CHAPTER 4

OPTICAL SPLICES, CONNECTORS, AND COUPLERS

LEARNING OBJECTIVES

Upon completion of this chapter, you should be able to do the following:

1. Describe a fiber optic splice, connector, and coupler and the types of connections they form in systems.
2. List the types of extrinsic and intrinsic coupling losses.
3. Understand the degree to which fiber alignment and fiber mismatch problems increase system loss.
4. Detail the score-and-break cleaving process for fiber-end preparation.
5. Identify the types of fiber optic mechanical and fusion splices. Outline the basic splicing techniques for each type of fiber optic splice.
6. List the types of fiber optic connectors. Detail the procedure for installing a fiber optic connector on an optical fiber.
7. Discuss the types of fiber optic passive couplers.

FIBER OPTIC CONNECTIONS

Chapter 1 states that a fiber optic data link performs three basic functions. First, the data link transmitter converts an electrical input signal to an optical signal. Then, the optical fiber transmits this optical signal. Finally, the data link receiver converts the optical signal back to an electrical signal identical to the original input. However, chapter 1 does not describe how optical power transfers from one optical component to another.

This chapter describes how optical power is transferred from one fiber optic component to another. It describes how an optical source launches optical power into a fiber as well as how one optical fiber couples light into another fiber. In fiber optic system design, this launching or coupling of optical power from one component to the next is important.

Fiber optic connections permit the transfer of optical power from one component to another. Fiber optic connections also permit fiber optic systems to be more than just point-to-point data communication links. In fact, fiber optic data links are often of a more complex design than point-to-point data links.

A system connection may require either a fiber optic splice, connector, or coupler. One type of system connection is a permanent connection made by splicing optical fibers together. A fiber optic **splice** makes a permanent joint between two fibers or two groups of fibers. There are two types of fiber optic splices--mechanical splices and fusion splices. Even though removal of some mechanical splices is possible, they are intended to be permanent. Another type of connection that allows for system reconfiguration is a fiber optic **connector**. Fiber optic connectors permit easy coupling and uncoupling of optical fibers. Fiber optic connectors sometimes resemble familiar electrical plugs and sockets. Systems may also divide or combine optical signals between fibers. Fiber optic **couplers** distribute or combine optical signals between fibers. Couplers can distribute an optical signal from a single fiber into several fibers. Couplers may also combine optical signals from several fibers into one fiber.

Fiber optic connection losses may affect system performance. **Poor fiber end preparation** and **poor fiber alignment** are the main causes of coupling loss. Another source of coupling loss is differences in optical properties between the connected fibers. If the connected fibers have different optical properties, such as different numerical apertures, core and cladding diameters, and refractive index profiles, then coupling losses may increase.

OPTICAL FIBER COUPLING LOSS

Ideally, optical signals coupled between fiber optic components are transmitted with no loss of light. However, there is always some type of imperfection present at fiber optic connections that causes some loss of light. It is the amount of optical power lost at fiber optic connections that is a concern of system designers.

The design of fiber optic systems depends on how much light is launched into an optical fiber from an optical source and how much light is coupled between fiber optic components, such as from one fiber to another. The amount of power launched from a source into a fiber depends on the optical properties of both the source and the fiber. The amount of optical power launched into an optical fiber depends on the radiance of the optical source. An optical source's **radiance**, or brightness, is a measure of its optical power launching capability. Radiance is the amount of optical power emitted in a specific direction per unit time by a unit area of emitting surface. For most types of optical sources, only a fraction of the power emitted by the source is launched into the optical fiber.

The loss in optical power through a connection is defined similarly to that of signal attenuation through a fiber. Optical loss is also a log relationship. The loss in optical power through a connection is defined as:

$$\text{loss} = 10 \log_{10} \frac{P_i}{P_o}$$

For example, P_o is the power emitted from the source fiber in a fiber-to-fiber connection. P_i is the power accepted by the connected fiber. In any fiber optic connection, P_o and P_i are the optical power levels measured before and after the joint, respectively.

Fiber-to-fiber connection loss is affected by intrinsic and extrinsic coupling losses. **Intrinsic coupling losses** are caused by inherent fiber characteristics. **Extrinsic coupling losses** are caused by jointing techniques. Fiber-to-fiber connection loss is increased by the following sources of intrinsic and extrinsic coupling loss:

- Reflection losses
- Fiber separation
- Lateral misalignment
- Angular misalignment
- Core and cladding diameter mismatch
- Numerical aperture (NA) mismatch
- Refractive index profile difference
- Poor fiber end preparation

Intrinsic coupling losses are limited by reducing fiber mismatches between the connected fibers. This is done by procuring only fibers that meet stringent geometrical and optical specifications. Extrinsic coupling losses are limited by following proper connection procedures.

Some fiber optic components are modular devices that are designed to reduce coupling losses between components. Modular components can be easily inserted or removed from any system. For example, fiber optic transmitters and receivers are modular components. Fiber optic transmitters and receivers are devices that are generally manufactured with fiber pigtails or fiber optic connectors as shown in figure 4-1. A **fiber pigtail** is a short length of optical fiber (usually 1 meter or less) permanently fixed to the optical source or detector. Manufacturers supply transmitters and receivers with pigtails and connectors because fiber coupling to sources and detectors must be completed during fabrication. Reduced coupling loss results when source-to-fiber and fiber-to-detector coupling is done in a controlled manufacturing environment. Since optical sources and detectors are pigtailed or connectorized, launching optical power is reduced to coupling light from one fiber to another. In fact, most fiber optic connections can be considered fiber-to-fiber.

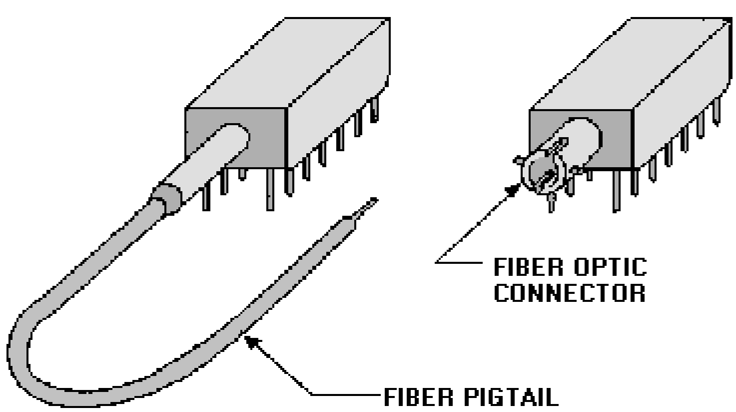


Figure 4-1.—Pigtailed and connectorized fiber optic devices.

REFLECTION LOSSES

When optical fibers are connected, optical power may be reflected back into the source fiber. Light that is reflected back into the source fiber is lost. This reflection loss, called Fresnel reflection, occurs at every fiber interface. **Fresnel reflection** is caused by a step change in the refractive index that occurs at the fiber joint. In most cases, the step change in refractive index is caused by the ends of each fiber being separated by a small gap. This small gap is usually an air gap. In Fresnel reflection, a small portion of the incident light is reflected back into the source fiber at the fiber interface. The ratio (R), shown below, approximates the portion of incident light (light of normal incidence) that is reflected back into the source fiber.

$$R = \left(\frac{n_1 - n_0}{n_1 + n_0} \right)^2$$

R is the fraction of the incident light reflected at the fiber n_1 is the refractive index of the fiber core. n_0 is the refractive index of the medium between the two fibers.

Fresnel refraction occurs twice in a fiber-to-fiber connection. A portion of the optical power is reflected when the light first exits the source fiber. Light is then reflected as the optical signal enters the receiving fiber. Fresnel reflection at each interface must be taken into account when calculating the total fiber-to-fiber coupling loss. Loss from Fresnel reflection may be significant. To reduce the amount of loss from Fresnel reflection, the air gap can be filled with an index matching gel. The refractive index of the index matching gel should match the refractive index of the fiber core. **Index matching gel** reduces the step change in the refractive index at the fiber interface, reducing Fresnel reflection.

In any system, index matching gels can be used to eliminate or reduce Fresnel reflection. The choice of index matching gels is important. Fiber-to-fiber connections are designed to be permanent and require no maintenance. Over the lifetime of the fiber connection, the index matching material must meet specific optical and mechanical requirements. Index matching gels should remain transparent. They should also resist flowing or dripping by remaining viscous. Some index matching gels darken over time while others settle or leak out of fiber connections. If these requirements are not met, then the fiber-to-fiber connection loss will increase over time. In Navy applications, this variation in connection loss over time is unacceptable. In Navy systems, index matching gels are only used in fiber optic splice interfaces.

FIBER ALIGNMENT

A main source of extrinsic coupling loss in fiber-to-fiber connections is poor fiber alignment. The three basic coupling errors that occur during fiber alignment are fiber separation (longitudinal misalignment), lateral misalignment, and angular misalignment. Most alignment errors are the result of mechanical imperfections introduced by fiber jointing techniques. However, alignment errors do result from installers not following proper connection procedures.

With **fiber separation**, a small gap remains between fiber-end faces after completing the fiber connection. Figure 4-2 illustrates this separation of the fiber-end faces.

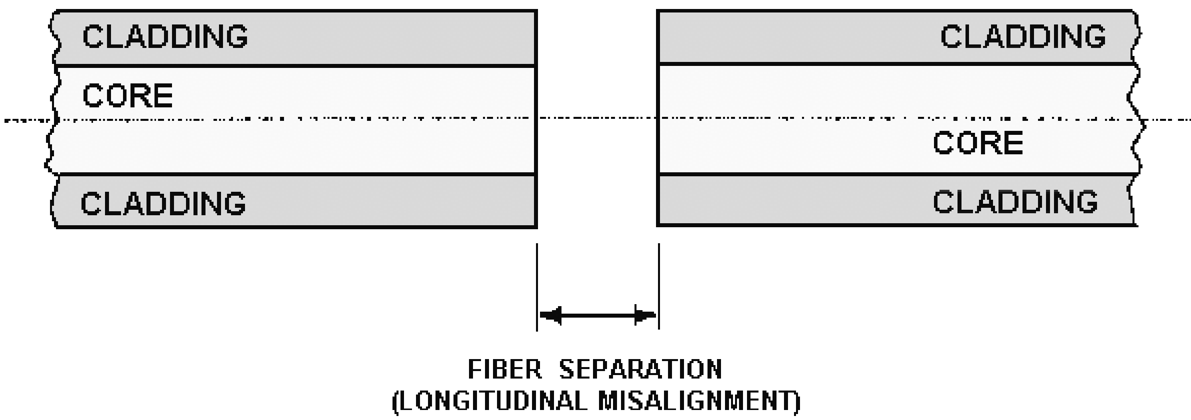


Figure 4-2.—Fiber separation.

Lateral, or axial, misalignment occurs when the axes of the two fibers are offset in a perpendicular direction. Figure 4-3 shows this perpendicular offset of the axes of two connecting fibers.

