OBJECTIVES

In addition to the need for coupling LED sources to fibers, you will also need to look at the problem of connecting fibers to fibers. Permanent splices will be implemented in this lab.

This experiment will start by exploring the effects of misalignments on the coupling of two fibers. This will give you an understanding of the loss mechanisms seen in connectors and splices. You will then go on to couple fibers together using splices.

THEORY

1. FIBER COUPLING COMPONENTS

Both permanent splices and connectors which can be repeatedly coupled and un-coupled are used for coupling fibers to fibers. Each has its own area of applications. The connector finds application in the connection of fiber cables to transmitter and receiver modules, and in the connection to devices in optical communication systems. Permanent splices are required for joining sections of fiber in long distance communications links as well as for the construction of integrated fiber sensor systems.

Connectors use alignment techniques which fall into two general categories, which are shown in Fig 4.1. Lensed systems (Fig. 4.1a) image the core of one fiber onto the core of the second fiber. Other techniques use butt-coupling of fibers to achieve the connection. Butt-coupled connectors can be further divided into subcategories. In some, precision grooves are used to align the fibers to each other (Fig. 4.1b). In others, snug-fitting tubes are used to align precision-machined ferrules.
with respect to each other (Fig 4.1c). Typical insertion losses for connections between multimode fibers are less than 1.0 dB.

![Diagram of connector types](image)

Fig. 4.1 Schematic depiction of connector types.

a) Lens type. b) Precision v-groove type. c) Snug-fitting tube type.

Fiber splicing is the permanent joining of two fibers to each other. The best results are obtained from thermal fusion of the two fibers. The fibers are aligned, either manually with precision stages under a microscope or with the aid of microprocessor control.

The fibers are then heated and fused together as shown in Fig. 4.2. This fusion is typically done with a carefully regulated electric arc or with a micro-torch. Skilled operators can achieve losses of less than 0.1 dB. The second method of splicing is a precision aligned groove technique which will be used in this project. The fibers are inserted in a groove formed by an arrangement of four glass rods which have been fused together as shown in Fig. 4.3. Index-matching epoxy is used to fix the splice in place. Untrained operators can routinely achieve splice losses on the order of 0.1-0.3 dB. When it is necessary to keep splice losses as low as possible, the thermal fusion
splice technique is the best choice, but the epoxy splices are easier and can be made with little practice.

Fig. 4.2 Fiber splices by thermal fusion. Fusion welder using electric arc. Micro-torch may also be used.

Fig. 4.3 Precision groove splice used in the lab

Permanent splices generally have lower losses than connectors since they do not need to be designed for repeated coupling and decoupling. Also, connectors require mating hardware attached to the fiber, making them more complicated. Both splices and connectors must be able to be done in the field by personnel who may not be highly trained. This dictates a design requiring a minimum of fiber handling. The resulting joints must be mechanically rugged, environmentally insensitive, and long lived.
2. ALIGNMENT LOSSES

The principal source of loss in both connectors and splices is fiber-to-fiber end face misalignment. There are three types of misalignment loss which may occur individually or in combination. These are lateral misalignment, axial separation, and angular misalignment. These misalignments are illustrated in Fig. 4.4. The design problem is to minimize these losses while making the devices, as far as possible, self-aligning.

![Misalignments of fiber cores in fiber-fiber connections](image)

Fig. 4.4 Misalignments of fiber cores in fiber-fiber connections. a) Lateral offset. b) Axial separation. c) Angular offset.

The first of these loss mechanisms, lateral misalignment, is the largest contributor to the total loss in a fiber connection. Lateral misalignment is the failure of the cross sections of the two fiber cores to perfectly overlap (Fig. 4.4a). This may be due to tolerances on the fiber diameter, eccentricity of the fiber outside diameter or of the core with respect to the fiber axis, or machine tolerances in the construction of the connector.

Axial separation contributes to the connection loss when the end surfaces of the two fibers do not come into contact with each other (Fig. 4.4b). In connectors, a slight separation will generally be designed into the device so that the fibers are not
damaged by butting against each other. This type of loss depends upon the numerical aperture of the fibers, since a large divergence will result in less of the beam from the first fiber being accepted by the second.

The third loss mechanism, angular misalignment (Fig. 4.4c), generally does not contribute significantly to connection losses, both because manufacturing tolerances virtually eliminate this misalignment in connectors and splices and because the fiber connection itself is more tolerant of angular misalignments.

