Lab #1

HANDLING FIBERS, NUMERICAL APERTURE

OBJECTIVES:

In this project, you will learn how to prepare fiber ends for use in the laboratory. You will be able to observe the geometry of a fiber and you will measure the numerical aperture (NA) of a telecommunications-grade fiber.

The method that is presented for determining the NA of a fiber is especially illustrative of what is to be learned.

FIBERGEOMETRY:

An optical fiber is illustrated in Fig. 1.1. It consists of a core, with refractive index $n_{\text{core}}$, of circularly-Symmetric cross section of radius $a$, and diameter $2a$, and a cladding, with refractive index $n_{\text{cladding}}$, which surrounds the core and has an outer diameter of $d$. Typical core diameters range from 4-8 μm (1 μm = 1 micrometer = $10^{-6}$ m) for single-mode fibers to 50-100 μm for multimode fibers used for communications to 200-1000 μm for large-core fibers used in power transmission applications. Communications-grade fibers will have $d$ in the range of 125-140 μm, with some single-mode fibers as small as 80 μm. In high-quality communications fibers, both the core and the cladding are made of silica glass, with small amounts of impurities added to the core to slightly raise the index of refraction.
There are also lower-quality fibers available which have a glass core surrounded by a plastic cladding, as well as some all-plastic fibers. The latter have very high attenuation coefficients and are used only in applications requiring short lengths of fiber.

Surrounding the fiber will generally be a protective jacket. This jacket may be made from a plastic and have an outside diameter of 500-1000 μm. However, the jacket may also be a very thin layer of varnish or acrylate material.

**FIBER MECHANICAL PROPERTIES:**

Before measuring the NA of a fiber, it will be necessary to prepare the ends of the fiber so that light can be efficiently coupled in and out of the fiber. This is done by using a scribe-and-break technique to cleave the fiber. A carbide or diamond blade is used to start a small crack in the fiber, as illustrated in Fig. 1.3. Evenly applied stress, applied by pulling the fiber, causes the crack to propagate through the fiber and cleave it across a flat cross section of the fiber perpendicular to the fiber axis.

In theory the breaking strength of glass fibers can be very large, up to about 725 kpsi (where 1 kpsi = 1000 pounds/sq. inch) or 5 GPa (where 1 Pa = 1 Newton/sq. meter and 1 GPa = 10^9 Pa). However, because of in-homogeneities and flaws, fibers do not exhibit strengths anywhere near that value. Before being wound on a spool, a fiber is stretched over a pair of pulleys, which apply a fixed amount of strain (stretching per unit length). This process is called proof testing. Typical commercial fibers may be proof tested to about 50 kpsi (345 MPa), which is equivalent to about a one-pound load on a 125 μm OD fiber. When a crack is introduced, this is reduced even further in the neighborhood of the
crack. Fracture occurs when the stress at the tip of the crack equals the theoretical breaking strength, even while the average stress in the body of the fiber is still very low. The crack causes sequential fracturing of the atomic bonds only at the tip of the crack. This is the reason that a straight crack will yield a flat, cleaved, fiber face.

Optical fibers are required to have high strength while maintaining flexibility. Fiber fracture usually occurs at points of high strain when the fiber is bent. For a fiber of radius \( \frac{d}{2} \), bent to a radius of curvature \( R \), as shown in Fig. 1.4, the surface strain on the fiber is the elongation of the fiber surface, \((R + \frac{d}{2})\theta - R\theta\), divided by the length of the arc, \(R\theta\). The strain is, then, \( \frac{d}{2R} \). Although silica fibers have been prepared which can withstand strains of several percent, an upper strain limit of a fraction of 1% has been found to be necessary to guarantee fiber survival in a cable installed in the field. If a strain limit of 0.5% is used as a reasonably conservative value, a 125\(\mu\)m diameter fiber will be able to survive a bend radius of 1.25 cm.

**MEASURING NUMERICAL APERTURE:**

The numerical aperture, NA, is a measure of how much light can be collected by an optical system, whether it is an optical fiber or a microscope objective lens or a photographic lens. It is the product of the refractive index of the incident medium and the sine of the maximum ray angle.

\[
NA = n_i \sin(\theta_{\text{max}})
\]

In most cases, the light is incident from air and \( n = 1 \). In this case, the numerical aperture of a step-index fiber by using Snell’s Law is

\[
NA = \sqrt{n_{\text{core}}^2 - n_{\text{cladding}}^2}.
\]

The NA of a fiber, in the weakly guiding approximation, was found to be

\[
NA = n_{\text{core}} \sqrt{2 \times \Delta}
\] (1-1)
where $n_{\text{core}}$, is the refractive index of the core of a step-index fiber or the refractive index at the center of the core of a graded-index fiber, and $\Delta$ is the fractional index difference,

$$\Delta = \frac{(n_{\text{core}} - n_{\text{cladding}})}{n_{\text{core}}}$$

As an example, a typical multimode communications-fiber may have $\Delta \approx 0.01$, in which case the weakly-guiding approximation, which assumes $\Delta \ll 1$, is certainly justified. For silica-based fibers, $n_{\text{core}}$ will be approximately 1.46.