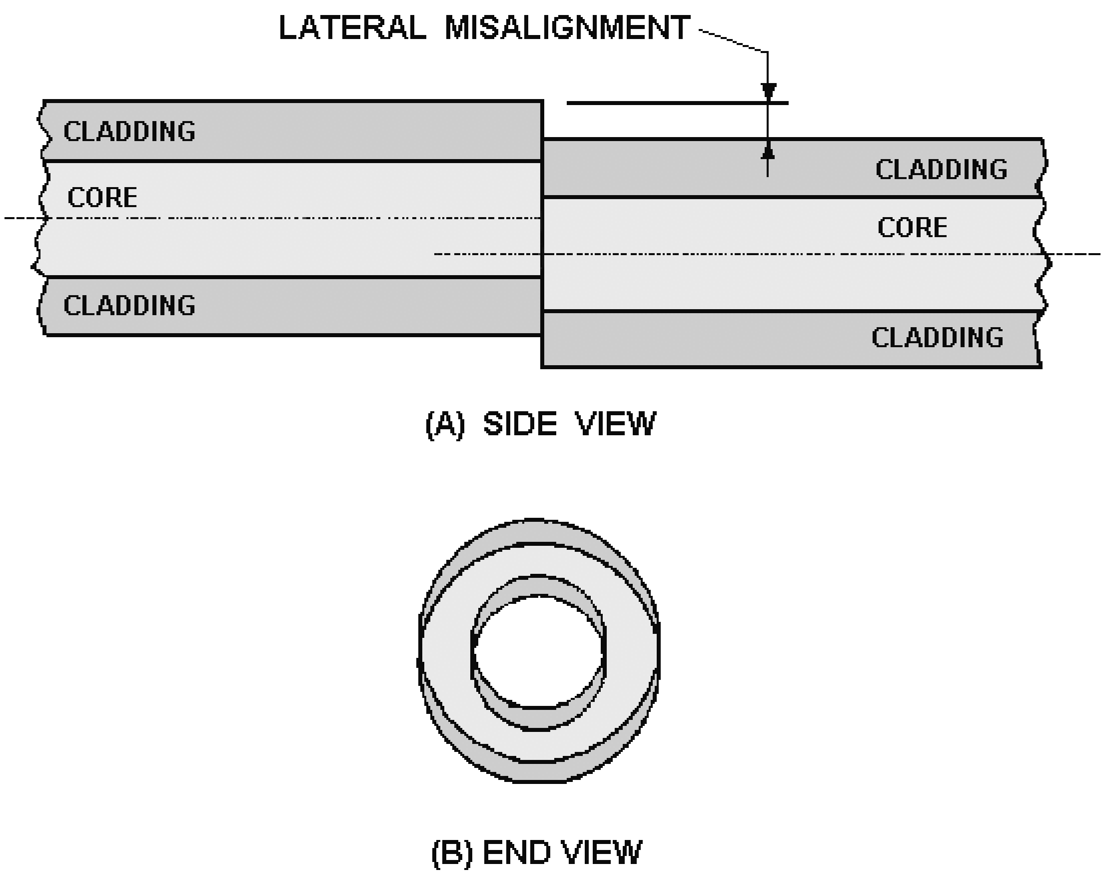


Figure 4-3.—Lateral misalignment.

Angular misalignment occurs when the axes of two connected fibers are no longer parallel. The axes of each fiber intersect at some angle (Θ). Figure 4-4 illustrates the angular misalignment between the core axes.

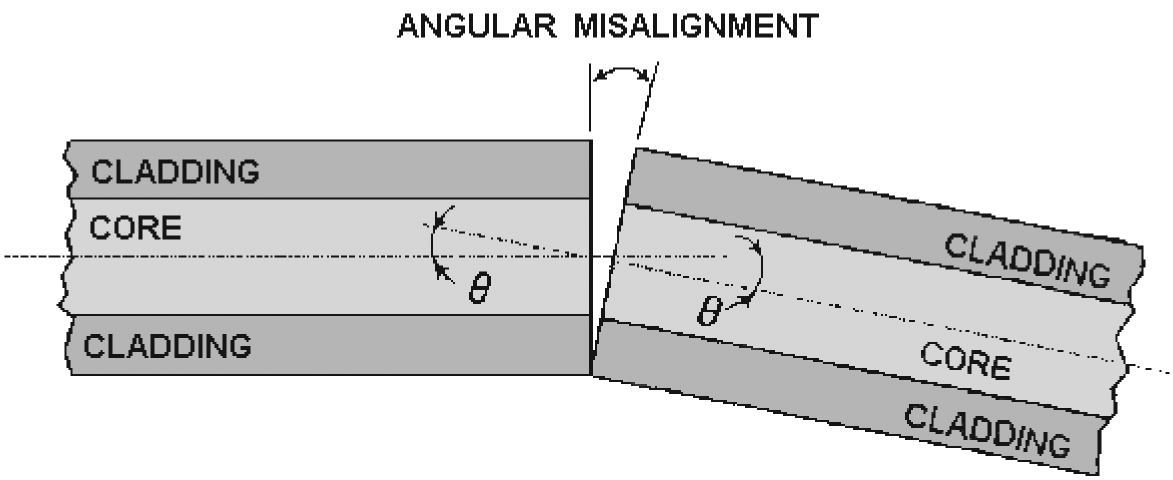


Figure 4-4.—Angular misalignment.

Coupling loss caused by lateral and angular misalignment typically is greater than the loss caused by fiber separation. Loss, caused by fiber separation, is less critical because of the relative ease in limiting the distance of fiber separation. However, in some cases, fiber optic connectors prevent fibers from actual contact. These fiber optic connectors separate the fibers by a small gap. This gap eliminates damage to fiber-end faces during connection. For connectors with an air gap, the use of index matching gel reduces the coupling loss.

Most newer connectors are designed so that the connector ferrule end faces contact when the connector is mated. The connector can be assembled onto the fiber so that the fibers also contact when mated. However, they also can be assembled so that the fibers do not. Whether or not the fibers contact is determined by whether the fiber sticks out slightly from the ferrule or is recessed inside the ferrule. The fiber position can be controlled by the connector polishing technique. The physical contact (PC) polish technique was developed for most connectors so that the fibers would touch when mated. In these types of connectors, index gel is not needed to reduce reflections.

While index matching gel reduces coupling loss from fiber separation, it does not affect loss in lateral misalignment. Additionally, index matching gel usually increases the fiber's coupling loss sensitivity to angular misalignment. Although angular misalignment involves fiber separation, index matching gel reduces the angle at which light is launched from the source fiber. Index matching gel causes less light to be coupled into the receiving fiber. To reduce coupling loss from angular misalignment, the angle Θ should be less than 1º.

Coupling losses due to fiber alignment depend on fiber type, core diameter, and the distribution of optical power among propagating modes. Fibers with large NAs reduce loss from angular misalignment and increase loss from fiber separation. Single mode fibers are more sensitive to alignment errors than multimode fibers because of their small core size. However, alignment errors in multimode fiber connections may disturb the distribution of optical power in the propagating modes, increasing coupling loss.

FIBER END PREPARATION

In fiber-to-fiber connections, a source of extrinsic coupling loss is poor fiber end preparation. An optical fiber-end face must be flat, smooth, and perpendicular to the fiber's axis to ensure proper fiber connection. Light is reflected or scattered at the connection interface unless the connecting fiber end faces are properly prepared. Figure 4-5 shows some common examples of poor fiber ends. It illustrates a fiber-end face **tilt, lip,** and **hackle**. Quality fiber-end preparation is essential for proper system operation.

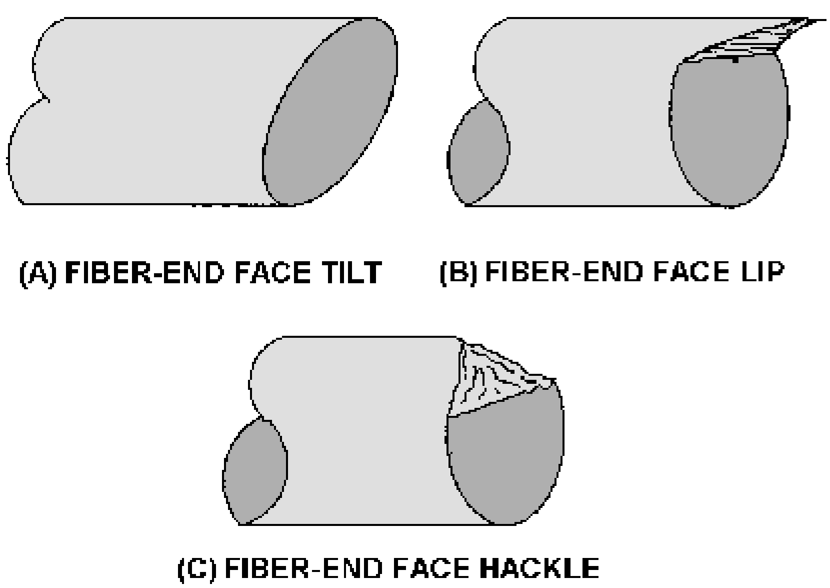


Figure 4-5.—Poor fiber-end preparation.

Fiber-end preparation begins by removing the fiber buffer and coating material from the end of the optical fiber. Removal of these materials involves the use of mechanical strippers or chemical solvents. When using chemical solvents, the removal process must be performed in a well-ventilated area. For this reason mechanical strippers are used for buffer and coating removal in the shipboard environment. After removing the buffer and coating material, the surface of the bare fiber is wiped clean using a wiping tissue. The wiping tissue must be wet with isopropyl alcohol before wiping.

The next step in fiber-end preparation involves cleaving the fiber end to produce a smooth, flat fiber-end face. The **score-and-break**, or scribe-and-break, method is the basic fiber cleaving technique for preparing optical fibers for coupling. The score-and-break method consists of lightly scoring (nicking) the outer surface of the optical fiber and then placing it under tension until it breaks. A heavy metal or diamond blade is used to score the fiber. Once the scoring process is complete, fiber tension is increased until the fiber breaks. The fiber is placed under tension either by pulling on the fiber or by bending the fiber over a curved surface.

Figure 4-6 shows the setup for the score-and-break procedure for fiber cleaving. Under constant tension, the score-and-break method for cleaving fibers produces a quality fiber end. This fiber end is good enough to use for some splicing techniques. However, additional fiber-end preparation is necessary to produce reliable low-loss connections when using fiber optic connectors.

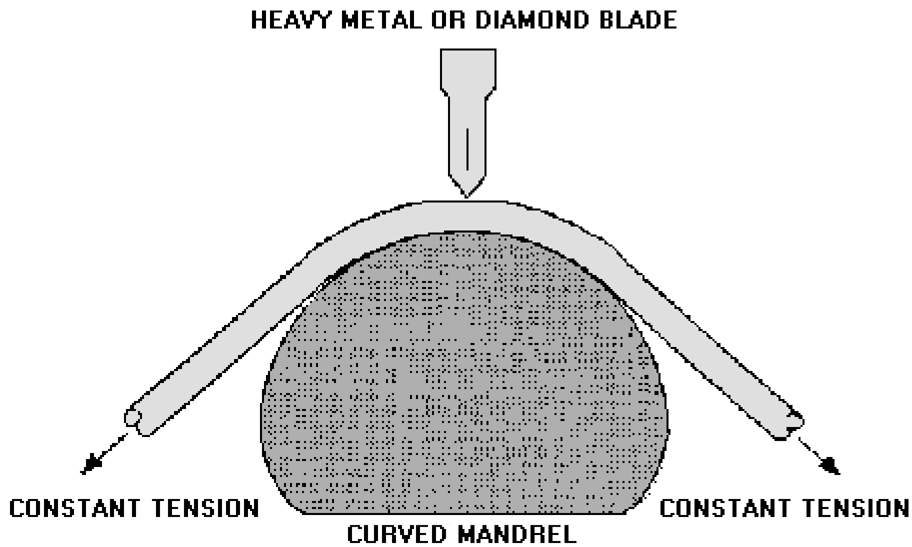


Figure 4-6.—Score-and-break procedure for fiber cleaving.

Polishing the fiber ends removes most surface imperfections introduced by the fiber cleaving process. Fiber polishing begins by inserting the cleaved fiber into the ferrule of a connector assembly. A ferrule is a fixture, generally a rigid tube, used to hold the stripped end of an optical fiber in a fiber optic connector. An individual fiber is epoxied within the ferrule. The connector with the optical fiber cemented within the ferrule can then be mounted into a special polishing tool for polishing.

Figure 4-7 shows one type of fiber polishing tool for finishing optical fibers in a connector assembly. Various types of connector assemblies are discussed later in this chapter. In this type of polishing tool, the connector assembly is threaded onto the polishing tool. The connector ferrule passes through the center of the tool allowing the fiber-end face to extend below the tool's circular, flat bottom. The optical fiber is now ready for polishing.

