Lab 6:
OPTICAL FIBERS (3 Lab Periods)

Objective   Stripping and cleaving of optical fibers for integration into optical devices. Measurement of the numerical aperture (NA) of multimode fibers and of the beam profile of a single-mode fiber.

References   Hecht section 5.6

I. Background

A. Fiber Geometry

An optical fiber is illustrated in Fig. 6.1. It consists of a core with a refractive index n_{core} and diameter $2a$ and a cladding, with a refractive index n_{cl} and diameter d. As shown in Fig. 6.2, typical core diameters range from 4 to 8 μm for single-mode fibers, from 50 to l00 μm for multimode fibers used for communications, and from 200 to l000 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 raise the index of refraction slightly.
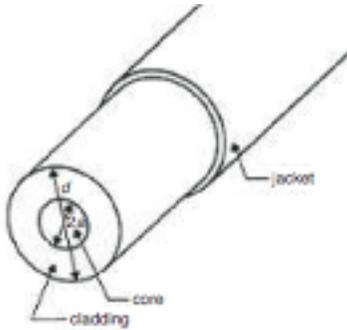

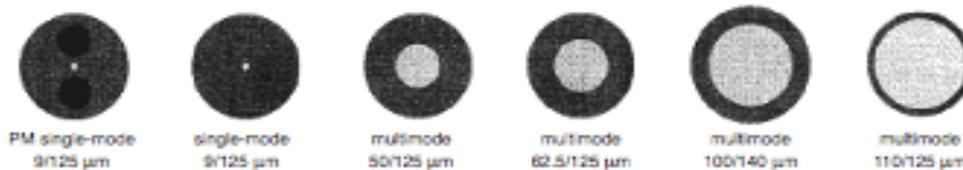Figure 6.1: *Geometry of an optical fiber, showing core, cladding, and jacket.*

Figure 6.2: *Some popular fiber sizes*

The transition of the optical parameters from the core to the cladding can be discontinuous (step-index fiber) or smooth (graded-index fiber). 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. The optical fiber will generally be surrounded by a protective jacket. This jacket may be made from a plastic and have an outside diameter of 500 – l000 μm. However, the jacket may also be a very thin layer of varnish or acrylate material.

B. 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, 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, θ_{max}:

$$NA = n_i \sin\theta_{max} \qquad (6.1)$$

In most cases, the light will be incident from air, and therefore $n_i = 1$. In this case, the NA of a step-index fiber can be obtained using Snell's Law, yielding

$$NA = \sqrt{n_{core}^2 - n_{cl}^2} \qquad (6.2)$$

The fractional refraction index difference between core and cladding is $\Delta = \left(n_{core} - n_{cl}\right)/n_{core}$. The situation with $\Delta \ll 1$ is denoted as the weakly guiding approximation, and in this case the NA of a fiber can be written as

$$NA = n_{core}\sqrt{2\Delta} \qquad (6.3)$$

As an example, a typical multimode communications-fiber may have $\Delta \approx 0.01$, in which case the weakly-guiding approximation is certainly justified. For silica-based fibers, $n_{core} \approx 1.46$. Using Eq. (6.1), these values of Δ and n_{core} give NA = 0.2. This gives a value of 11.5° for θ_{max} and a total core angle of 23°. Values of NA range from about 0.1 for single-mode fibers, 0.2 − 0.3 for multi-mode communications fibers, up to about 0.5 for large-core fibers.

C. Fiber Attenuation

Attenuation (loss) is a logarithmic relationship between the optical output power and the optical input power in a fiber optical system. It is a measure of the decay of signal strength, or loss of light power, that occurs as light pulses propagate through the length of the fiber. The decay along the fiber is exponential and can be expressed as:

$$I(z) = I_0 \times 10^{-(\Gamma z/10)} \qquad (6.4)$$

The length of the fiber, z, is given in kilometers and the attenuation coefficient, Γ, is given in decibels per kilometer (dB/km). Because the designers of fiber optic systems need to know how much light will remain in a fiber after propagating a given distance, one of the most important specifications of an optical fiber is the fiber's attenuation. In principle, the fiber attenuation is the easiest of all fiber measurements to make. The method which generally used is called the "cutback method". All that is required is to launch power from a source into a long length of fiber, measure the power at the far end of the fiber using a detector with a linear response, and then, after cutting off a length of the fiber, measure the power transmitted by the shorter length. The

reason for leaving a short length of fiber at the input end of the system is to make sure that the loss that is measured is due solely to the loss of the fiber and not to loss which occurs when the light source is coupled to the fiber. Figure 6.3 shows a schematic illustration of the measurement system.
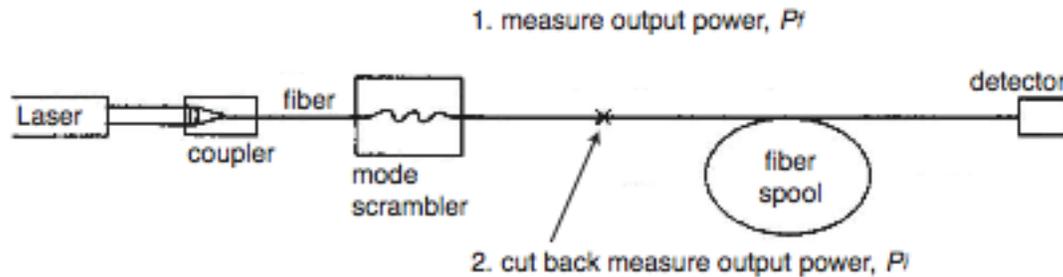

