3.0 PROJECT #3: SINGLE-MODE FIBERS I

(Est. Time Required: 2:30 hrs.)

This project will be the first of two exercises that will consider the modal properties of fibers and the properties of single-mode fibers. The student will learn to couple laser light into a 4 µm diameter core, single-mode fiber. The student will then measure the far-field power distribution of the fiber as a function of angle and determine how well it fits the optical model which will be described in the following discussion.

3.1 SINGLE-MODE FIBERS

In the first two projects, some of the properties of multimode fibers were explored. The properties of multimode fibers are easily described in terms of the 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 knowledge of 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. The solution of Maxwell's equations for the allowed modes of a fiber was outlined in **Section 0.3.1**.

In that section, it was found that an important qualitative measure in characterizing a fiber waveguide is called the V-number of the fiber. Recalling Eq. 0-15, it was written as

$$V = k_f \, a \, NA, \tag{3-1}$$

where k_f is the free-space wavenumber, $2\pi/\lambda_0$ (where λ_0 is the wavelength of the light in free space), a is the radius of the core, and NA is the numerical aperture of the fiber. The V-number can be used to characterize which guided modes are allowed to propagate in a particular waveguide structure. When $V < 2.405$, only a single mode, the HE_{11} mode, may propagate in the waveguide. This is the single-mode regime. The wavelength at which V is equal to 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 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. 3-1, this fiber has a V-number of 2.19 for 633 nm light, putting it well within the single-mode regime.

3.2 GAUSSIAN APPROXIMATION

In waveguides in which the diameter of the core is extremely large compared to the wavelength of the light (for example, the HeNe laser tube described in **Section 0.4.2** and **Fig. 0.27**), the lowest order mode has an irradiance pattern which is **Gaussian**. That is, the irradiance as a function of distance from the beam axis has the form

$$I(r) = I(0) \exp(-r/r_0)^2, \qquad (3\text{-}2)$$

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 $1/e^2$ of that at the center of the beam. **Fig. 3.1** shows the irradiance of a Gaussian beam.

The HE_{11} mode of a fiber is very close to a Gaussian mode when the light is near the cut-off wavelength.[1] **Fig. 3.2** shows the shape of the fundamental HE_{11} mode near the cutoff of the next-higher-order mode (that is, with V only slightly less than 2.405), as a function of r/a, where r is the radial position and a is the core radius. While the red line in the figure represents the actual distribution of the mode, the black line is a Gaussian. The two curves are quite similar and the exact solution near the cut-off wavelength is often approximated by a Gaussian. In the case of a parabolic profile fiber with an infinite core diameter, the Gaussian function is the exact solution for the fundamental mode.

Fig. 3.3 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. In this project, the Gaussian approximation for a single-mode fiber will be explored.

3.3 COUPLING TO A SINGLE-MODE FIBER

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.

The mode 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[2]

$$w_0 = a(0.65+1.619\, V^{-1.5}+2.879\, V^{-6}), \qquad (3\text{-}3)$$

where a is the fiber core radius. For example, when 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 to a spot size which is 1.1 times the fiber core diameter at the fiber's end face.

Fig. 3.4 is a plot of the normalized radius of the Gaussian distribution as a function of the V-number. It can be seen that, for a fiber of given radius, as V becomes smaller (as λ becomes longer) the spot size increases. As the wavelength increases, the electromagnetic field of the mode is less well confined within the waveguide. For this reason, single-mode fibers are designed so 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 at which the fiber's design wavelength.

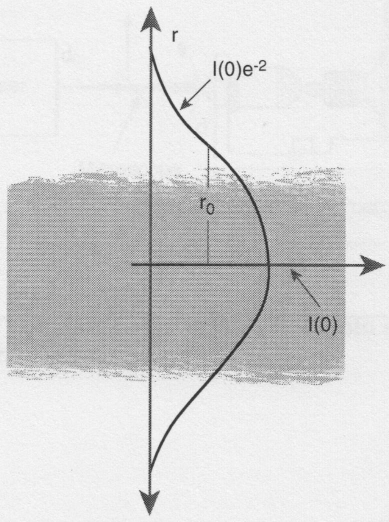

Figure 3.1. Irradiance of a Gaussian beam.

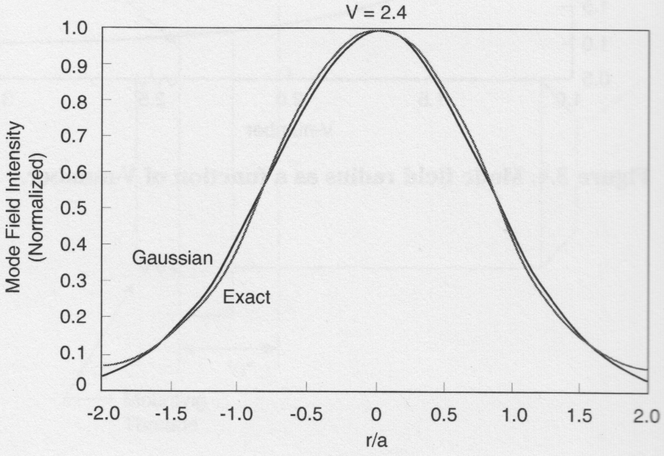

Figure 3.2. Comparison of the exact mode field intensity and its Gaussian approximation near the cut-off wavelength (V=2.4).