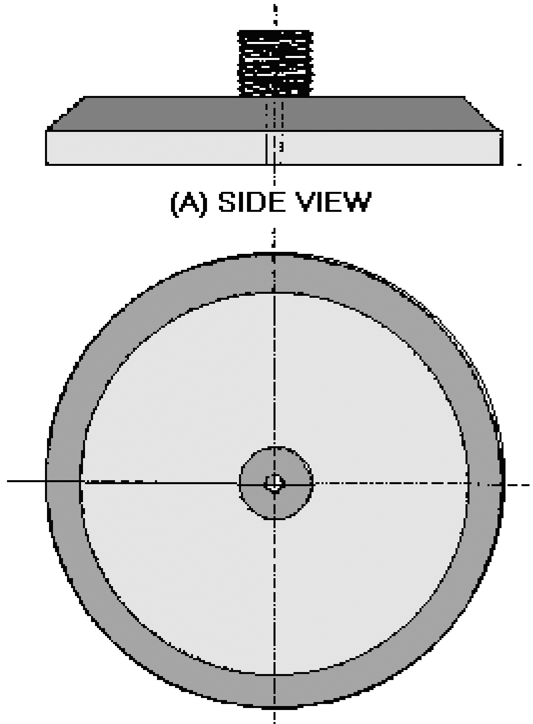


Figure 4-7.—Fiber polishing tool.

Fiber polishing involves a step-down approach. The first step is to give the surface of the fiber end a rough polish. **Rough-polishing** occurs when the fiber, mounted to the polishing tool, moves over a 5µ to 15µ gritabrasive paper. The mounted fiber moves over the abrasive paper in a figure-eight motion. The next step involves giving the surface of the fiber end a fine polish. **Fine-polishing** occurs when the mounted fiber moves over a 0.3µ to 1µ gritabrasive paper in the same figure-eight motion. Fiber inspection and cleanliness are important during each step of fiber polishing. Fiber inspection is done visually by the use of a standard microscope at 200 to 400 times magnification.

A standard microscope can be used to determine if the fiber-end face is flat, concave, or convex. If different parts of the fiber-end face have different focus points, the end face is not flat. If all parts of the fiber-end face are in focus at the same time, the end face is flat.

FIBER MISMATCHES

Fiber mismatches are a source of intrinsic coupling loss. As stated before, intrinsic coupling loss results from differences (mismatches) in the inherent fiber characteristics of the two connecting fibers. Fiber mismatches occur when manufacturers fail to maintain optical or structural (geometrical) tolerances during fiber fabrication.

Fiber mismatches are the result of inherent fiber characteristics and are independent of the fiber jointing techniques. Types of fiber mismatches include fiber geometry mismatches, NA mismatch, and refractive index profile difference. Fiber geometry mismatches include core diameter, cladding diameter, core ellipticity, and core-cladding concentricity differences. Figure 4-8 illustrates each type of optical and geometrical fiber mismatch. Navy fiber specifications tightly specify these parameters to minimize coupling losses from fiber mismatches.

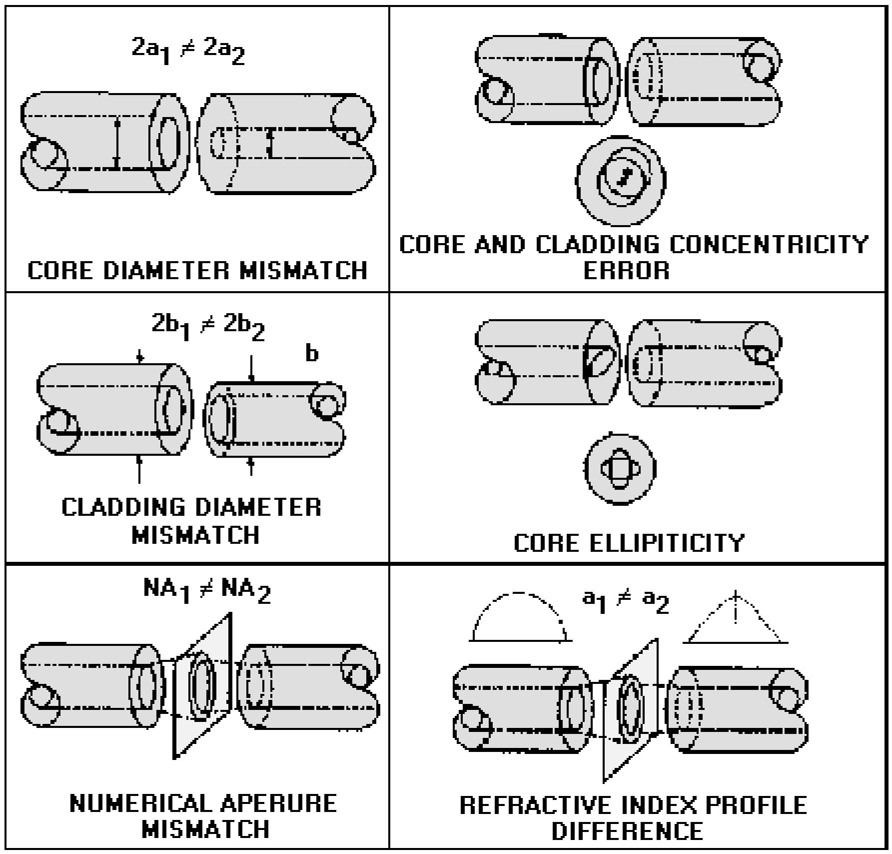


Figure 4-8.—Types of optical and geometrical fiber mismatches that cause intrinsic coupling loss.

Core diameter and NA mismatch have a greater effect on intrinsic coupling loss than the other types of fiber mismatches. In multimode fiber connections, the coupling loss resulting from core diameter mismatch, NA mismatch, and refractive index profile difference depends on the characteristics of the launching fiber. Coupling loss from **core diameter mismatch** results only if the launching fiber has a larger core radius (a) than the receiving fiber. Coupling loss from **NA mismatch** results only if the launching fiber has a higher NA than the receiving fiber. Coupling loss from **refractive index profile difference** results only if the launching fiber has a larger profile parameter (α) than the receiving fiber.

FIBER OPTIC SPLICES

A **fiber optic splice** is a permanent fiber joint whose purpose is to establish an optical connection between two individual optical fibers. System design may require that fiber connections have specific optical properties (low loss) that are met only by fiber-splicing. Fiber optic splices also permit repair of optical fibers damaged during installation, accident, or stress. System designers generally require fiber splicing whenever repeated connection or disconnection is unnecessary or unwanted.

Mechanical and fusion splicing are two broad categories that describe the techniques used for fiber splicing. A **mechanical splice** is a fiber splice where mechanical fixtures and materials perform fiber alignment and connection. A **fusion splice** is a fiber splice where localized heat fuses or melts the ends of two optical fibers together. Each splicing technique seeks to optimize splice performance and reduce splice loss. Low-loss fiber splicing results from proper fiber end preparation and alignment.

Fiber splice alignment can involve passive or active fiber core alignment. Passive alignment relies on precision reference surfaces, either grooves or cylindrical holes, to align fiber cores during splicing. Active alignment involves the use of light for accurate fiber alignment. Active alignment may consist of either monitoring the loss through the splice during splice alignment or by using a microscope to accurately align the fiber cores for splicing. To monitor loss either an optical source and optical power meter or an optical time domain reflectometer (OTDR) are used. Active alignment procedures produce low-loss fiber splices.

MECHANICAL SPLICES

Mechanical splicing involves using mechanical fixtures to align and connect optical fibers. Mechanical splicing methods may involve either passive or active core alignment. Active core alignment produces a lower loss splice than passive alignment. However, passive core alignment methods can produce mechanical splices with acceptable loss measurements even with single mode fibers.

In the strictest sense, a mechanical splice is a permanent connection made between two optical fibers. Mechanical splices hold the two optical fibers in alignment for an indefinite period of time without movement. The amount of splice loss is stable over time and unaffected by changes in environmental or mechanical conditions.

If high splice loss results from assembling some mechanical splices, the splice can be reopened and the fibers realigned. Realignment includes wiping the fiber or ferrule end with a soft wipe, reinserting the fiber or ferrule in a new arrangement, and adding new refractive index material. Once producing an acceptable mechanical splice, splice realignment should be unnecessary because most mechanical splices are environmentally and mechanically stable within their intended application.

The types of mechanical splices that exist for mechanical splicing include glass, plastic, metal, and ceramic tubes; and V-groove and rotary devices. Materials that assist mechanical splices in splicing fibers include transparent adhesives and index matching gels. **Transparent adhesives** are epoxy resins that seal mechanical splices and provide index matching between the connected fibers.

Glass or Ceramic Alignment Tube Splices

Mechanical splicing may involve the use of a glass or ceramic alignment tube, or capillary. The inner diameter of this glass or ceramic tube is only slightly larger than the outer diameter of the fiber. A transparent adhesive, injected into the tube, bonds the two fibers together. The adhesive also provides index matching between the optical fibers. Figure 4-9 illustrates fiber alignment using a glass or ceramic tube. This splicing technique relies on the inner diameter of the alignment tube. If the inner diameter is too large, splice loss will increase because of fiber misalignment. If the inner diameter is too small, it is impossible to insert the fiber into the tube.

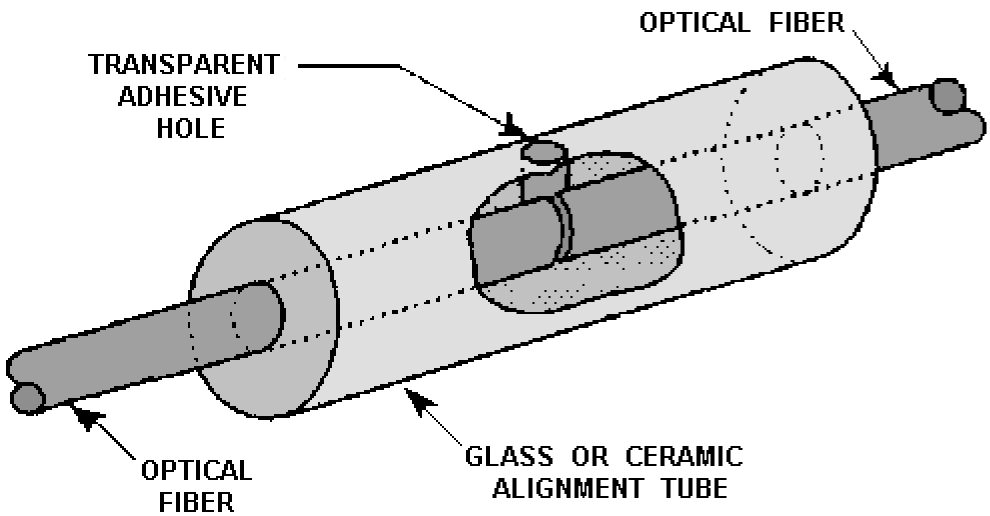


Figure 4-9.—A glass or ceramic alignment tube for mechanical splicing.

V-Grooved Splices

Mechanical splices may also use either a grooved substrate or positioning rods to form suitable V-grooves for mechanical splicing. The basic V-grooved device relies on an open grooved substrate to perform fiber alignment. When inserting the fibers into the grooved substrate, the V-groove aligns the cladding surface of each fiber end. A transparent adhesive makes the splice permanent by securing the fiber ends to the grooved substrate. Figure 4-10 illustrates this type of open V-grooved splice.

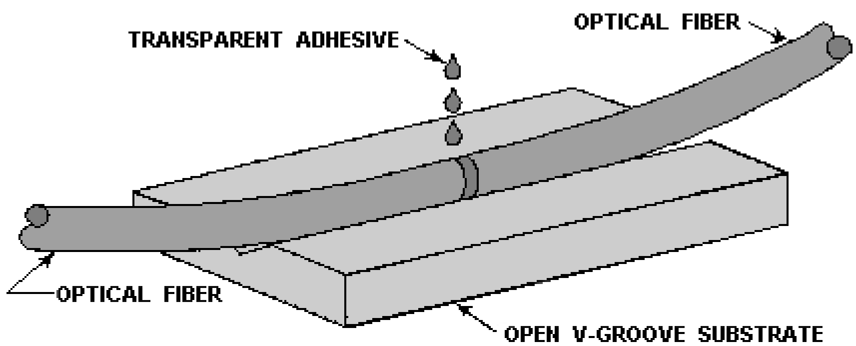


Figure 4-10.—Open V-grooved splice.

V-grooved splices may involve sandwiching the butted ends of two prepared fibers between a V-grooved substrate and a flat glass plate. Additional V-grooved devices use two or three positioning rods to form a suitable V-groove for splicing. The V-grooved device that uses two positioning rods is the spring V-grooved splice. This splice uses a groove formed by two rods positioned in a bracket to align the fiber ends. The diameter of the positioning rods permits the outer surface of each fiber end to extend above the groove formed by the rods. A flat spring presses the fiber ends into the groove maintaining fiber alignment. Transparent adhesive completes the assembly process by bonding the fiber ends and providing index matching. Figure 4-11 is an illustration of the spring V-grooved splice. A variation of this splice uses a third positioning rod instead of a flat spring. The rods are held in place by a heat-shrinkable band, or tube.