<u>Figure 6.3</u>: *Schematic laboratory setup for the cutback method of determining fiber attenuation.*

The transmission through the fiber is $T = P_f/P_i$ where the initial and final power output has been substituted for I_0 and $I(z)$, respectively. A logarithmic result for the loss in decibels (dB), is given by

$$L(\text{dB}) = -10\log(P_f / P_i)$$
(6.5)

The minus sign causes the loss to be expressed as a positive number. This allows losses to be summed and then subtracted from an initial power if that is also expressed logarithmically. In working with fiber optics, you often find powers expressed in dBm, which means "dB with respect to l mW of optical power". Thus, 0 dBm = 1 mW, 3 dBm = 2 mW and −10 dBm = 100 pW. Note that when losses in dB are subtracted from powers in dBm, the result is in dBm. For example, an initial power of +3 dBm minus a loss of 3 dB results in a final power of 0 dBm. This is a shorthand way of saying "An initial power of 2 mW with a 50% loss results in a final power of 1 mW."

The attenuation coefficient, Γ, in dB/km is found by dividing the loss, L, by the length of the fiber, z. The attenuation coefficient is then given by

$$\Gamma(\text{dB/km}) = \frac{-10\log(P_f / P_i)}{z}$$
(6.6)

The total attenuation can be found by multiplying the attenuation coefficient by the fiber length, giving a logarithmic result, in dB, for the fiber loss.
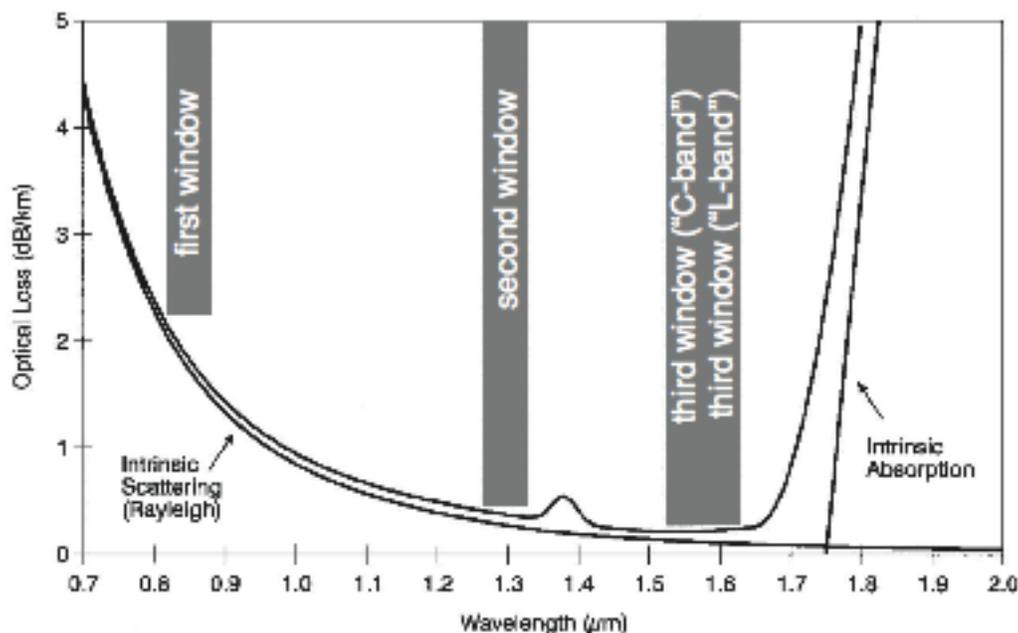
Figure 6.4:   *Wavelength dependence of the optical losses in a typical fiber.*

Fiber		Optical Loss (dB/km)			
Size	**Type**	**780 nm**	**850 nm**	**1310 nm**	**1550 nm**
9/125 μm	SM	...	...	0.5-0.8	0.2-0.3
50/125 μm		4.0-8.0	3.0-7.0	1.0-3.0	1.0-3.0
62.5/125 μm		4.0-8.0	3.0-7.0	1.0-4.0	1.0-4.0
100/140 μm	MM	4.5-8.0	3.5-7.0	1.5-5.0	1.5-5.0
110/125 μm		...	15.0	...	...
200/230 μm		...	12.0	...	...

Table 6.1:   *Typical loss parameters for various optical fibers.*

D. Single-Mode *vs.* Multimode Fibers

The properties of multi-mode fibers can be described in terms of the geometrical paths of light rays propagating down the fibers. This ray picture of light propagation is adequate for describing large core-diameter fibers with many propagating modes, but it fails for small core-diameter fibers with only a few modes or with only a single mode. For fibers of this type, it is necessary to describe the allowed modes of propagation of light in the fibers.

A detailed description of the propagation characteristics of an optical fiber can be obtained by solving Maxwell's equations for the cylindrical fiber waveguide. This leads to a solution for the allowed modes that may propagate in the fiber. When the number of allowed modes is very large, the mathematics becomes very complex; this is when the ray picture is used to describe the waveguide properties.