Theoretical loss curves for these three misalignments when graded-index fibers are coupled together are shown in Fig. 4.5. In the case of step-index fibers, the loss from offset misalignment can be found by simply calculating the overlap area of the cores because the irradiance is constant over the face of a step-index fiber. In the case of graded-index fibers shown here (Fig. 4.5a), the calculation is much more complicated because the irradiance varies as a function of position within the fiber core. The loss from the separation of two fiber ends (Fig. 4.5b) is found by comparing the area of the receiving fiber with the area of the beam from the first fiber at a distance z from its end face. The loss from angular misalignment (Fig. 4.4c) has the same form as the offset loss, with sin θ/NA replacing z/a as the scaling factor.

(Fig. 4.5a)
Fig. 4.5 Theoretical loss curves for three misalignments when graded-index fibers coupled together. (a) Lateral offset loss. Note that the offset has been normalized to the fiber core radius. (b) Axial separation loss. Note the
separation has been normalized to the core radius. NA=0.30 was used in the calculation. (c) Angular misalignment loss. Note the angle has been normalized to the fiber NA.

As an example of the tolerances which are allowable in making a fiber-to-fiber connection, consider a step-index fiber with core diameter = 50 µm and NA = 0.20. Losses of 0.1 dB occur for approximately 1 µm lateral offset, 4 µm axial separations, or 0.5° angular misalignments. The problem is much more difficult when single-mode fibers are used. If a single-mode fiber with core diameter = 4 µm and NA = 0.10 is used, then 0.1 dB losses occur for 0.1 µm lateral offset, 0.7µm axial separation, and 0.2° angular misalignment. In each case, these are only the misalignment losses. Fresnel reflection losses will contribute about 0.2 dB loss per fiber face in dry connections. Imperfections in fiber end preparation may also contribute to the loss.

The losses which have been described here are for the butt-coupling types of connectors. Connectors which use lens systems to minimize the connection loss are useful in eliminating lateral offset and axial separation losses, but are very highly sensitive to angular misalignment.

**PROCEDURE**

1. **Fiber Alignment Losses**
   1. Prepare two segments of FMLD fiber, each about 1-2 meters in length, as you did in previous section. Couple light from the He-Ne laser into one of the fibers using the F-916 Fiber Coupler as you did before. Insert the other end of this fiber into a post-mounted FP-1. Measure the output power from this fiber segment.
   2. Insert one end of the second fiber segment into an FPH-S holder and place this in a FP-1 Fiber Positioner which has been post-mounted on the RSX-2 rotation stage, as you did in lab #3. Place the far end of this fiber in another post-mounted FP-1 so that the power coupled through the two fibers can be measured with the 1815C Power Meter.
   3. Extend the fiber ends so that the fibers can be butt-coupled over the center of the rotation stage. Centering of the fibers on the stage can be checked by rotating the
stage and adjusting the fibers until the ends do not move relative to each other as the stage is turned. Adjust the x-y-z of the fibers to achieve maximum throughput in the butt coupling.

4. Measure the power transmitted through the second fiber segment. Calculate the loss of the butt coupling of the fibers, using the power out of the first fiber measured in Step 1 and the power coupled into the second fiber as measure in this step. A loss of less than 0.25 dB is excellent for this dry connection.

5. Measure the excess loss as a function of lateral misalignment as follows: Measure the power coupled into the second fiber and calculate the total coupling loss as a function of position. After finding this total coupling loss, subtract the loss measured in Step 4 from it. There is no direct calibration for measuring the offset from the FP-1, so it is best to calibrate from the rotation of the adjusting screws. These are 80 thread/inch screws, which mean that one turn of the screw will give 0.0125 inch or 0.3175 mm of offset. (Be sure to move in one direction only so as to eliminate backlash in the movement. If you wish to go in the other direction, reset the system and start over again.) Normalize the offset to the fiber core radius by dividing the offset by the fiber core radius. This will allow you to plot the loss as function of offset expressed in core radii. Plot the excess loss which you have obtained as a function of lateral offset. Comparing the plotted curves with the curve shown in Fig. 4.5a. The deviation from the theoretical curve is due to the fact that the laser-fiber coupling under-fills the fiber. This causes more of the light to concentrate towards the center of the fiber core, reducing the misalignment loss.

6. Realign the fiber ends and measure the excess loss as a function of longitudinal separation. The screw at the back of the FP-1 which controls this separation is also an 80-Pitch screw which gives 0.0125 inch or 0.3175 µm per turn. Normalize the separation to the fiber core radius and plot the results. Contrast it with the theoretical curve of Fig. 4.5b. The deviation has the same origin as discussed in the previous step.