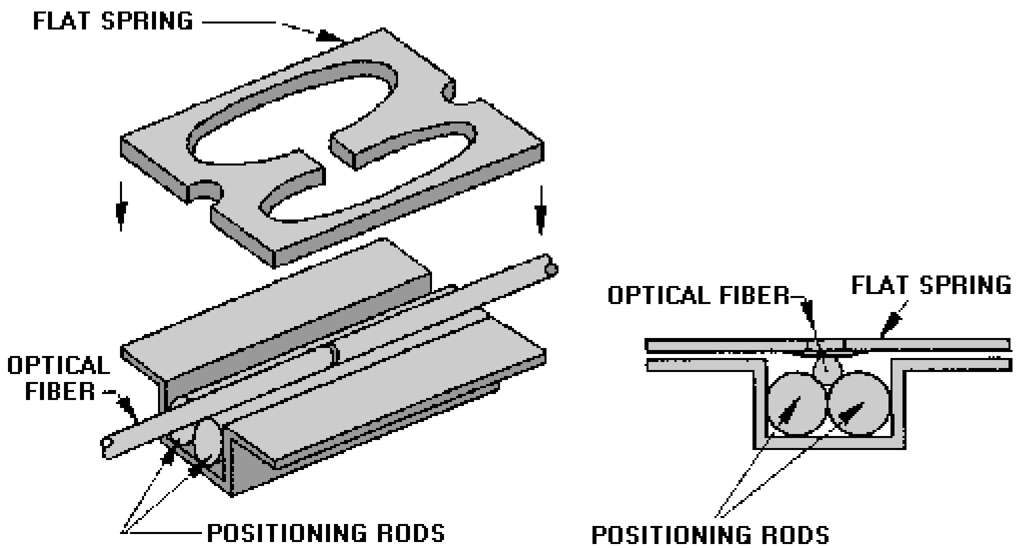


Figure 4-11.—Spring V-grooved mechanical splice.

Rotary Splices

In a rotary splice, the fibers are mounted into a glass ferrule and secured with adhesives. The splice begins as one long glass ferrule that is broken in half during the assembly process. A fiber is inserted into each half of the tube and epoxied in place using an ultraviolet cure epoxy. The endface of the tubes are then polished and placed together using the alignment sleeve. Figure 4-12 is an illustration of a rotary splice. The fiber ends retain their original orientation and have added mechanical stability since each fiber is mounted into a glass ferrule and alignment sleeve. The rotary splice may use index matching gel within the alignment sleeve to produce low-loss splices.

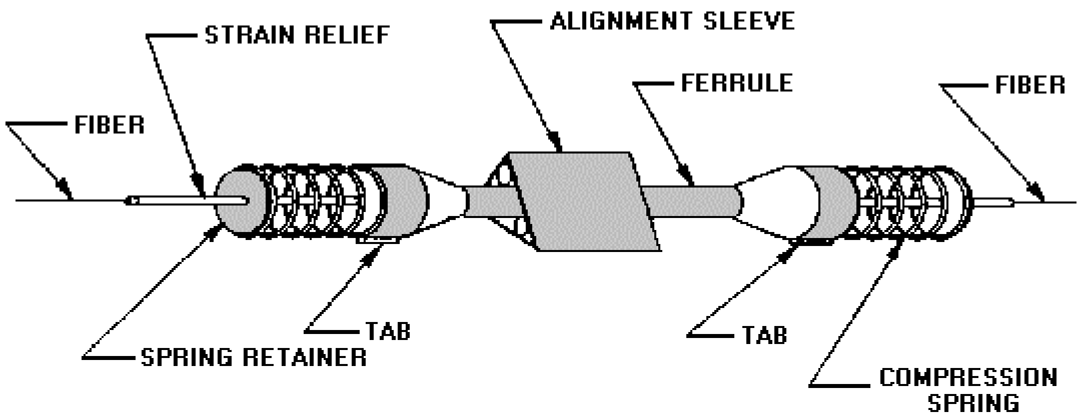


Figure 4-12.—Rotary mechanical splice.

In shipboard applications, the Navy recommends using the rotary splice. The rotary splice is a low-loss mechanical splice that provides stable environmental and mechanical performance in the Navy environment. Stable performance means that splice loss does not vary significantly with changes in temperature or other environmental or mechanical conditions. Completing a rotary splice also requires only a small amount of training, or expertise. This shorter training time is another reason why the Navy recommends using the rotary splice over other mechanical or fusion splicing techniques.

FUSION SPLICES

The process of fusion splicing involves using localized heat to melt or fuse the ends of two optical fibers together. The splicing process begins by preparing each fiber end for fusion. Fusion splicing requires that all protective coatings be removed from the ends of each fiber. The fiber is then cleaved using the score-and-break method. The quality of each fiber end is inspected using a microscope. In fusion splicing, splice loss is a direct function of the angles and quality of the two fiber-end faces.

The basic fusion splicing apparatus consists of two fixtures on which the fibers are mounted and two electrodes. Figure 4-13 shows a basic fusion-splicing apparatus. An inspection microscope assists in the placement of the prepared fiber ends into a fusion-splicing apparatus. The fibers are placed into the apparatus, aligned, and then fused together. Initially, fusion splicing used nichrome wire as the heating element to melt or fuse fibers together. New fusion-splicing techniques have replaced the nichrome wire with carbon dioxide (CO_2) lasers, electric arcs, or gas flames to heat the fiber ends, causing them to fuse together. The small size of the fusion splice and the development of automated fusion-splicing machines have made **electric arc fusion** (arc fusion) one of the most popular splicing techniques in commercial applications.

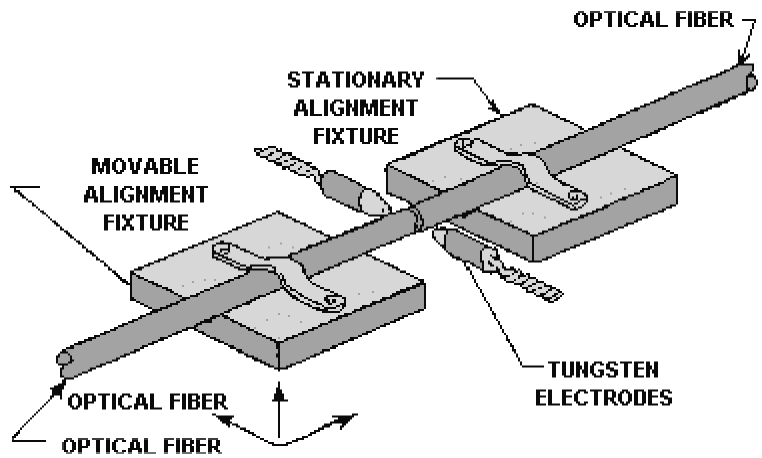


Figure 4-13.—A basic fusion splicing apparatus.

Arc fusion involves the discharge of electric current across a gap between two electrodes. By placing the fiber ends between the electrodes, the electric discharge melts or fuses the ends of each fiber. Figure 4-13 shows the placement of the fiber ends between tungsten electrodes during arc fusion. Initially, a small gap is present between the fiber ends. A short discharge of electric current is used to prepare the fiber ends for fusion. During this short discharge, known as **prefusion**, the fiber ends are cleaned and rounded to eliminate any surface defects that remain from fiber cleaving. Surface defects can cause core distortions or bubble formations during fiber fusion. A fusion splice results when the fiber ends are pressed together, actively aligned, and fused using a longer and stronger electric discharge. Automated fusion splicers typically use built-in local optical power launch/detection schemes for aligning the fibers.

During fusion, the surface tension of molten glass tends to realign the fibers on their outside diameters, changing the initial alignment. When the fusion process is complete, a small core distortion may be present. Small core distortions have negligible effects on light propagating through multimode fibers. However, a small core distortion can significantly affect single mode fiber splice loss. The core distortion, and the splice loss, can be reduced by limiting the arc discharge and decreasing the gap distance between the two electrodes. This limits the region of molten glass. However, limiting the region of molten glass reduces the tensile strength of the splice.

Fusion splicing yields typically vary between 25 and 75 percent depending on the strength and loss requirements for the splice and other factors. Other factors affecting splice yields include the condition of the splicing machine, the experience of the splice personnel, and environmental conditions. Since fusion splicing is inherently permanent, an unacceptable fusion splice requires breakage and refabrication of the splice.

In general, fusion splicing takes a longer time to complete than mechanical splicing. Also, yields are typically lower making the total time per successful splice much longer for fusion splicing. Both the yield and splice time are determined to a large degree by the expertise of the fusion splice operator. Fusion splice operators must be highly trained to consistently make low-loss reliable fusion splices. For these reasons the fusion splice is not recommended for use in Navy shipboard applications.

MULTIFIBER SPLICING

Normally, multifiber splices are only installed on ribbon type fiber optic cables. Multifiber splicing techniques can use arc fusion to restore connection, but most splicing techniques use mechanical splicing methods. The most common mechanical splice is the ribbon splice.

A ribbon splice uses an etched silicon chip, or grooved substrate, to splice the multiple fibers within a flat ribbon. The spacing between the etched grooves of the silicon chip is equal to the spacing between the fibers in the flat ribbon. Before placing each ribbon on the etched silicon chip, each fiber within the ribbon cable is cleaved. All of the fibers are placed into the grooves and held in place with a flat cover. Typically, an index matching gel is used to reduce the splice loss. Figure 4-14 shows the placement of the fiber ribbon on the etched silicon chip.

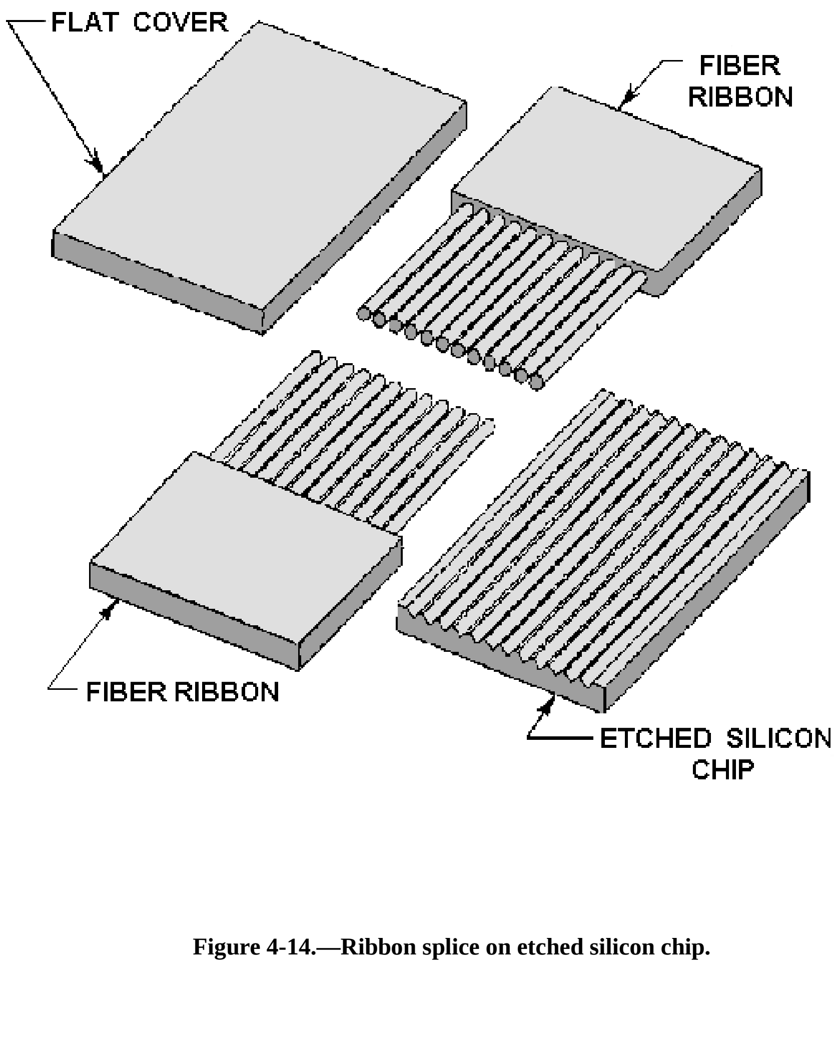


Figure 4-14.—Ribbon splice on etched silicon chip.