An important qualitative measure in characterizing a fiber waveguide is called the *V*-number of the fiber, given by

$$V = k_f \, a \, NA \tag{6.7}$$

where k_f is the free-space wavenumber, $2\pi/\lambda$ (with λ the wavelength of the light in free space), and a is the radius of the core. *V* can be used to characterize which guided modes are allowed to propagate in a particular waveguide structure, as shown in Fig. 6.5. When $V < 2.405$, only a single mode, the LP_{01} or HE_{11} mode, can propagate in the waveguide. This is the single-mode regime. The wavelength at which $V = 2.405$ is called the "cut-off wavelength" (denoted by λ_c) because that is the wavelength at which the next higher-order mode is cut off and no longer propagates.

The single-mode fiber that will be used in this project is the Newport F-SV fiber, which has a core diameter of 4 μm and an NA of 0.11. Therefore, according to Eq. (6.7), this fiber is characterized by $V = 2.19$ for $\lambda = 633$ nm, putting it well within the single-mode regime.
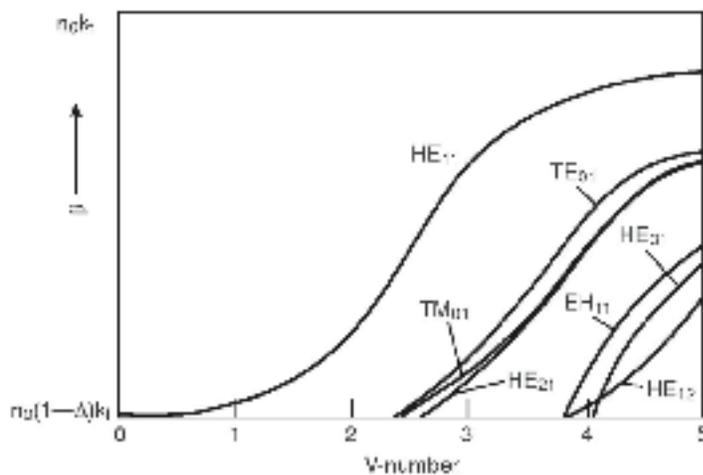

Figure 6.5: *Low-order modes of light propagating in an optical fiber. The propagation constant β is shown as a function of V. Each V represents a different fiber configuration or a different light wavelength in a given fiber configuration.*

For waveguides in which the diameter of the core is extremely large compared to λ, the lowest order mode has an irradiance profile which is Gaussian. That is, the irradiance as a function of distance from the beam axis has the form

$$I(r) = I_0 \exp\left(-2r^2/r_0^2\right) \tag{6.8}$$

where I_0 is the irradiance at the center of the beam and r_0 is the radius of the beam at which the irradiance is I_0/e^2.

The fundamental HE_{11} mode of a fiber is very close to a Gaussian mode when the light is near the cut-off wavelength. Figure 6.6 shows the shape of this HE_{11} mode near the cutoff of the next-higher mode (that is, with *V* only slightly less than 2.405), as a function of r/a. The exact solution

and the Gaussian curve are quite similar. In the case of a parabolic profile fiber with an infinite core diameter, the Gaussian function is the exact solution for the fundamental mode.

Figure 6.7 shows the exact modal distribution along with the Gaussian approximation for a longer wavelength further from cutoff. It can be seen that the Gaussian approximation is not as good as one gets away from the cut-off wavelength. However, the qualitative shape of the exact solution curve is still not too far from Gaussian. Later in this project, the Gaussian approximation for a single-mode fiber will be explored.

Figure 6.6: *Comparison of the exact mode field intensity with its Gaussian approximation near the cut-off wavelength (V = 2.400).*
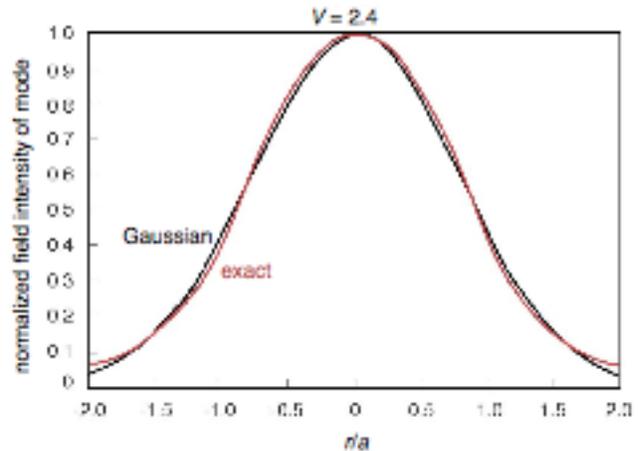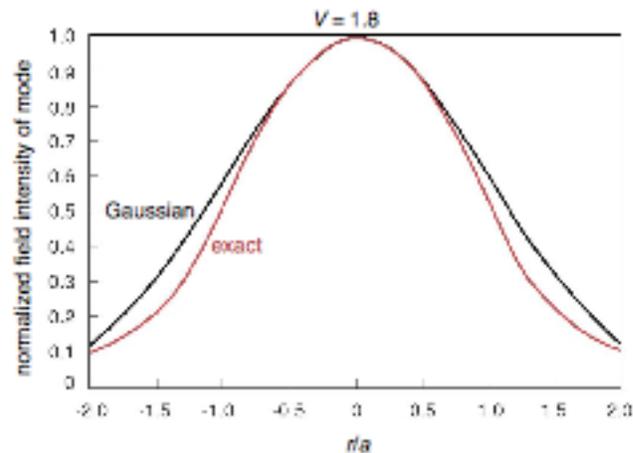