7. Realign the fiber ends once more and measure the excess loss as a function of angular misalignment using the RSX-2 Rotation Stage to change the angular
orientation of the fiber ends. Normalize the sine of the angle of misalignment to the numerical aperture of the fiber. Plot the curve and contrast with the theoretical curve from Fig. 4.5c. The deviation at low angles is for the reason discussed above. At high angles, light is being launched into the cladding of the second fiber. Some of this light reaches the detector and decreases the apparent misalignment loss.

(2) Splice Assembly and Test

1. Prepare two segments of F-MLD fiber, each about 1 meter in length.

2. Identify the component parts of the Model # F-SK-S. The parts contained in the plastic envelope are: one fiber alignment guide, which comes in a protective plastic tube, two silicone rubber strain reliefs, and one stainless steel sleeve (Fig. 4.6).

3. Place the alignment guide into the splice fixture (F-SK-C) (Fig. 4.7).

4. Slide the stainless steel sleeve onto one of the F-MLD fiber segments to be spliced. Slide one of the silicone rubber strain reliefs onto each of the fibers. The tapered end of the strain relief leads up the fiber, away from the fiber end to be spliced (Fig. 4.8).
5. Cleave both of the fiber ends which are to be joined together. When the cleave is completed, each fiber should have about 7/16-1/2 inch of bare fiber extending out of the fiber jacket. Couple one of the fibers to be spliced to the He-Ne laser, using the F-916 Fiber Coupler as you did in lab #3. Simply go on to Step 6.

6. Measure the optical power coming from the first fiber. Place the two fibers in the dry fiber alignment guide (no epoxy has yet been applied), one at each end of the guide, as in Fig. 4.9a. Insert the fibers until they butt together at the middle of the guide. Measure the optical power coming from the far end of the second fiber. The loss which is now measured will be Fresnel-reflection limited, since the splice is still dry, but it will give you a good indication of the quality of the fiber ends. If the measured loss is not less than about 0.5 dB, it is a good indication that the fiber ends have not been properly cleaved. The other major contributor to splice loss is fiber eccentricity. If rotating the fiber changes the measured splice loss, then fiber eccentricity is a problem in this splice. If the splice loss is too high and eccentricity is not a problem, return to Step 5 and re-cleave the fibers.
Fig. 4.9 (a) Insertion of the fiber ends into the alignment guide. (b) Placing strain reliefs on the alignment guide substrate.

7. Now is a good time to return to Step 6 and gain experience in handling fibers in this alignment guide before you make the permanent splice.

8. Remove the fibers from the alignment guide. Mix the epoxy to be used, as you did in Step 2 of the connector procedure above.

9. Coat the bare ends of the fibers with epoxy. A toothpick or the end of a small paper clip makes a good applicator. The epoxy will both wick into the alignment guide and be carried into the guide by the fibers when they are inserted.

10. Again insert the fibers into the alignment guide as you did in Step 5. Minimize the splice loss by again rotating the fibers, if necessary. The epoxy will be cured and the splice may be handled in about 10 minutes. The curing of the epoxy can be checked by testing the remnant of the mixed epoxy which was not used in the splice.

11. After the epoxy is cured, remove the alignment guide from the splice fixture. Slide the rubber strain reliefs down the fiber and onto the alignment guide substrate. Note that the flat side of the strain relief sits on the alignment guide substrate and that the tabs on the substrate fit into the notches in the strain relief (Fig. 4.9b).

12. Slide the stainless cover over the splice. Use the crimp tool on the back side of the splice fixture to complete the splice, as shown in Fig. 4.10. Crimp at the red bands on the cover. The permanently spliced fiber is now complete.
Fig. 4.10. Crimping the completed splice in the crimp tool at the back of the splice fixture.

13. Measure the power through the completed splice. Calculate the splice loss again. Compare this with the value found in Step 6.

14. Losses in permanent splice are sensitive to the way in which light is launched into the fiber in the same way that connectors are, as discussed in Step 15 of the connector assembly procedure. Use the FM-1 Mode Scrambler to generate an approximation of a stable mode distribution as you did in Step 15 of the connector assembly and re-measure the splice loss.

15. When you find that you can make a good splice using the multimode F-MLD fiber, you may wish to try splicing the F-SV single-mode fiber which you used in lab #3. Typical high-quality splices will have ~0.5 dB loss for the single-mode fiber, compared to ~0.2 dB for the multimode fiber.

Questions:

1. How many types of misalignment are there? What are they and what are their characteristics respectively?

2. Analyze and compare the curves you got in “Fiber Alignment Losses” section with the theoretical curves, and try to explain the reasons of deviation.

3. What are the major contributors to splice loss?