FIBER OPTIC CONNECTORS

A fiber optic connector is a demateable device that permits the coupling of optical power between two optical fibers or two groups of fibers. Designing a device that allows for repeated fiber coupling without significant loss of light is difficult. Fiber optic connectors must maintain fiber alignment and provide repeatable loss measurements during numerous connections. Fiber optic connectors should be easy to assemble (in a laboratory or field environment) and should be cost effective. They should also be reliable. Fiber optic connections using connectors should be insensitive to environmental conditions, such as temperature, dust, and moisture. Fiber optic connector designs attempt to optimize connector performance by meeting each of these conditions.

Fiber optic connector coupling loss results from the same loss mechanisms described earlier in this chapter. Coupling loss results from poor fiber alignment and end preparation (extrinsic losses), fiber mismatches (intrinsic loss), and Fresnel reflection. The total amount of insertion loss for fiber optic connectors should remain below 1 dB. Fiber alignment is the critical parameter in maintaining the total insertion loss below the required level. There is only a small amount of control over coupling loss resulting from fiber mismatches, because the loss results from inherent fiber properties. Index matching gels cannot be used to reduce Fresnel losses, since the index matching gels attract dust and dirt to the connection.

Fiber optic connectors can also reduce system performance by introducing modal and reflection noise. The cause of modal noise in fiber optic connectors is the interfering of the different wavefronts of different modes within the fiber at the connector interface. Modal noise is eliminated by using only single mode fiber with laser sources and only low-coherence sources such as light-emitting diodes with multimode fiber. Fiber optic connectors can introduce reflection noise by reflecting light back into the optical source. Reflection noise is reduced by index matching gels, physical contact polishes, or antireflection coatings. Generally, reflection noise is only a problem in high data rate single mode systems using lasers.

Butt-jointed connectors and **expanded-beam connectors** are the two basic types of fiber optic connectors. Fiber optic **butt-jointed connectors** align and bring the prepared ends of two fibers into close contact. The end-faces of some butt-jointed connectors touch, but others do not depending upon the connector design. Types of butt-jointed connectors include cylindrical ferrule and biconical connectors. Fiber optic **expanded-beam connectors** use two lenses to first expand and then refocus the light from the transmitting fiber into the receiving fiber. Single fiber butt-jointed and expanded beam connectors normally consist of two plugs and an adapter (coupling device). Figure 4-15 shows how to configure each plug and adapter when making the connection between two optical fibers.

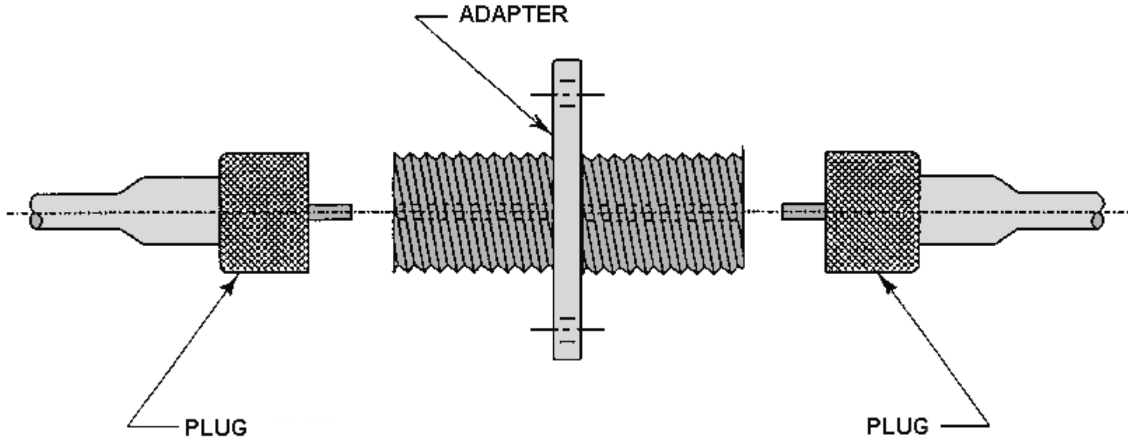


Figure 4-15.—Plug-adapter-plug configuration.

Ferrule connectors use two cylindrical plugs (referred to as ferrules), an alignment sleeve, and sometimes axial springs to perform fiber alignment. Figure 4-16 provides an illustration of this basic ferrule connector design. Precision holes drilled or molded through the center of each ferrule allow for fiber insertion and alignment. Precise fiber alignment depends on the accuracy of the central hole of each ferrule. When the fiber ends are inserted, an adhesive (normally an epoxy resin) bonds the fiber inside the ferrule. The fiber-end faces are polished until they are flush with the end of the ferrule to achieve a low-loss fiber connection. Fiber alignment occurs when the ferrules are inserted into the alignment sleeve. The inside diameter of the alignment sleeve aligns the ferrules, which in turn align the fibers. Ferrule connectors lock the ferrules in the alignment sleeve using a threaded outer shell or some other type of coupling mechanism.

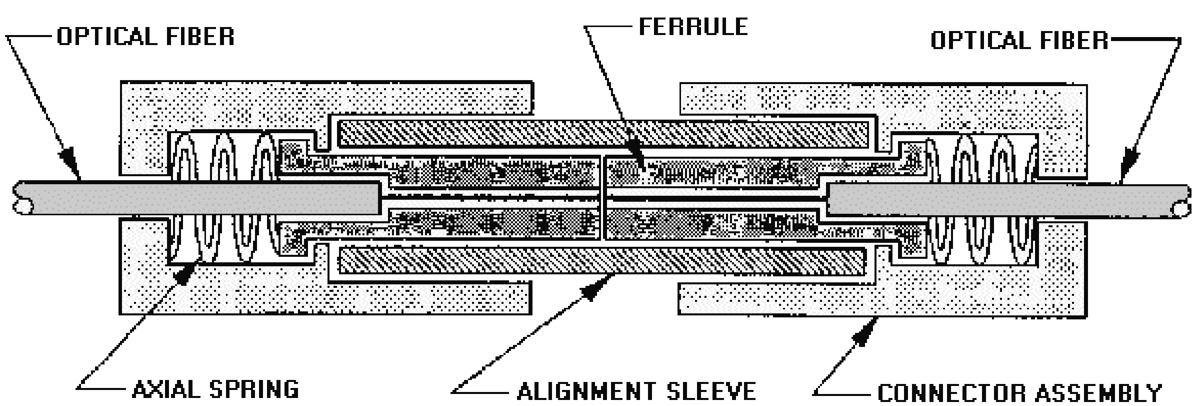


Figure 4-16.—Basic ferrule connector design.

As stated before, fiber alignment depends on an accurate hole through the center of the ferrule. Normally, ferrule connectors use ceramic or metal ferrules. The center hole is generally drilled in a metal ferrule. Drilling an accurate hole through the entire metal ferrule can be difficult. To improve fiber alignment, some metal ferrule connectors use precision watch-jeweled centering. In precision watch-jeweled centering, a watch jewel with a precision centered hole is placed in the tip of the ferrule. The central hole of the watch jewel centers the fiber with respect to the axis of the cylindrical ferrule. The watch jewel provides for better fiber alignment, because regulating the hole tolerance of the watch jewel is easier than maintaining a precise hole diameter when drilling through an entire ferrule.

The center hole in a ceramic ferrule is created by forming the ferrule around a precision wire, which is then removed. This method produces holes accurately centered in the ferrule. Most cylindrical ferrule connectors now use ceramic ferrules. The Straight Tip (ST® connector is an example of a ceramic ferrule connector. (ST is a registered trademark of AT&T.)

Other cylindrical ferrule connectors have a ferrule that contains both metal and ceramic. For these connectors a ceramic capillary is placed within the tip of a metal ferrule to provide for precision fiber alignment. The ceramic capillary is a ceramic tube with a small inner diameter that is just larger than the diameter of the fiber. Figure 4-17 shows the placement of the ceramic capillary within the metal ferrule.

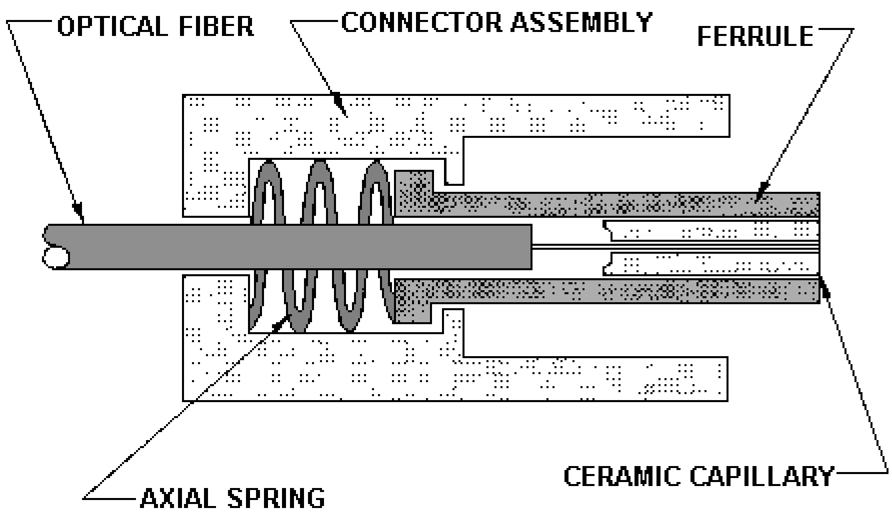


Figure 4-17.—A ceramic capillary set within a metal ferrule.

Another type of butt-jointed connector is the biconical connector. Biconical connectors use two conical plugs, a double conical alignment sleeve, and axial springs to perform fiber alignment. Figure 4-18 is an illustration of this basic biconical connector design. Formation of the plugs and alignment sleeve involves transfer molding. Transfer molding uses silica-filled epoxy resin to mold the conical plug directly to the fiber or around a cast (precision wire). After connecting the conical plugs to the optical fibers, the fiber-end faces are polished before the plugs are inserted into the molded alignment sleeve. During fiber insertion, the inside surface of the double conical sleeve performs fiber alignment, while the axial springs push the fiber ends into close contact. If the alignment sleeve permits the fibers to actually become in contact, then the axial spring provides enough force to maintain fiber contact but prevent damage to the fiber-end faces. Normally, biconical connectors lock the fibers in alignment using a threaded outer shell.

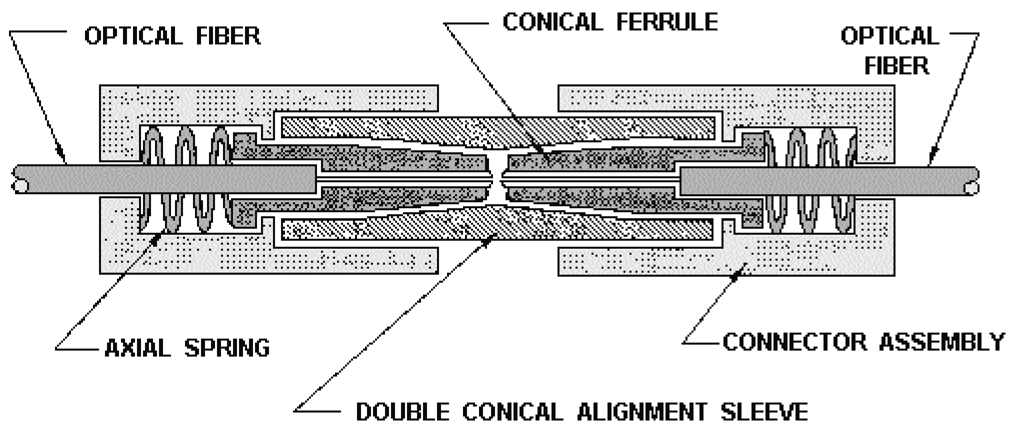


Figure 4-18.—Biconical connector design.