Figure 6.7: *Comparison of the exact mode field intensity with its Gaussian approximation further away from the cut-off wavelength (V = 1.800).*
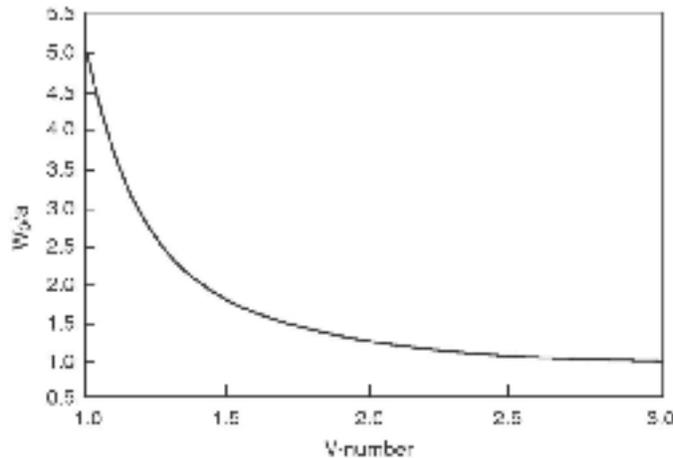

E. Coupling to Single-Mode Fibers

Coupling light into a multimode fiber is relatively easy. However, maximizing the coupling to a single-mode fiber is much more difficult. In addition to very precise alignment of the fiber to the incoming beam, it is necessary to match the incident electromagnetic field distribution to that of the mode which will be propagated by the fiber.

You need to realize that the profile of a mode and the fiber core size *a* are related, but there is no simple relation between the two, even for a step-index fiber. The profile of the HE_{11} mode of a step-index single-mode fiber can be approximated by a Gaussian distribution with a $1/e^2$ spatial half-width given by

$$w_0 = a\left(0.65 + 1.619V^{-1.5} + 2.879V^{-6}\right) \qquad (6.9)$$

Eq. (6.9) demonstrates that a and w_0 are by no means connected by a fixed proportionality, but that the relationship between the two rather depends on the value of V. For example, at $V = 2.405$, the Gaussian spot size is approximately 10% larger than the core diameter. Therefore, in this case, the incident light should be focused at the fiber's end face to a spot size which ~ 1.1 times the fiber core diameter.

Figure 6.8 shows a plot of the normalized radius of the Gaussian distribution as a function of V. It shows that for a fiber of given radius, w_0 increases as V becomes smaller (*i.e.*, as λ becomes larger). As w_0 increases, the electromagnetic field of the mode is less well confined within the waveguide. Single-mode fibers are therefore designed such that the cutoff wavelength is not too far from the wavelength of the light intended for use with the fiber. Typically, λ_c will be about 80-90% of the wavelength for which the fiber is designed.

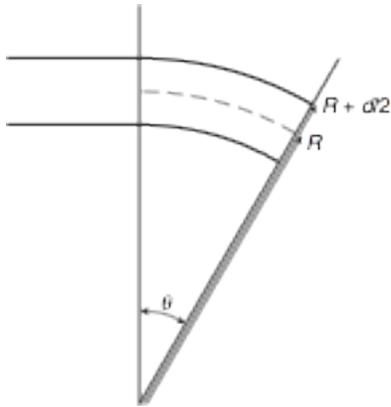Figure 6.8: *HE$_{11}$ mode filed radius as a function of V.*

II. Handling and Technical Procedures

A. Mechanical Properties of Fibers. Cleavage and Preparation of Fiber Ends.

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 (Fig. 6.9), the surface strain on the fiber is the elongation of the fiber surface divided by the length of the arc and results in the strain,

$$\varepsilon = \frac{(R + d/2)\theta - R\theta}{R\theta} = d/2R \tag{6.10}$$

Although silica fibers have been designed that can withstand strains of several percent, only an upper strain limit of a fraction of l% is 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 μm diameter fiber will be able to survive a bend radius of l.25 cm. In theory, the breaking strength of glass fibers can be very large, up to 5 GPa (1 GPa = 10^9 N/m^2). However, because of inhomogeneities 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 force per unit length). This process is called proof testing. Typical commercial fibers may be
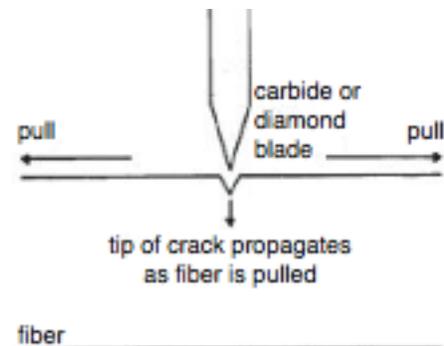
proof tested to about 350 MPa, which is equivalent to about a one-pound load on a 125 μm OD fiber.

Figure 6.9: *Strain of a bent fiber*

Before using an optical fiber in any kind of measurement device, it will be necessary to prepare its ends so that light can be efficiently coupled in and out. This is done by 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. 6.10. Evenly distributed stress, applied by pulling the fiber, causes the crack to propagate through the fiber and cleaves it across a flat cross section of the fiber perpendicular to the fiber axis. When a crack is introduced, the breaking strength is further reduced 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 cleavage area across the fiber face.

