.
16. Mechanical splices hold fiber ends together mechanically or with glue. Losses are slightly higher than fusion splices, but they do not require a costly fusion splicer to install.
17. Splices are mounted in indoor or outdoor enclosures for protection against stress and the environment.

What's Next?

In Chapter 14, I will look at fiber-optic couplers, which join three or more fiber ends, and other passive optical components. Chapter 15 will cover the optics used in wavelength-division multiplexing.

Further Reading

Bob Chomycz, *Fiber Optic Installer's Field Manual* (McGraw-Hill, 2000). See Chapter 11, "Splicing and Termination."

Hassaun Jones-Bey, "Connector pace accelerates to meet telecomm demand," *Laser Focus World,* September 1999, pp. 137–139

Gerd Keiser, *Optical Fiber Communications* (McGraw-Hill, 2000). See Chapter 5, "Power Launching and Coupling," for general discussion of light transfer.

Kathleen Richards, "SFF connector battle is far from over," *Lightwave,* October 1999, pp. 43–46

Note that manufacturers often have detailed information on their own connectors.

Questions to Think About

1. What is the loss caused by core-diameter mismatch when going from a single-mode step-index fiber with 9-μm core to a graded-index multimode fiber with 50-μm core?
2. You are transferring light from a 62.5/125-μm graded-index fiber with $NA = 0.275$ to a single-mode step-index fiber with 9-μm core and $NA = 0.13$. You're going to lose a lot of light from the core-size mismatch. How much loss comes from the *NA* mismatch? How much from the area mismatch, assuming even light distribution?
3. You saw earlier that Fresnel reflection loss for an air gap between a pair of fibers is 0.32 dB. Recall that the loss depends on the difference between the refractive indexes of the material in the gap and the glass. If you have water with refractive index of 1.33 in the gap, what is the Fresnel loss?
4. If two step-index fibers with core radius a are offset a distance d from each other, as shown in Figure 13.1, the area of the two cores that overlap is

$$A_{\text{overlap}} = 2a^2 \arccos \frac{d}{2a} - d\left(a^2 - \frac{d^2}{4}\right)^{0.5}$$

   Suppose your connector makes a 1-μm error in aligning the otherwise identical cores of two step-index single-mode fibers with 9-μm cores. How much loss does that cause?
5. Using the formula of Question 4, go back and estimate how precisely the same step-index single-mode fibers would have to be aligned to have offset loss of only 0.3 dB. (*Hint:* You can try the formula for different values of offset if you program it into a computer spreadsheet.)
6. Why can't two twist-on connectors be assembled into a unit as a duplex connector?
7. A major telephone carrier puts you in charge of field repairs for a major urban center. You need to outfit a special truck for skilled technicians to use in repairing breaks in overhead and buried cables. What type of splicer do you buy?
8. A large retail company hires you to manage its data-transmission networks. The company has many regional offices in separate cities, each with fiber running to a dozen desks. You want to supply every office with a repair kit in case someone trips over a cable. What type of splice equipment do you buy?

Chapter Quiz

1. Connectors

a. permanently join two fiber ends.

b. make temporary connections between two fiber ends or devices.

c. transmit light in only one direction.

d. merge signals coming from many devices.

2. Index-matching gel

a. holds the fibers in place.

b. keeps dirt out of the space between fiber ends.

c. prevents reflections at fiber ends.

d. eliminates effects of numerical aperture mismatch.

e. all of the above

3. What is the excess loss caused by the mismatch in core diameters when a connector transmits light from a 62.5/125 multimode fiber into a 50/125 multimode fiber?

a. 0 dB

b. 0.19 dB

c. 0.8 dB

d. 1.9 dB

e. 12.5 dB

4. The largest excess loss probably will occur in which case?

a. transfer of light from a single-mode to a multimode fiber

b. when an air gap of 2 μm is left between identical fibers

c. when a 20-μm soot particle is spliced near the core of a pair of single-mode fibers

d. when a 2° angle is left between a pair of fibers when they are spliced

e. when index-matching gel is left out of a mechanical splice

5. How many matings and unmatings is a typical fiber-optic connector rated to survive?

a. 100

b. 1000

c. 10,000

d. 100,000

e. 1 million

6. Ferrules do what in a fiber-optic connector?

a. relieve strain on the cable

b. allow adjustment of attenuation

c. hold the fiber precisely in place
d. prevent back-reflection

7. How does an SC connector attach mechanically to an adapter or patch panel?
a. It pushes straight in and snaps into place.
b. with a special tool
c. It must be screwed into place.
d. It twists with a bayonet-type latch.
e. only with duct tape

8. Which of the following mechanisms is *not* used in small form-factor connectors?
a. Latching in place like telephone jacks.
b. Twisting in place like coaxial-cable connectors.
c. 1.25-μm miniature ferrules.
d. V-groove alignment.
e. Mounting a pair of fibers in a single ferrule.

9. Splices
a. permanently join two fiber ends.
b. make temporary connections between two fiber ends or devices.
c. transmit light in only one direction.
d. merge signals coming from many devices.

10. Typical splice loss is around
a. 0.01 dB.
b. 0.1 dB.
c. 0.5 dB.
d. 0.8 dB.
e. 1.0 dB.

11. What would happen if fibers with identical outer diameters but different core diameters were spliced together?
a. The splice would fail mechanically.
b. Loss would be high in both directions.
c. Loss would be high going from the large-core fiber to the small-core fiber, and low in the opposite direction.
d. Loss would be high going from the small-core fiber to the large-core fiber, and low in the opposite direction.
e. impossible to predict

12. Splice housings are important because they
a. reduce splice attenuation.
b. protect splices from physical and environmental stresses.

c. prevent hydrogen from escaping from splices.
d. allow measurement of splice attenuation.
e. contain light sources.

13. Identify the connector type that is *not* a small form-factor type.

a. MT-RJ
b. VF-45
c. LC
d. ST
e. Fiber-Jack

14. Which connector mounts two fibers in the same ferrule?

a. MT-RJ
b. VF-45
c. LC
d. ST
e. Fiber-Jack