Multifiber connectors join and align multifiber cables to reduce the time it takes to connect multiple fibers. One type of multifiber connector is the array connector. The array connector is used to connect individual ribbons of ribbon-type cables. The array connector is similar to the ribbon splice. In the array connector, the fibers of each ribbon are epoxied into grooves of a silicon chip so that the fiber ends protrude from the end of the chip. The chip and the protruding fibers are polished flat for connection. Each half of the connector is prepared separately before being butt-jointed. A spring clip and two grooved metal-backed plates are used to align and connect the stacked ribbons of the two ribbon cables. Array connectors may also use an alignment sleeve with V-grooved silicon chips and metal springs to align and connect stacked ribbons. Figure 4-19 shows the spring clip method of array connector alignment. The multifiber array connector is only one example of a multiple connector. Many types of multiple connectors exist that connect different types of multifiber cables.

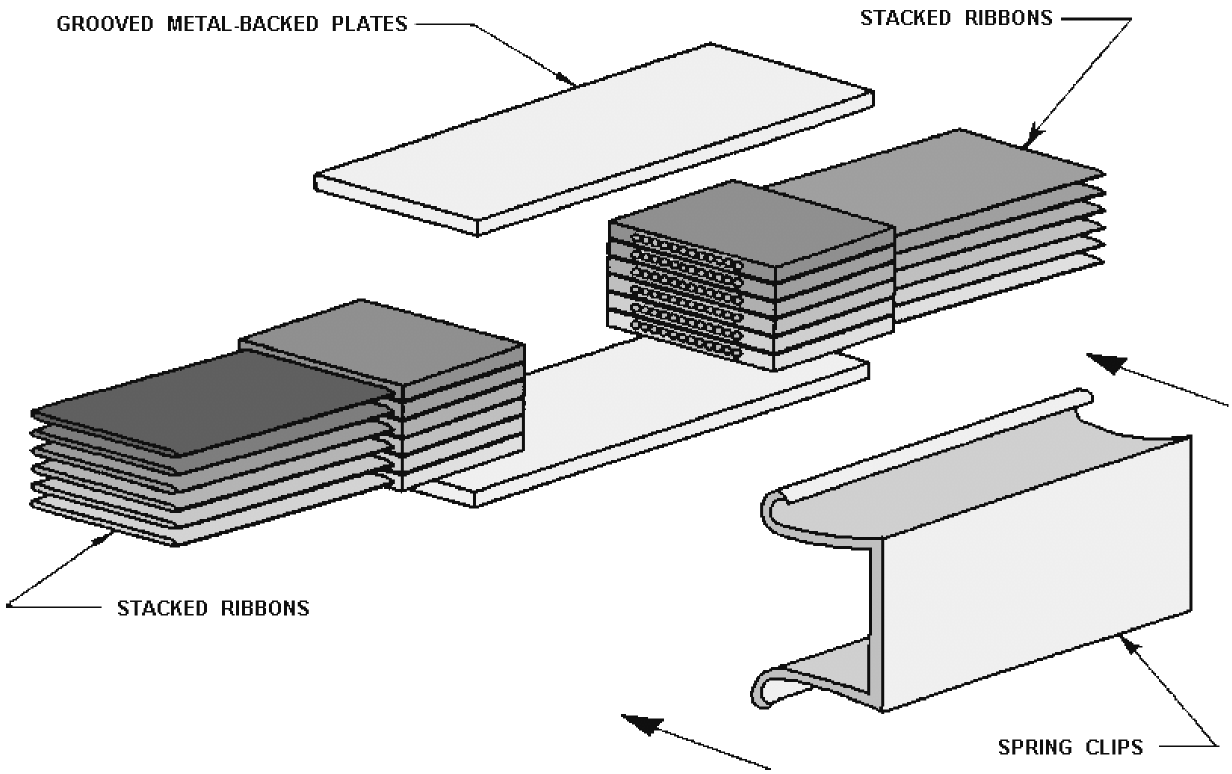


Figure 4-19.—Spring clip method of ribbon connection.

Figure 4-20 shows how an expanded-beam connector uses two lenses to expand and then refocus the light from the transmitting fiber into the receiving fiber. Expanded-beam connectors are normally plug-adapter-plug type connections. Fiber separation and lateral misalignment are less critical in expanded-beam coupling than in butt-jointing. The same amount of fiber separation and lateral misalignment in expanded beam coupling produces a lower coupling loss than in butt-jointing. However, angular misalignment is more critical. The same amount of angular misalignment in expanded-beam coupling produces a higher loss than in butt-jointing. Expanded-beam connectors are also much harder to produce. Present applications for expanded-beam connectors include multifiber connections, edge connections for printed circuit boards, and other applications.

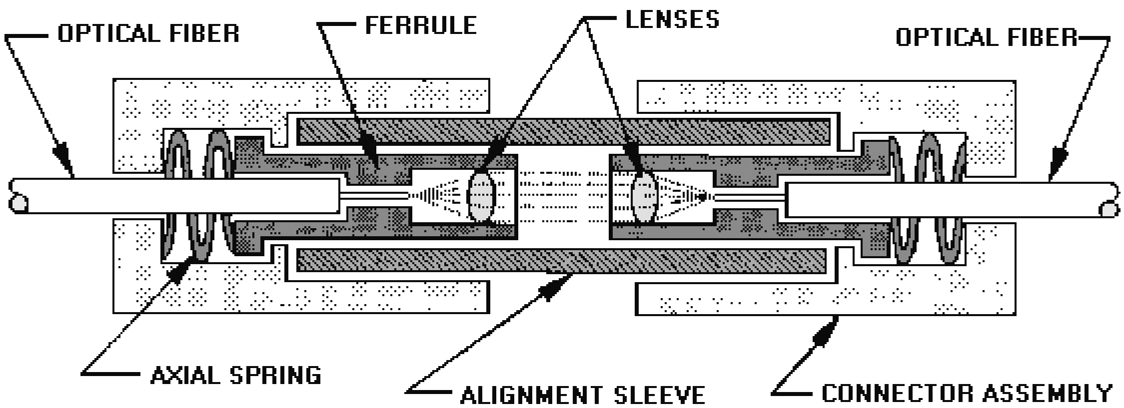


Figure 4-20.—Expanded-beam connector operation.

MILITARY CONNECTORS

Light-duty connectors and **heavy-duty connectors** are two ways that the Navy classifies fiber optic connectors. Light-duty connector shipboard applications include locations that protect the connectors from the environment, such as in a junction box or equipment enclosure. Heavy-duty applications require a very rugged, stand-alone, sealed connector. A heavy-duty connector must also withstand pulls and tugs on the fiber cable without disrupting system operation. Light-duty connectors can be of the ferrule, biconical, or expanded-beam designs. Ferrule-type ST® connectors are becoming the commercial connector of choice for local area network (LAN) and data transfer links and are the standard connector for Navy light duty applications. This connector is described in specification sheets 16, 17, and 18 of MIL-C-83522. Figure 4-21 shows the ST type of light-duty connector.

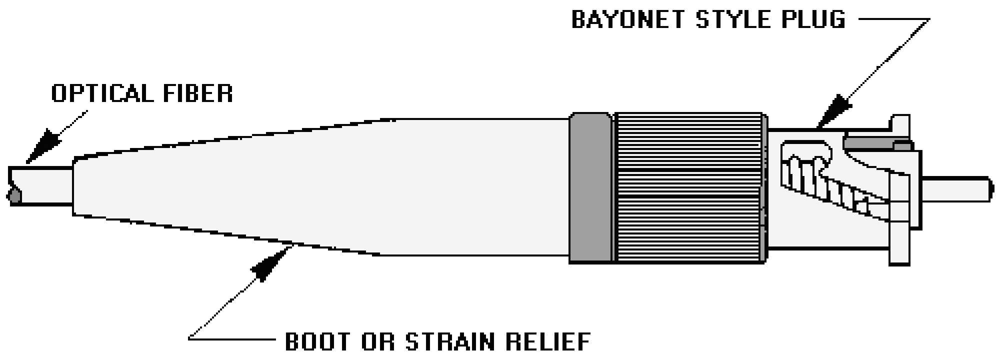


Figure 4-21.—ST light-duty connector.

Figure 4-22 shows one type of heavy-duty connector designed for use in harsh Navy environments. This connector is described by the military specification MIL-C-28876. This connector comes in various sizes capable of terminating 2, 4, 6, or 8 fibers. Each fiber termination, called a terminus, is of the cylindrical ferrule type. Two slightly different termini are used to form a connection; a pin terminus and a socket terminus. The pin terminus consists of a terminus body, which holds the terminus within the connector shell and a ceramic ferrule. The socket terminus consists of a terminus body, a ceramic ferrule, and an alignment sleeve, which attaches to the ceramic ferrule. Fiber alignment occurs when the pin terminus slides into the alignment sleeve of the socket terminus. The termini are held within an insert in the connector shell. When the connector halves are mated, the connector inserts align the mating termini, which then align the mating fibers. The connector shell and backshell protect the termini from the surrounding environment and provide strain relief for the multifiber cable.

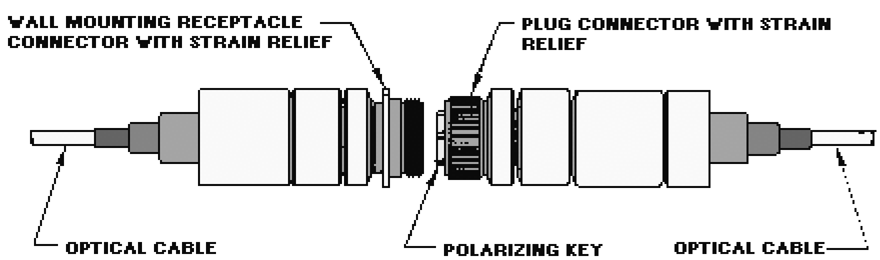


Figure 4-22.—MIL-C-28876 heavy-duty connector.

FIBER OPTIC COUPLERS

Some fiber optic data links require more than simple point-to-point connections. These data links may be of a much more complex design that requires multi-port or other types of connections. Figure 4-23 shows some example system architectures that use more complex link designs. In many cases these types of systems require fiber optic components that can redistribute (combine or split) optical signals throughout the system.

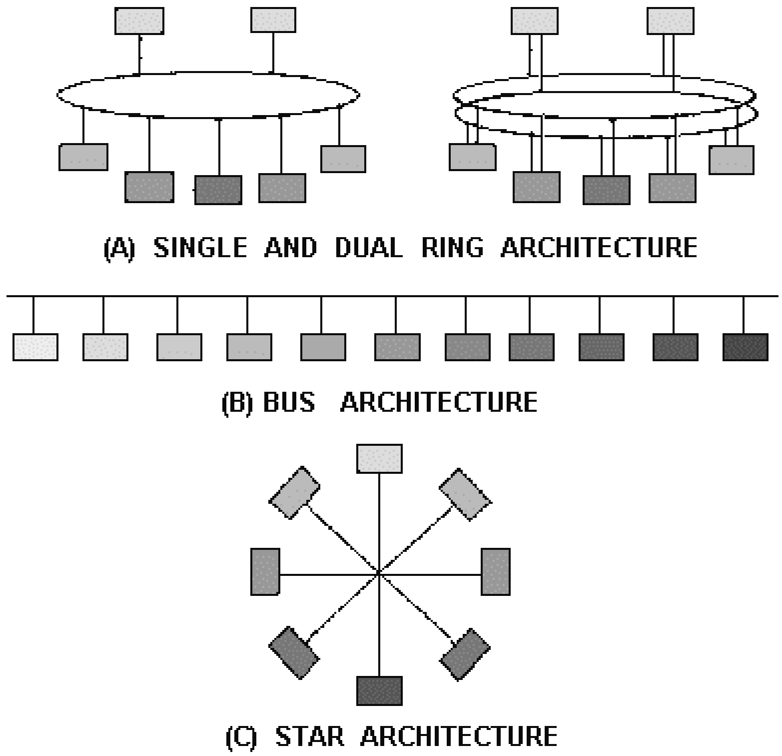


Figure 4-23.—Examples of complex system architectures.