Figure 6.10:   *Scribe-and-break technique of fiber cleavage. A carbide blade makes a small nick in the fiber. The fiber is pulled to propagate the crack through the cladding and core.*

III. Equipment

- Newport Fiber Optics Project Kit
- Diamond Cleaver for optical fibers
- Optics Breadboard and Optical Rail with Rail-Riders
- He-Ne Laser
- Laser Power Meter

IV. LAB SAFETY: Do not look into the Laser beam. Eye injury and blindness may result.
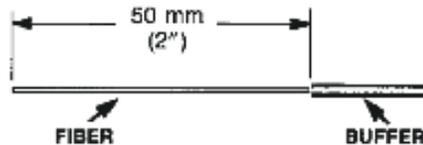
V. Procedure

A. Preparing Fiber Ends

(See Illustration in Fig. 6.11, below and associated text on next page)

1. FIBER SIZE:

Ensure that the fiber to be broken is a glass fiber of nominal diameter. 125μm* and buffer O.D. is: 250μm to 1.5mm *(fiber diameters other than 125μm can be accommodated – consult factory).
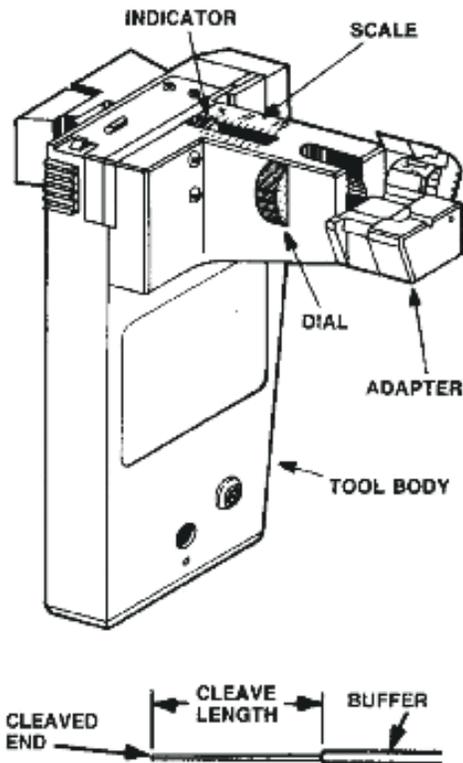
2. FIBER PREPARATION:

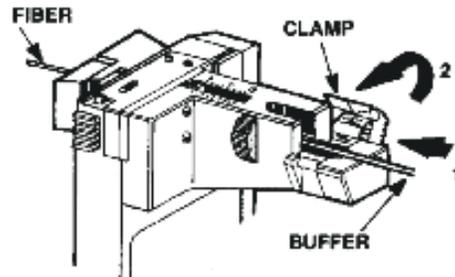Prepare fiber for cleaving by removing 50 mm (2") of buffer.

3. ADAPTER ADJUSTMENT:

Adapter has a cleave length scale of 3 to 20 mm (each division on scale is 1 mm). Set indicator to desired cleave length by turning dial.
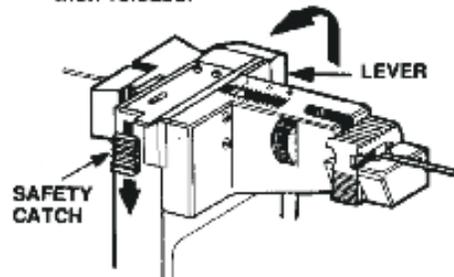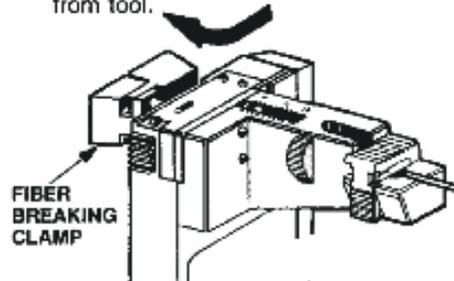
4. FIBER BREAKING:

A. Insert fiber into adaptor until it stops (fiber should be protruding out of tool), then press clamp down into lock position.

B. Slide safety latch down. While latch is in down position, squeeze lever until it stops, then release.

C. Firmly squeeze fiber-breaking clamp and while squeezing, slide clamp slightly away from tool.

D. Removed fiber stub from fiber-breaking clamp and safely discard, then unlock clamp on adapter and remove cleaved fiber.

*Note: Do not slide safety latch down and actuate lever <u>without</u> fiber inserted, as this will damage tool.

Figure 6.11: Use of the fiber breaker tool and preparation of fiber ends.

Start with a ~ 2 m length of the F-MLD multimode fiber, removed from the 50 m spool. Remove ~ 2 inches of the cladding layer from one end of the fiber using the fiber stripping tool. Be sure to pull the stripping tool in the direction indicated by the arrow on the head of the tool. Use the Fiber Breaker to cleave the stripped end of the fiber, as described in Fig. 6.11.

