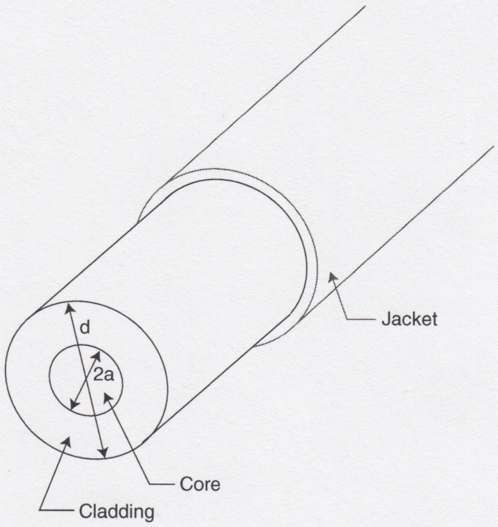

Figure 1.1. Geometry of an optical fiber, showing core, cladding, and jacket.

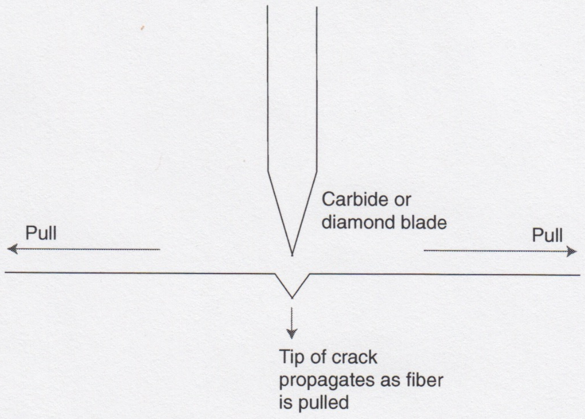

Figure 1.2. Scribe-and-break technique of fiber cleaving. A carbide blade makes a small scribe, or nick, in the fiber. The fiber is pulled to propagate the scribe through the fiber.

1.0 PROJECT #1: HANDLING FIBERS, NUMERICAL APERTURE

(Est. Time Required: 2:00 hrs.)

In this first project, the student will learn how to prepare a bare fiber for use in the laboratory. Observations will be made of a fiber's geometry, and a measurement of the numerical aperture (NA) of a telecommunications-grade fiber will be performed. The method presented for determining the NA of a fiber especially illustrates the concept to be learned. Another technique for measuring a fiber's NA is one that is often used in standard practice and will be used in **Project #3**.

1.1 FIBER GEOMETRY

An optical fiber, which is illustrated in **Fig. 1.1**, consists of a core with a circularly-symmetric cross section, a radius of a (diameter 2a), a cladding of diameter d, and a jacket. The refractive indices of the core and cladding are n_{core} and n_{cl}, respectively. 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 trans-mission applications. (See **Section 0.5** for a discussion of these applications.) Communication-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 (**Section 0.4.1**) 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 plastic and have an outside diameter of 500-1000 μm. However, the jacket may also be a very thin layer (~250 μm outer diameter) of acrylate material.

1.2 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. 1.2**. 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 inhomogeneities and flaws, fibers do not exhibit strengths anywhere near this 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.[1] 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 d/2, bent to a radius of curvature R, as shown in **Fig. 1.3**, the surface strain on the fiber is the elongation of the fiber surface, $(R + d/2)\theta - R\theta$, divided by the length of the arc, $R\theta$. The strain is, then, $d/2R$. 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.[2] If a strain limit of 0.5% is used as a reasonably conservative value, a 125 μm diameter fiber will be able to survive a bend radius of 1.25 cm.

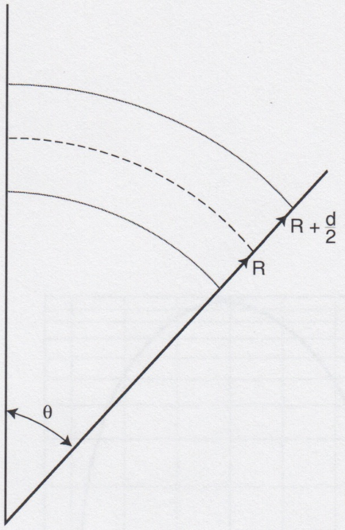

Figure 1.3. Strain of a bent fiber.

1.3 MEASURING NUMERICAL APERTURE

A detailed derivation of the expression for the NA of a fiber was given in **Section 0.2.3**. Recalling Eq. 0-9, the NA of a fiber, in the weakly-guiding approximation, was found to be

$$NA = n_{core}\,(2\Delta)^{1/2} \qquad (1\text{-}1)$$

where n_{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 Δ is the fractional index difference, $\Delta = (n_{core} - n_{cl})/n_{core}$.