One type of fiber optic component that allows for the redistribution of optical signals is a fiber optic coupler. A fiber optic coupler is a device that can distribute the optical signal (power) from one fiber among two or more fibers. A fiber optic coupler can also combine the optical signal from two or more fibers into a single fiber. Fiber optic couplers attenuate the signal much more than a connector or splice because the input signal is divided among the output ports. For example, with a 1×2 fiber optic coupler, each output is less than one-half the power of the input signal (over a 3 dB loss).

Fiber optic couplers can be either active or passive devices. The difference between active and passive couplers is that a **passive coupler** redistributes the optical signal without optical-to-electrical conversion. Active couplers are electronic devices that split or combine the signal electrically and use fiber optic detectors and sources for input and output.

Figure 4-24 illustrates the design of a basic fiber optic coupler. A basic fiber optic coupler has N input ports and M output ports. N and M typically range from 1 to 64. The number of input ports and output ports vary depending on the intended application for the coupler. Types of fiber optic couplers include optical splitters, optical combiners, X couplers, star couplers, and tree couplers.

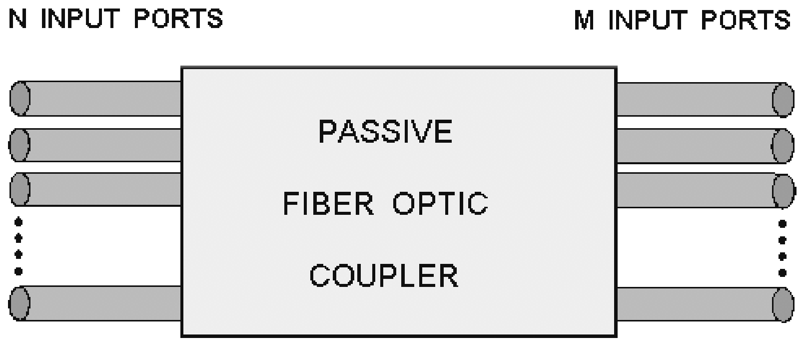


Figure 4-24.—Basic passive fiber optic coupler design.

An **optical splitter** is a passive device that splits the optical power carried by a single input fiber into two output fibers. Figure 4-25 illustrates the transfer of optical power in an optical splitter. The input optical power is normally split evenly between the two output fibers. This type of optical splitter is known as a **Y-coupler**. However, an optical splitter may distribute the optical power carried by input power in an uneven manner. An optical splitter may split most of the power from the input fiber to one of the output fibers. Only a small amount of the power is coupled into the secondary output fiber. This type of optical splitter is known as a T-coupler, or an optical tap.

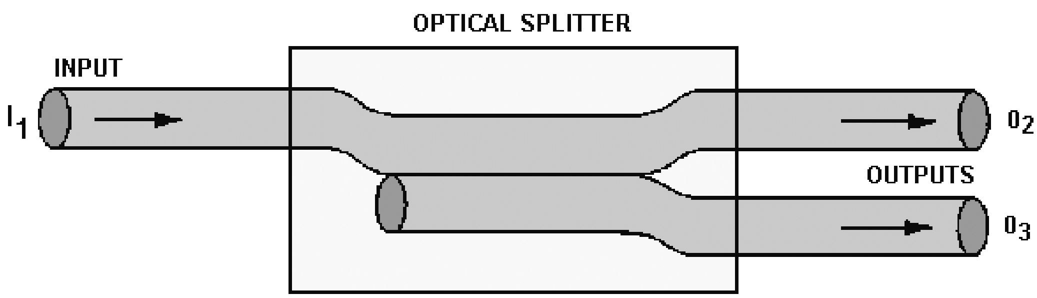


Figure 4-25.—Optical splitter.

An **optical combiner** is a passive device that combines the optical power carried by two input fibers into a single output fiber. Figure 4-26 illustrates the transfer of optical power in an optical combiner.

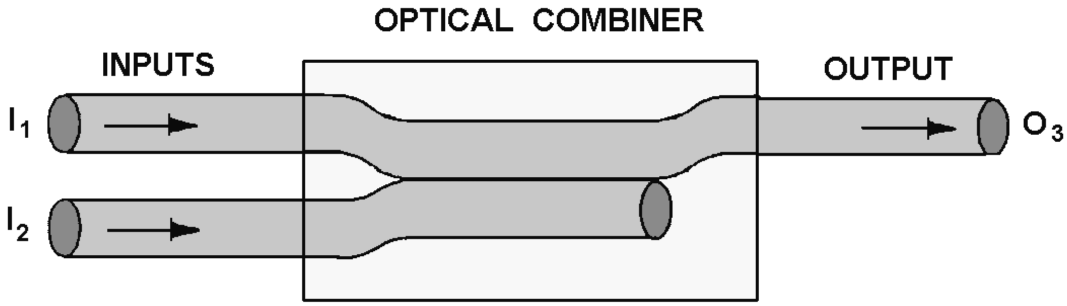


Figure 4-26.—Optical combiner.

An **X coupler** combines the functions of the optical splitter and combiner. The X coupler combines and divides the optical power from the two input fibers between the two output fibers. Another name for the X coupler is the 2×2 coupler.

Star and **tree couplers** are multiport couplers that have more than two input or two output ports. A **star coupler** is a passive device that distributes optical power from more than two input ports among several output ports. Figure 4-27 shows the multiple input and output ports of a star coupler. A **tree coupler** is a passive device that splits the optical power from one input fiber to more than two output fibers. A tree coupler may also be used to combine the optical power from more than two input fibers into a single output fiber. Figure 4-28 illustrates each type of tree coupler. Star and tree couplers distribute the input power uniformly among the output fibers.

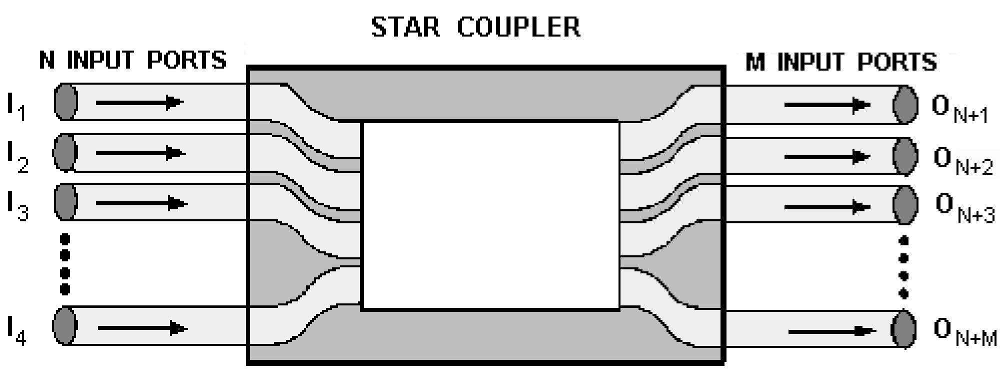


Figure 4-27.—Star coupler.

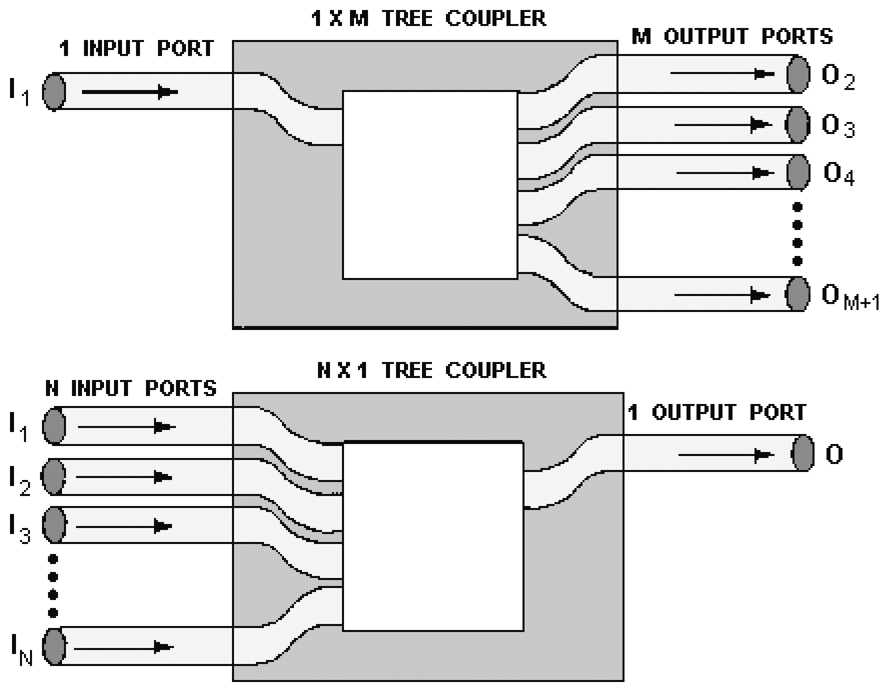


Figure 4-28.—(1 × M) and (N × 1) tree coupler designs.

Fiber optic couplers should prevent the transfer of optical power from one input fiber to another input fiber. **Directional couplers** are fiber optic couplers that prevent this transfer of power between input fibers. Many fiber optic couplers are also symmetrical. A **symmetrical coupler** transmits the same amount of power through the coupler when the input and output fibers are reversed.

Passive fiber optic coupler fabrication techniques can be complex and difficult to understand. Some fiber optic coupler fabrication involves beam splitting using microlenses or graded-refractive-index (GRIN) rods and beam splitters or optical mixers. These beamsplitter devices divide the optical beam into two or more separated beams. Fabrication of fiber optic couplers may also involve twisting, fusing, and tapering together two or more optical fibers. This type of fiber optic coupler is a fused biconical taper coupler. Fused biconical taper couplers use the radiative coupling of light from the input fiber to the output fibers in the tapered region to accomplish beam splitting. Figure 4-29 illustrates the fabrication process of a fused biconical taper coupler.

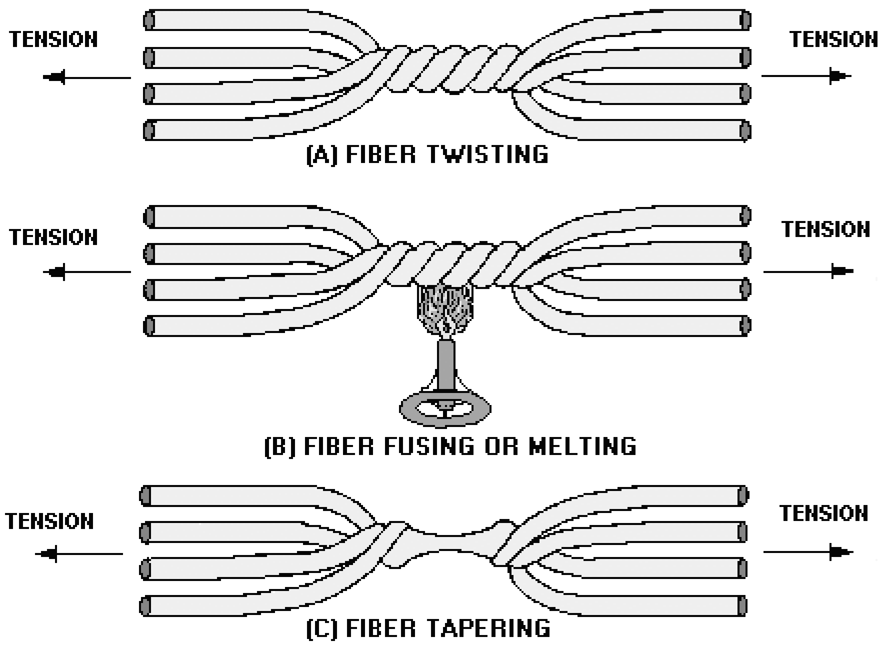


Figure 4-29.—Fabrication of a fused biconical taper coupler (star coupler).

SUMMARY

Now that you have completed this chapter, let's review some of the new terms, concepts, and ideas you have learned. You should have a thorough understanding of these principles before moving on to chapter 5.

FIBER OPTIC CONNECTIONS transfer optical power from one component to another. Fiber optic connections also permit fiber optic systems to be more than just a point-to-point data link.

A **FIBER OPTIC SPLICE** is a permanent joint between two fibers or two groups of fibers.

FIBER OPTIC CONNECTORS permit easy coupling and uncoupling of optical fibers.

FIBER OPTIC COUPLERS distribute or combine optical signals between fibers.