Using Eq. 1-1, these values of $\Delta$ and $n_{\text{core}}$ give $NA = 0.2$. This gives a value of 11.5° for the maximum incident angle in and a total core angle of 23°. Values of NA range from about 0.1 for single-mode fibers to 0.2-0.3 for multi-mode communications fibers up to about 0.5 for large-core fibers.

The way in which light is launched into the fiber in the method used here to measure the fiber NA is shown in Fig.1.5. The light from the laser represents a wave front propagating in the $z$-direction. The width of the Laser beam, ~1 mm, is much larger than the diameter of the fiber core, 100 μm in this case. In the neighborhood of the fiber core, the wave front of the laser light takes on the same value at all points having the same $z$, so we say that we have a plane wave propagating parallel to the $z$-axis. When a plane wave is incident on the end face of a fiber, then we can be sure that all of the light launched into the fiber has the same incident angle, $\theta_c$, in Fig.1.5.

If the fiber end face is then rotated about the point O in Fig. 1.5, we can then measure the amount of light accepted by the fiber as a function of the incident angle, $\theta_c$.

Fig. 1.6 shows the light accepted by a Newport F-MLD fiber as a function of acceptance angle using the method just described. The point where the accepted
radiation has fallen to a specified value is then used to define the maximum incident angle for the acceptance cone. The Electronic Industries Association uses the angle at which the accepted power has fallen to 5% of the peak accepted power as the definition of the experimentally determined NA. The 5% intensity points are chosen as a compromise to reduce requirements on the power level, which has to be distinguished from background noise.

Note in Fig. 1.6, the radiation levels were measured for both positive and negative rotations of the fiber and the NA was determined using one half of the full angle between the two 5%-intensity points. This eliminates any small errors resulting from not perfectly aligning $\theta_c = 0$ to the plane wave laser beam. The NA obtained in this test case was 0.29, which compares well with the manufacturer's specification of NA = 0.30.

PART LIST

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<td>XSN-22</td>
<td>2x2 Breadboard</td>
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<td>U-130IP</td>
<td>1 mw He-Ne laser</td>
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<td>F-CL1</td>
<td>Fiber cleaver</td>
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<td>RSX-2</td>
<td>Rotating stage</td>
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<td>FP-1</td>
<td>Fiber positioner</td>
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Figure 1.7 Fiber Positioner FP-1 (Fibercoupler)

Figure 1.8 Rotation Stage RSX-2

Figure 1.9 Micro-series holder M-MPH-1

Figure 1.10 Posts a) MSP-1, b) SP-2
A microscope for viewing the cleaved ends of fibers is essential. If your laboratory is not already equipped with an adequate high-power microscope, you may wish to consider using the Newport FML1 Inspection Microscope for inspecting fiber ends. You may also wish to use the F-BK2 fiber breaker in place of the F-CL1 fiber cleaver.

**PROCEDURE:**

1. **PREPARING FIBER ENDS**

   1. Remove ~1-1/2 inches of fiber jacket from a ~2 meter segment of FMLD fiber, by dipping the fiber end in methylene chloride and letting it soak for ~3 minutes. Some people prefer to use a single-edge razor blade held at a low angle to do the stripping of the fiber jacket. This requires some practice, but goes much faster once you are used to it.

   2. Use the F-CL1 Fiber Cleaver to cleave the stripped end of the fiber. The cleaver should be placed on the top of the table with the blade pointing up. Draw the fiber over the blade with a light motion. Be sure that the fiber is normal to the blade. You should not attempt to cut the fiber with the cleaver. You are only starting a small nick, which will propagate through the fiber when you pull it. Gently, but firmly, pull the fiber to cleave it.

   3. Check the quality of the cleave by examining it under a high-power microscope. Carefully examine the end face of the fiber. The end face should appear flat and should be free of defects, as in Fig. 1.11a. However, chips or cracks that appear near the periphery of the fiber are acceptable if they do not extend into the central region of the fiber. Some poorly cleaved fiber ends are illustrated in Fig. 1.11b and c. The problems associated with the poor cleaves are discussed in Step 4.

   4. If the inspection of the fiber end face in Step 3 does not show that the end face has been properly cleaved, you should consider the following common sources of error: There are two principal reasons for obtaining a bad cleave, 1) a poor scribe and 2) a non-uniform pull of the fiber. A scribe, which is too deep may cause an irregular cleave and may cause multiple cracks to propagate through the fiber (Fig.1.11b). A scribe which is too shallow will be the same
as no scribe at all and the fiber will break randomly if the pull which propagates the crack through the fiber is not uniform, and especially if it includes twisting of the fiber, irregularities may show up on the fiber end face or a lip may be formed on the end of the fiber, as in Fig. 1.11c.

If the fiber end is cleaved at an angle, the fiber was probably scribed at an angle other than 90° across the fiber axis, although this, too, can be caused by a non-uniform pull of the fiber. (This will not be a problem if you have chosen to use the F-BK2 Fiber Breaker, but will have to be considered if you are using the F-CLI Fiber Cleaver. See the note after Step 5.)