Insert the fiber into the FMA-BF2 holder so that the cleaved end is approximately flush with the plastic face of the holder. Clean the end with the Aero-Duster. Screw the FMA-BF2 holder onto the end of the 400× microscope. Examine the end face of the fiber with the microscope. The face should appear flat and perpendicular to the length of the fiber, and should be free of defects, as in Fig. 6.12 (a). 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 Figs. 6.12 (b) and (c). *Show your cleaved end (through the microscope) to the Lab Instructor for approval, before continuing with the lab.*

Strip and cleave the other end of the fiber as well, repeating this step until a good end face, free of defects, is obtained.
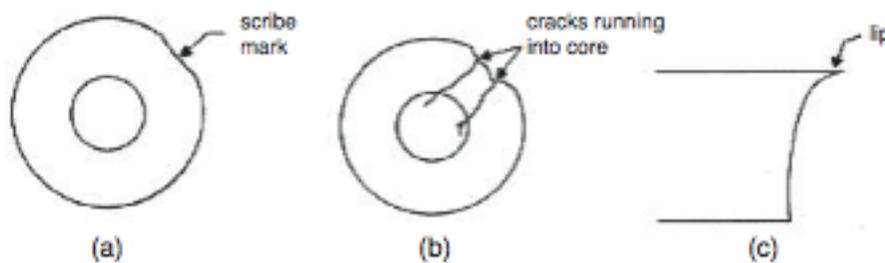

Figure 6.12:   *Cleaved fiber ends. (a) Good cleave. (b) Cracked fiber. (c) Side view of a lip on the end of a fiber.*

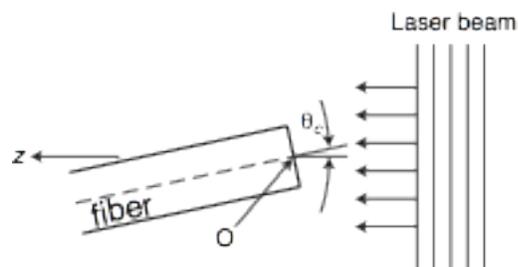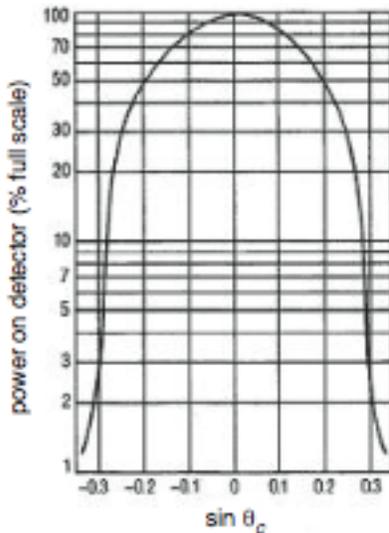## B. Launching Light into the Fiber End

Figure 6.13: *Geometry of launching light from a Laser into an optical fiber.*

If the fiber end face is rotated about the point O (Fig. 6.13), we can measure the amount of light accepted by the fiber as a function of the incident angle, θ_c.

Fig. 6.14 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 experimental

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. 6.14, that 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.

Figure 6.14: _Transmitted power through an optical fiber (Newport F-MLD) as a function of the rotation angle θ_c of the accepting fiber end (see illustration in Fig. 6.13). Such a measurement can be used to determine the fiber NA._

1. Measuring the Numerical Aperture of a Multimode Fiber

Use a fiber segment with a good cleave at each end face. Insert one end of the fiber into the Fiber Holder (this is the shiny brass-colored rod that's sticking out of the fiber positioner). Insert the holder into the fiber positioner that has been post-mounted onto the rotation stage.

Extend the tip of the fiber and orient the 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.

Ensure that the Laser beam is horizontal. Direct the beam to the end of the fiber extending out from the positioner. 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 set-up achieves plane-wave launching into the end of the fiber.

Mount the far end of the fiber in the adaptor, mounted on a post. You can get a quick approximate measure of the fiber's NA using the image formed on a piece of paper placed a distance, L, away from the end of the fiber in a darkened room, as shown in Fig. 6.15. Measure the width, _W_, of the spot and the distance, _L_, between the fiber end and the card. The NA of the fiber is approximately

$$NA = \sin\left(\tan^{-1}\left(W/2L\right)\right) \approx W/2L \tag{6.10}$$

This provides a quick estimate which is used when only an approximate measurement of a fiber's NA is needed.
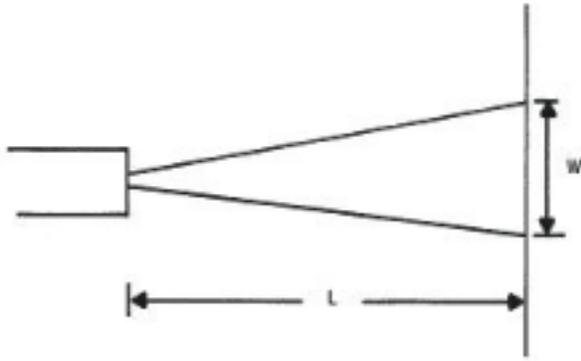
Figure 6.15: *Quick estimate of NA for a fiber Approximate measurements of the NA of a fiber.*

Mount the detector head of the Model 815 Power Meter so that the output beam from the fiber is incident on the detector head (Figure 6.16). If necessary make a hood of aluminum foil to keep stray room light off of the detector. This may 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.