As an example, a typical multimode communications fiber may have $\Delta \approx 0.01$, in which case the weakly-guiding approximation, which assumes $\Delta << 1$, is certainly justified.

For silica-based fibers, n_{core} will be approximately 1.46. Using Eq. 1-1, these values of Δ and n_{core} give NA = 0.2. This gives a value of 11.5° for the maximum incident angle in **Fig. 0.8** and a total cone angle of 23°. Values of NA range from about 0.1 for single-mode fibers to 0.2–0.3 for multimode 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. 1.4**. 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 wavefront 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, θ_c in **Fig. 1.4**.

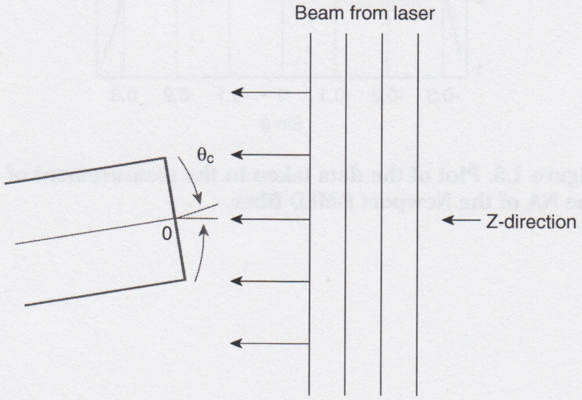

Figure 1.4. Geometry of a plane-wave launch of a laser beam into an optical fiber.

If the fiber end face is then rotated about the point O in **Fig. 1.4**, we can then measure the amount of light accepted by the fiber as a function of the incident angle, θ_c.

Fig. 1.5 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

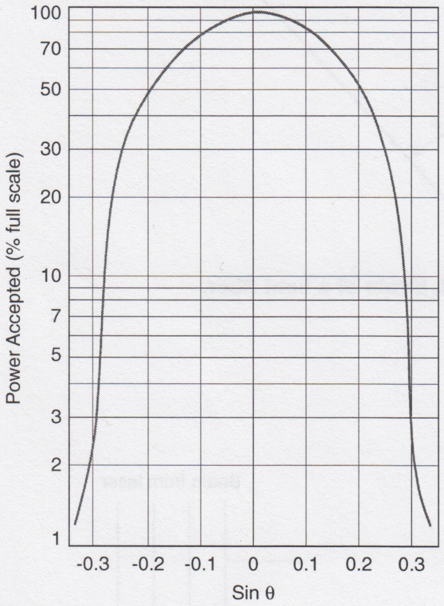

Figure 1.5. Plot of the data taken in the measurement of the NA of the Newport F-MLD fiber.

the accepted power has fallen to 5% of the peak accepted power as the definition of the experimentally determined NA.[3] The 5% intensity points are chosen as a compromise to reduce requirements on the power level which has to be distinguished from background noise.[4]

Note that in **Fig. 1.5**, 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 θ_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.

1.4 REFERENCES

1. D. Kalish, et al., “Fiber Characterization-Mechanical”, in *Optical Fiber Communications,* S. E. Miller and A. G. Chynoweth, eds., Academic Press (New York) 1979, p. 406

2. D. Gloge and W. B. Gardner, “Fiber Design Considerations”, in *Optical Fiber Communications,* S. E. Miller and A. G. Chynoweth, eds., Academic Press (New York) 1979, p. 152

3. TIA/EIA Standard 455-47B, Section 6.1,2, EIA, Engineering Dept. (Arlington, VA) 1992

4. D. L. Franzen and E. M. Kim, “Interlaboratory measurement comparison to determine the radiation angle (NA) of graded-index optical fibers”, Applied Optics 20, p. 1220 (1981)

1.5 PARTS LIST

Catalog Model#	**Description**	**Qty.**
F-MLD	100/140 MM Fiber, 50 meters	1
R-30025	1.5 mW HeNe Laser	1
ULM-TILT	Laser Mount	1
340-RC	Rod Clamp	1
41	Short Rod	1
F-CL1	Fiber Cleaver	1
F-STR-175	Fiber Stripper	1
FK-BLX	Allen Wrench Set	1
SK-25A	Screw Kit, ¼-20	1
SK-08A	Screw Kit, 8-32	1
RSP-2T	Rotation Stage, 2"	1
VPH-2	Post Holder, 2"	1
SPV-2	Post, 2"	1
SPV-3	Post, 3"	1
MPH-2	Micro-Series Holder, 2"	1
MSP-2	Micro-Series Post, 2"	1
FP-1A	Fiber Positioner	2
818-FA2	Bare Fiber Holder Mount	1
FP3-FH1	Bare Fiber Holder	1
1918-C	Power Meter	1
918D-SL-OD3	Low Power Detector, Silicon	1
B-1A	Sliding Base	1
423	Translation Stage	1
SM-13	Micrometer, 13 mm	1
IMIC-1	Inspection Microscope	1
FPH-S	Fiber Chuck	2
RSA-2TI	Solid Insert (included in RSP-2T)	1
TA-8Q20-10	Thread Adapter	1