5. Once you have a fiber segment with two well-cleaved ends, you may look at the geometry of the fiber, as it was described in the introduction. View a fiber end as you did in Step 3. Use an incandescent lamp to illuminate the far end of the fiber. You will be able to see the light shining through the central portion of the fiber. This is the fiber core. The region surrounding the core is the fiber cladding. You will not be able to see the fiber jacket, because you have stripped that away from the end of the fiber.

![Figure 1.11 cleaved fiber ends. (a) Good cleave. (b) Cracked fiber. (c) Side view of a lip on the end of a fiber.](image)

**Note:** The F-CLI Fiber Cleave is much more dependent on operator skill than is the F-BK2 which you may choose to use as an option in place of the F-CLI. In that case, follow the directions that are included with the F-BK2 Fiber Breaker and cleave the ends of the fiber.
2. MEASURING NUMERICAL APERTURE

1. Bolt the Model 807 Laser Mount to the Model 340C Clamp using ¼-20 bolts from the SK-25 Screw kit. Place the 340C clamp on the Model 4l Short Rod. Mount this on the LS-22 Breadboard. Place the Model U-I30lP He-Ne laser into the 807 Mount. Tighten the setscrew. Do not over tighten, as this will damage the laser. Plug the laser power supply into a 110V outlet. Plug the cord from the laser head into the power supply. Note that the plug from the laser head to its power supply can only be inserted one way. The laser is turned on at the key switch on the front of the power supply. The combination of the 807 Mount and the 340C Clamp will align the laser parallel to a line of bolt holes on the table if the Model 4l Short Rod is properly mounted on the table. Check the laser alignment with the line of bolt holes and adjust the Model 4l Short Rod, if necessary.

2. Mount the RSX-2 Rotation Stage to the breadboard so that the beam from the He-Ne laser passes over the center hole of the rotation stage. The RSX-2 Rotation Stage will have to be placed at an angle to the line of bolt holes in order to bolt it into place as instructed, as shown in Fig. 1.12. Mount the MPH-1 Micro-Series Post Holder on the rotation stage. Use an 8-32 screw to mount the MPH-1. The ¼-20 threaded hole in the bottom of the MPH-1 is used only as a through hole. Place the MSP-l Micro-Series Post in the MPH-1, as shown in Fig. 1.12.

3. Prepare a fiber segment, ~ 2 meters long, with a good cleave at each end face. The FPH-S Fiber Holder comes as part of the FP-1 Fiber Positioner. Insert one end of the fiber into an FPH-S Fiber Holder (you will need to have stripped at least 3” of the jacket from the fiber in order to do this and the following step) and place this holder into its FP-1 Fiber positioner that has been post-mounted on the RSX-2 rotation stage, using the MSP series post holder and the MSP series post.

4. Extend the tip of the fiber and orient the FP1 positioner so that the fiber tip is at the center of rotation of the stage. This is a critical Step if an accurate value for the fiber NA is to be obtained.

5. Re-check the alignment of your light-launching system by making sure that the tip of the fiber remains at the center of the laser beam as the stage is rotated. This setup achieves plane-wave launching into the end of your fiber.
6. Mount the far end of the fiber in an FPH-S Fiber Holder (taken from an FP-I Fiber Positioner) and the FP-I Fiber Positioner. You can get a quick approximate measure of the fiber's NA with a 3x5 card placed a distance, \( L \), away from the laser in a darkened room, as shown in Fig. 1.12. Measure the width, \( W \) on the card of the spot out of the fiber and the distance, \( L \), from the fiber to the card. The NA of the fiber is approximately \( \frac{1}{2} \frac{W}{L} \). This is a quick method which is used when only an approximate measurement of a fiber's NA is needed.

7. Mount the detector head of the Model 815 Power Meter so that the output beam from the fiber is incident on the detector head. Make a hood of aluminum foil to keep stray room light off of the detector. You will find this to be necessary because the power levels obtained in plane-wave launching are low. Block the laser beam and note the power measured by the power meter. This determines the Stray light seen by the meter. You will need to subtract this amount from all of your data.

8. Measure the power accepted by the fiber as a function of the incident angle of the plane-wave laser beam. Change the angle of the fiber with respect to original direction in step of 5 degree then translate the laser beam horizontally with two axis positioner until the laser is launched inside the fiber (figure 1.13). Make sure you adjust the translation of the laser to receive the maximum output power.
Fiber Positions (0°, 5°, 10°, 15°)

Laser Positions (horizontally translation)

Figure 1.13  Experiment setup: a) Lase-fiber coupling b) Power meter detector-fiber coupling

9. Plot the power received by the detector as a function of the sine of the acceptance angle. Semi-log paper is recommended. Measure the full width of the curve at the points where the received power is at 5% of the maximum intensity. The half-width at this intensity is the experimentally determined numerical aperture of the fiber. Compare your results with the results of Step 6 and Fig. 1.6.