POOR FIBER END PREPARATION and **POOR FIBER ALIGNMENT** are the main causes of coupling loss.

RADIANCE is the amount of optical power emitted by a unit area of emitting surface per unit time in a specified direction. An optical source's radiance, or brightness, is a measure of its optical power launching capability.

FIBER-TO-FIBER COUPLING LOSS is affected by intrinsic and extrinsic coupling losses. **INTRINSIC COUPLING LOSSES** are caused by inherent fiber characteristics. **EXTRINSIC COUPLING LOSSES** are caused by jointing techniques.

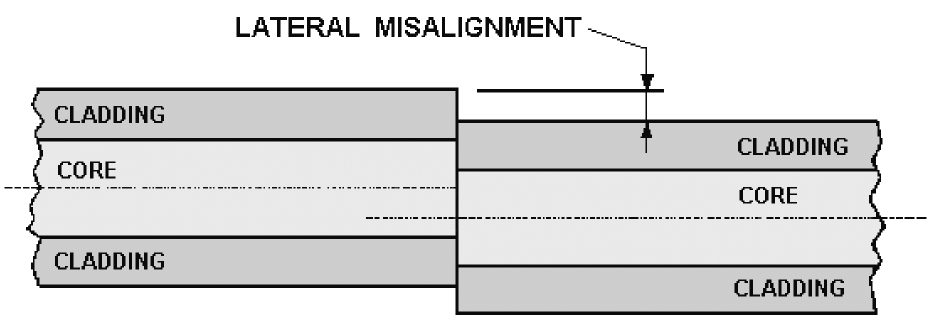
A **FIBER PIGTAIL** is a short length of optical fiber (usually 1 meter or less) permanently fixed to a fiber optic component, such as an optical source or detector.

FRESNEL REFLECTION occurs twice in a fiber-to-fiber connection. A portion of the optical power is reflected when the light first exits the source fiber. Light is then reflected as the optical signal enters the receiving fiber.

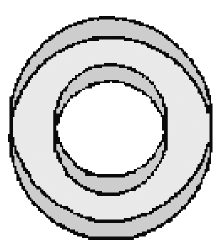
INDEX MATCHING GEL eliminates or reduces the step change in the refractive index at the fiber interface, reducing Fresnel reflection.

POOR FIBER ALIGNMENT is a main source of coupling loss in fiber-to-fiber connections. The three basic coupling errors that occur during fiber alignment are fiber separation (longitudinal misalignment), lateral misalignment, and angular misalignment.

In **FIBER SEPARATION** a small gap remains between fiber-end faces after completing the fiber connection. **LATERAL**, or **AXIAL**, **MISALIGNMENT** is when the axes of the two fibers are offset in a perpendicular direction. **ANGULAR MISALIGNMENT** is when the axes of the two fibers are no longer parallel.



(A) SIDE VIEW



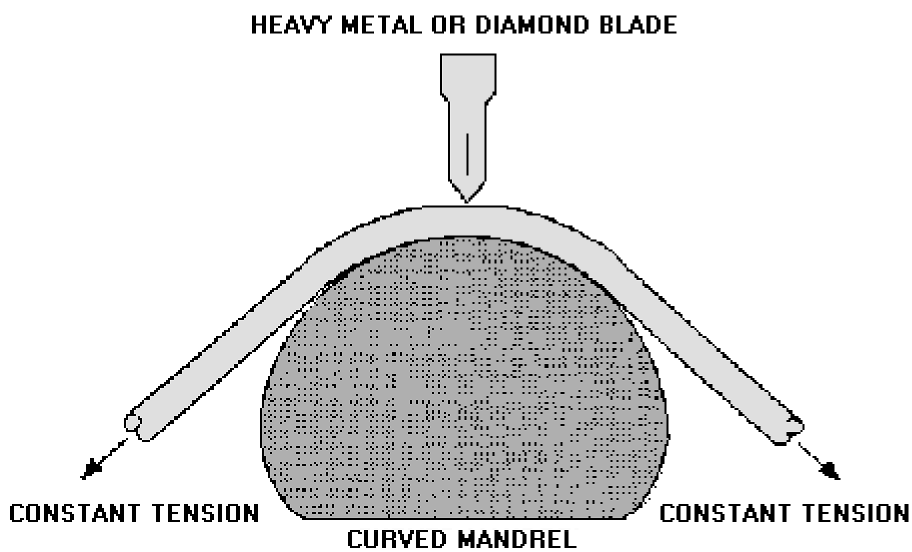
(B) END VIEW

SINGLE MODE FIBERS are more sensitive to alignment errors than multimode fibers because of their small core diameters and low numerical apertures.

The **MODE POWER DISTRIBUTION (MPD)** is the distribution of radiant power among the various modes propagating along the optical fiber.

Poor **FIBER END PREPARATION** is another source of extrinsic coupling loss. An optical fiber end face must be flat, smooth, and perpendicular to the fiber's axis to ensure proper fiber connection.

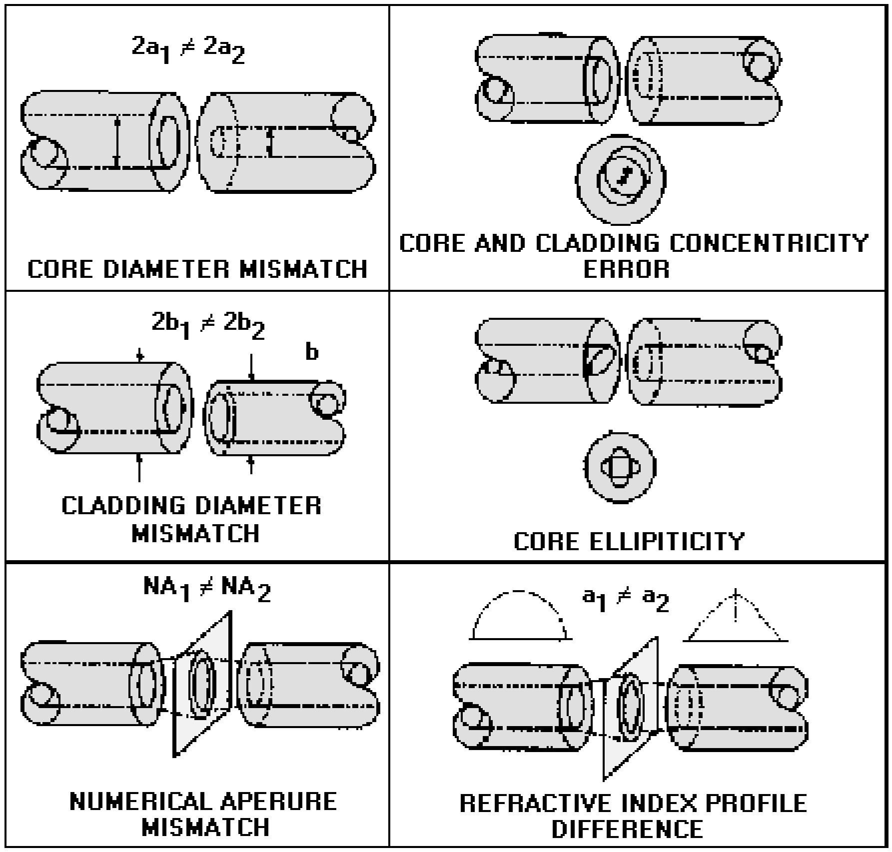
The **SCORE-AND-BREAK** method is the basic fiber cleaving technique for preparing optical fibers for coupling.



POLISHING the fiber ends removes most surface imperfections introduced by the fiber cleaving or cutting process. Fiber polishing involves a step-down approach. The first step is to give the surface of the fiber end a rough polish. The next step involves giving the surface of the fiber end a fine polish.

FIBER MISMATCHES are a source of intrinsic coupling loss. Types of fiber mismatches include fiber geometry mismatches, NA mismatch, and refractive index profile difference.

FIBER GEOMETRY MISMATCHES include core diameter, cladding diameter, core ellipticity, and core-cladding concentricity differences.



CORE DIAMETER MISMATCH causes coupling loss only if the launching fiber has a larger core radius than the receiving fiber.

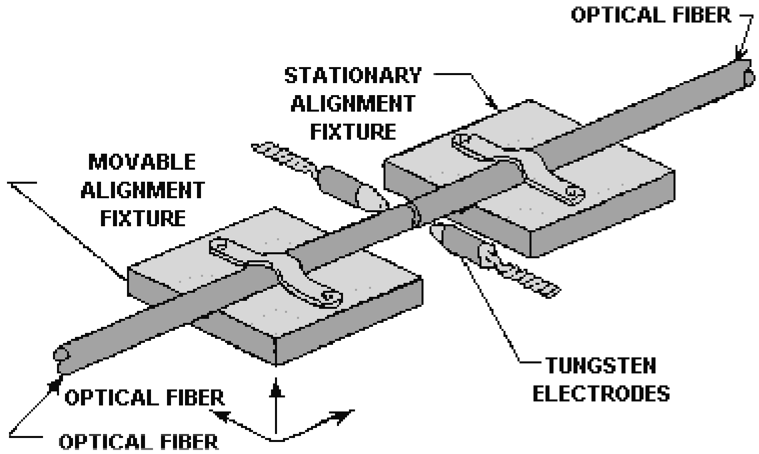
NA MISMATCH causes coupling loss only if the launching fiber has a higher NA than the receiving fiber.

A **REFRACTIVE INDEX PROFILE DIFFERENCE** causes coupling loss only if the launching fiber has a larger profile parameter than the receiving fiber.

MECHANICAL and **FUSION SPLICING** are two broad categories that describe the techniques used for fiber splicing. A mechanical splice is a fiber splice where mechanical fixtures perform fiber alignment and connection. A fusion splice is a fiber splice where localized heat fuses or melts the ends of two lengths of optical fiber together.

In **MECHANICAL SPLICING**, mechanical fixtures hold the two optical fibers in alignment for an indefinite period of time without movement. The amount of splice loss is stable over time and unaffected by changes in environmental or mechanical conditions.

ARC FUSION involves the discharge of electric current across a gap between two electrodes. By placing the fiber end between the electrodes, the electric discharge melts or fuses the ends of the fibers.



PREFUSION involves a short discharge of electric current across the gap between the electrodes. In prefusion the fiber ends are cleaned and rounded to eliminate any surface defects that remain from fiber cleaving.

A **FIBER OPTIC CONNECTOR** is a demateable device that permits the coupling of optical power between two optical fibers or two groups of fibers.

FIBER ALIGNMENT in a fiber optic connector is the critical parameter in maintaining total insertion loss below the required level.

FIBER OPTIC CONNECTORS can affect system performance by increasing modal and reflection noise.

MODAL NOISE is eliminated by using only single mode fiber with laser sources and only low-coherence sources such as light-emitting diodes with multimode fiber.

REFLECTION NOISE is reduced by index matching gels, physical contact polishes, or antireflection coatings.

BUTT-JOINTED and **EXPANDED BEAM CONNECTORS** are two ways to classify fiber optic connectors. Butt-jointed connectors bring the prepared ends of two fibers into close contact. Expanded beam connectors use two lenses to first expand and then refocus the light from the transmitting fiber into the receiving fiber.

LIGHT-DUTY and **HEAVY-DUTY CONNECTORS** are two ways that the Navy classifies fiber optic connectors. Light-duty connector shipboard applications include locations that protect the connectors from the environment such as in a junction box. Heavy-duty applications require a very rugged, stand-alone, sealed connector.

A **PASSIVE COUPLER** redistributes an optical signal without optical to electrical conversion.

An **OPTICAL SPLITTER** is a passive device that splits the optical power carried by a single input fiber into two output fibers.

An **OPTICAL COMBINER** is a passive device that combines the optical power from two input fibers into a single output fiber.

A **STAR COUPLER** is a passive device that distributes optical power from more than two input ports among several output ports.

A **TREE COUPLER** is a passive device that splits the optical power from one input fiber to more than two output fibers. A tree coupler may also be used to combine the optical power from more than two input fibers into a single output fiber.

DIRECTIONAL COUPLERS are fiber optic couplers that prevent the transfer of optical power from one input fiber to another input fiber.

A **SYMMETRICAL COUPLER** transmits the same amount of power through the coupler when the input and output fibers are reversed.