Measure the power accepted by the fiber as a function of the incident angle of the plane-wave laser beam. Use both positive and negative rotation directions to compensate for any remaining error in laser-fiber alignment.

Plot the power received by the detector as a function of the sine of the acceptance angle. A semi-log plot as in Fig. 6.14 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 this result for the numerical aperture, as determined from your intensity plot, with the quick approximation, which you determined previously from the method illustrated in Fig. 6.15, using Eq. (6.10). Does the quick approximation compare favorably to the more precise determination?
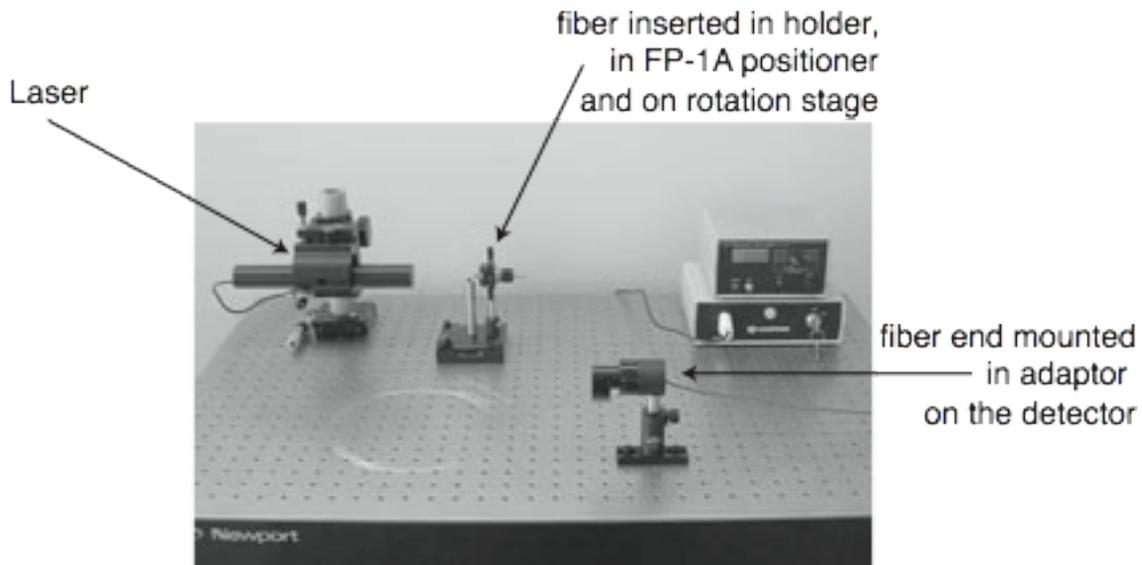

Figure 6.16: *Laboratory set-up for determination of the NA of an optical fiber.*

2. Beam Profile of a Single-Mode Fiber

(a.) Laser beam coupling into the single-mode fiber

Cut a segment of F-SV fiber ~ 2 m in length and cleave both ends as for the multimode fibers. Mount one end of the fiber in the fiber holder of the coupler. This device is used to couple light from a HeNe Laser into a fiber as illustrated in Fig 6.17. Align the HeNe Laser so that its beam shines along the z axis of the coupler. A 20× microscope objective is placed in the coupler. Insert the cleaved front end of the fiber into the holder and into the positioner which is part of the fiber coupler. Align the fiber positioner to maximize the light launched into the fiber, using the power meter to monitor the launched power. Use a microscope slide cover glass in the path of the Laser beam to look at the Fresnel reflection from the fiber end face. Focus the Fresnel-reflected beam by adjusting the z position of the fiber, as defined in Fig. 6.17, by turning the z adjustment knob on the fiber positioner (or manually moving the holder). When the reflection is focused, the fiber end face is in the focal plane of the coupler's microscope objective lens. Thereby you should get the z axis fiber alignment approximately correct so that the Laser beam is at least striking the fiber end face, if not the core. Note that rough alignment can be monitored by noting the orientation of back reflections from the various optical surfaces.
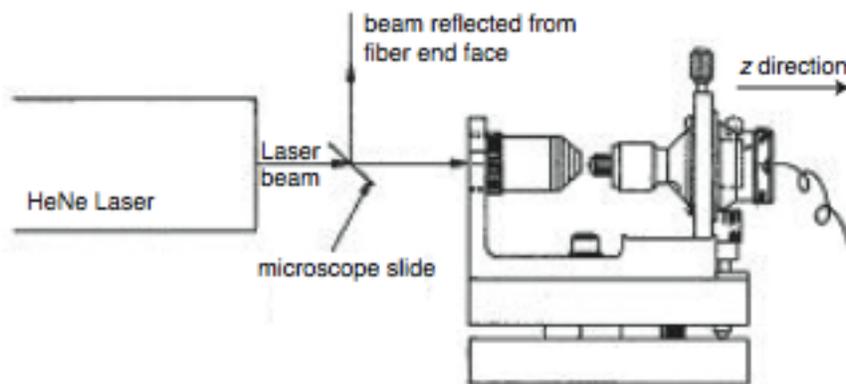

Figure 6.17: *F-916 fiber coupler*

After you've optimized coupling to the single-mode fiber, separate the adapter (containing the far end of the fiber) from the power detector, and place those two items in carriers on the optical rail as shown in Fig. 6.18.