1.6 INSTRUCTION SET

1.6.1 PREPARING FIBER ENDS

1. Remove 1.5" of fiber coating (or jacket) from a ~2 meter segment of F-MLD Fiber, using the F-STR-175 Fiber Stripper.

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. Do not attempt to cut the fiber with the cleaver. Only start a small nick, which will propagate through the fiber when pulled. Gently, but firmly, pull the fiber to cleave it.

NOTE: The F-CL1 Fiber Cleaver is much more dependent on operator skill than is the F-BK3 which may be chosen as an option to use in place of the F-CL1. In this case, follow the directions that are included with the F-BK3 Fiber Breaker and cleave the ends of the fiber. (The F-CL1 will have to be used in Project #4, so it may be helpful to gain some experience with it at this time.)

3. Check the quality of the cleave by examining it with the IMIC-1 Fiber Inspection Microscope. Carefully examine the end face of the fiber. The end face should appear flat and should be free of defects, as in **Fig. 1.6a**. Chips or cracks which 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. 1.6b** 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, two sources of error should be considered: 1) a poor scribe or 2) a non-uniform pull of the fiber.

A scribe that is too deep may cause an irregular cleave and may cause multiple cracks to propagate through the fiber (**Fig. 1.6b**). A scribe that 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. 1.6c**.

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 the F-BK3 Fiber Breaker has been chosen as an option, but will have to be considered if the F-CL1 Fiber Cleaver is being used.)

5. Once the fiber segment has been prepared with two well-cleaved ends, the geometry of the fiber may be examined as was described in the introduction. View a fiber end as in Step 3. Use an incandescent lamp to illuminate the far end of the fiber. The light shining through the central portion of the fiber should be visible. This is the fiber core. The region surrounding the core is the fiber cladding. The fiber coating will not be visible, because it has been stripped away from the end of the fiber.

1.6.2 MEASURING NUMERICAL APERTURE

1. Attach the Model ULM-TILT Laser Mount to the Model 340-RC Rod Clamp, using 1/4-20 screws from the SK-25A Screw Kit. Place the 340-RC Rod Clamp on the Model

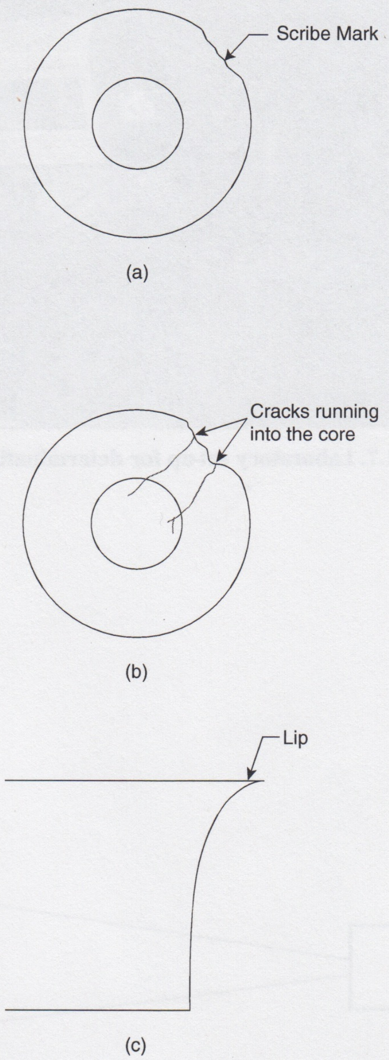

Figure 1.6. Cleaved fiber ends. (a) good cleave. (b) cracked fiber. (c) Side view of a lip on the end of a fiber.