Adjust the x and y components of the fiber alignment, using the fine adjustment knobs on the tilt stage of the fiber coupler to achieve maximum coupling of the Laser beam into the fiber. Monitor the output power using the power meter. Note that alignment of this single-mode fiber is more difficult than for multimode fibers, but with some patience, coupling of a relatively strong signal into the fiber can be achieved.
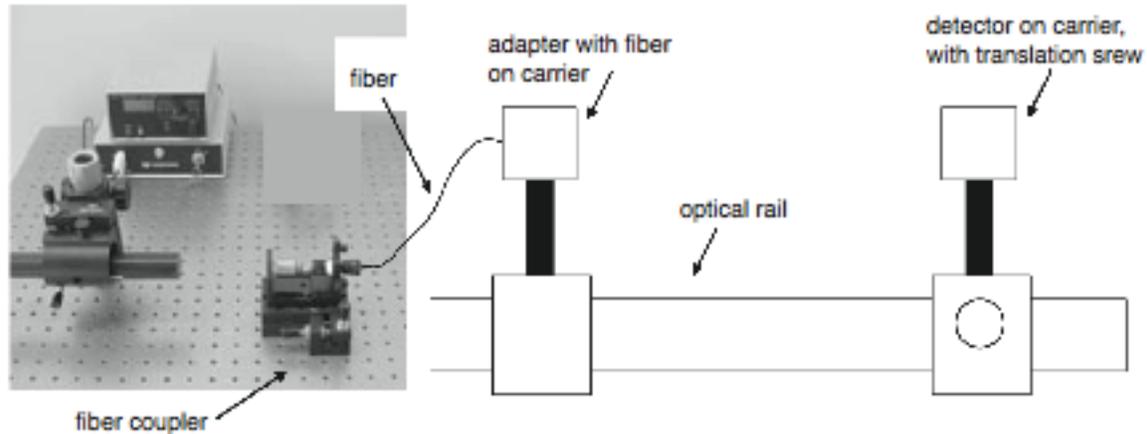
<u>Figure 6.18:</u>   *Experimental set-up for determining the beam profile of a single-mode fiber.*

(b.) Beam profile determination

Mount the power detector about 2 inches away from the fiber end in a carrier with the screw-type translation adjustment. You'll have to post-mount the detector, and for this purpose you can use the post from the center of the rotary stage used with the multimode fiber. When screwing the post into the detector, note that the threaded hole marked "M" is metric, which you **should not use**. Instead, use the other threaded hole that's not labeled.

You will measure the far-field distribution of the fiber output by translating the power detector. The far field is effectively the region where the fact that the core diameter is non-zero plays no role in the energy distribution. It is usually thought to start at a distance $z_0 = (2a)^2/\lambda$ from the end of the fiber. Note that for a fiber with a 4 μm core at $\lambda = 632.8$ nm, this implies a far-field distance of under 1 mm. For this purpose, construct a slit on the detector by taping two razor blades to it with a separation between the blades of about 1 mm, as in Fig. 6.19.
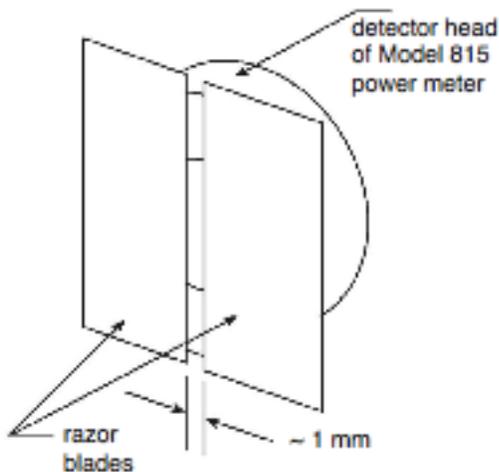

<u>Figure 6.19:</u>   *Masking of the detector with a slit made from two razor blades.*

Scan the Detector using the translation screw on the carrier to measure the profile of the beam emitted from the fiber. The carriers in the lab have a scale marking of 1 mm, and their screw adjustment corresponds to 1 mm travel for 1 full revolution. When measuring the intensity profile you should take measurements at consecutive 90° positions of the screw. For best results, begin taking measurements at the minimum on one side of the beam profile, and continue scanning through the maximum on through to the opposing side's minimum power reading. Do not back up the screw since this will result in some mechanical backlash.

Plot the far-field distribution of power output from the fiber as a function of position. Find the maximum recorded output power from your data. Call this value I_0. Now find the points where the output power is $I_0 e^{-2}$. Measure the full width between these two points. Take half of that full width and call it x_0. Plot a Gaussian curve, $I(x) - I_0 \exp(-2x^2/x_0^2)$, on the same graph with your experimental data, and comment on any differences between the computation and the experiment.

Using either your measured profile or the Gaussian that you have matched to it, locate the 5% intensity points and estimate the NA of the fiber using the same method as in Fig. 6.15. For this purpose, you will need to know the distance between the fiber end and the active element within the power detector. ***Please do not disassemble the detector!*** Rather, use a value of 37.5 ± 0.5 mm as the distance from the photodiode to the front face of the 818-FA2 piece on the front of the detector. Simply add that value to a measurement of the distance from the front face of the 818-FA2 to the fiber end. Compare the NA you obtain with the value given by the manufacturer for the Newport F-SV fiber (NA = 0.11), and comment on any discrepancy.