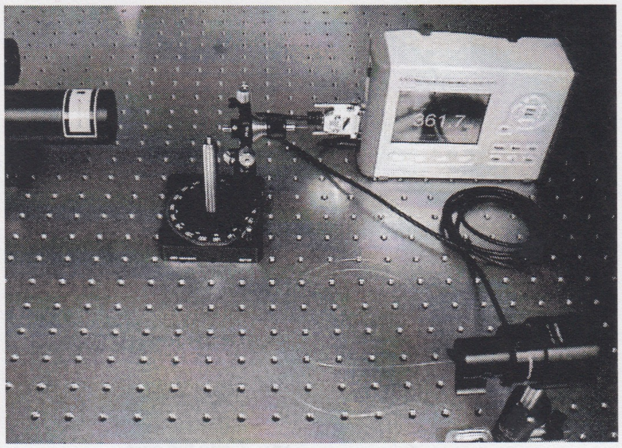

Figure 1.7. Laboratory set-up for determination of fiber NA.

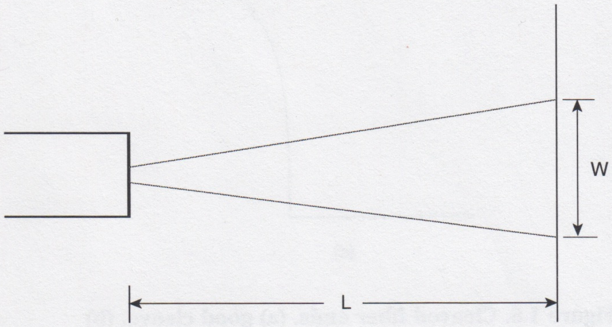

Figure 1.8. Approximate measure of the NA of a fiber.

41 Short Rod. Mount the 41 Short Rod to the 423 Translation Stage and mount the 423 Translation Stage to a Breadboard. Place the HeNe Laser into the ULM-TILT Laser Mount. Tighten the set screw. Do not over tighten as this will damage the laser. Plug the laser power supply into a 110V (or possibly 220V if using outside the U.S.) wall 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. **NOTE: The laser should be turned on and left on for ~30 minutes before taking any measurements to ensure proper stability.** The combination of the ULM-TILT Mount and the 340-RC Rod Clamp should align the laser parallel to a line of bolt holes on the table.

2. Position the beam from the HeNe Laser so that it passes over the center hole of the RSP-2T Rotation Stage. This can be done by means of the 423 Translation Stage mounted under the 41 Short Rod. Mount the MPH-2 Micro-Series Post Holder on the RSP-2T Rotation Stage using the TA-8Q20-10. Place the MSP-2 Micro-Series Post in the MPH-2, as shown in **Fig. 1.7**.

3. Prepare a fiber segment, ~2 meters long, with a good cleave at each end face. (The fiber prepared in the previous section may be used.) Insert one end of the fiber into an FPH-S Fiber Holder (At least 3" of the jacket should be stripped from the fiber in order to do this and the following step) and place this holder into its FP-l Fiber Positioner, which has been post-mounted on the RSP-2T Rotation Stage, using the MPH-2 Post Holder and the MSP-2 Post.

4. Extend the tip of the fiber and orient the FP-1A 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. (To help align the fiber tip, mount an SPV-3 Post in the center hole of the RSP-2T Rotation Stage with the 8-32 stud pointing up toward the fiber. Then align the fiber end over this 8-32 stud.)

5. Re-check the alignment of the 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 the fiber.

6. Mount the far end of the fiber in an FPH-S Fiber Holder, which is mounted in the FP-lA, mounted on the SPV-2, VPH-2 and B-1A. A quick approximation of the fiber's NA may be made with a 3 x 5 card placed a distance, L, away from the laser in a darkened room, as shown in **Fig. 1.8**. 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 $\sin^{-1}[(1/2)(W/L)]$ This is a quick method, which is used when only an approximate measurement of a fiber's NA is needed.

7. For a direct reading, remove the FP-1A Fiber Positioner from the SPV-2 Post and replace it with the 918D-SL-OD3. Remove the fiber from the FPH-S Fiber Holder and place it in the FP3-FH1 Bare Fiber Holder. Screw the 818-FA2 Bare Fiber Mount Holder onto the face of the 918D-SL-OD3. Then, snap the FP3-FH1, with the fiber in it, into the 818-FA2, so the output beam from the fiber is incident on the detector head. Block the laser beam and zero the power meter before taking a reading.

8. Measure the power accepted by the fiber as a function of the incident angle of the plane-wave laser beam. For the best continuity, begin taking measurements at the minimum power on one side and continue through the maximum to the minimum power on the other side. (An angle of about 30° should be traversed.)
Measurements may be taken in 1-2 degree increments.

9. Plot the power received by the detector as a function of the sine of the acceptance angle. Use the semi-log paper in the back of the manual. 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. 1.5**.