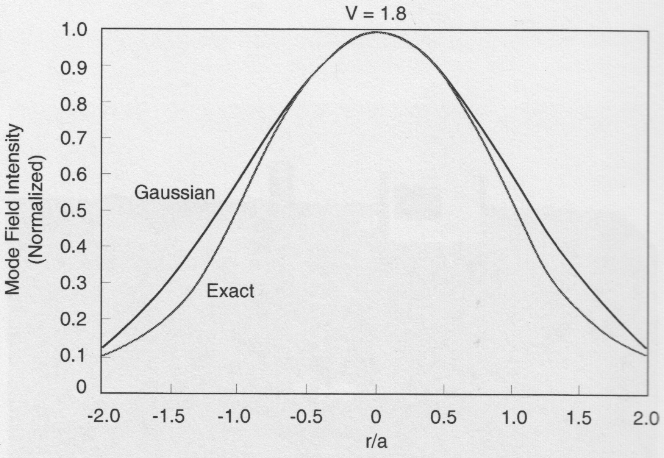

Figure 3.3. Comparison of the exact mode field intensity and its Gaussian approximation further from the cut-off wavelength (V=1.8).

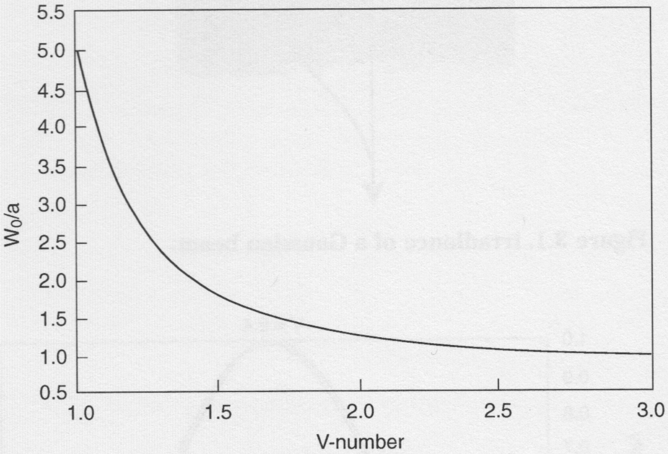

Figure 3.4. Mode field radius as a function of V-number.

3.4 REFERENCES

1. L. B. Jeunhomme, Single-Mode Fiber Optics, Principles and Applications, Marcel Oekker (New York) 1983, p.16

2. ibid, p. 18, or D. Marcuse, “Loss analysis of single-mode fiber splices,” Bell Sys. Tech. J., vol. 56, pp. 703-718, 1977

3. Fiber Optic Systems - A White Paper, 1997, Charles M. Smith

4. Single-Polarization Single-Mode Optical Fibers, IEEE Journal of Quantum Electronics, Vol. QE-17, June 1981, pp. 879-884, Okoshi T.

3.5 PARTS LIST

Cat#	Description	Qty.
F-SV	4/125 SM at 633 nm fiber, 20 meters	20
R-30025	1.5 mW HeNe Laser	1
ULM-TILT	Laser Mount	1
340-RC	Clamp	1
41	Short Rod	1
F-916	Fiber Coupler (without lens)	1
FPH-S	Fiber Chuck	2
M-20X	20X Objective Lens	1
F-CL1	Fiber Cleaver	1
1918-C	Power Meter	1
918D-SL-OD3	Low Power Detector, Silicon	1
FK-BLX	Allen Wrench Set	1
SK-25A	Screw Kit, ¼-20	1
SK-08A	Screw Kit, 8-32	1
RSP-1T	Rotation Stage, 1"	1
RSA-1TI	Solid insert (included in RSP-1T)	1
SPV-2	Post, 2”	1
SPV-3	Post, 3”	1
VPH-2	Post Holder, 2”	1
B-1A	Sliding Base	1
TA-8Q20-10	Thread Adapter	1
MPH-2	Micro Series Holder, 2"	1
MSP-2	Micro Series Post, 2"	1
F-STR-175	Fiber Stripper	1
IMIC-1	Fiber Inspection Microscope	1
FP-1A	Fiber Positioner	1

Additional equipment required: Razor blades, microscope cover glass, and tape to construct the slit mask for the power meter detector.

3.6 INSTRUCTION SET

3.6.1 OPTIMIZING SINGLE-MODE COUPLING

1. Using Eq. 3-1, confirm that V=2.19 at a wavelength of 633 nm for the F-SV fiber (NA=0.11). Use Eq. 3-3 to find the spot size of the fiber mode for this V-number. (Spot diameter = $2w_0 = 1.2 \times 2a$.)

2. When coupling light into a single-mode fiber, one begins by using a microscope objective lens to focus the collimated beam from a laser to a small spot. The diameter, d_1, of the spot size at the waist of the focused laser beam can be determined from the focal length, f = 8.3 mm, of the microscope objective lens, and the diameter, d, of the laser beam at the rear focal plane of the objective lens, using $d_1 = 4\lambda f/\pi d$. (where d may be found from the divergence of the laser, which is 1.4 mrad, and the distance from the laser to the objective lens, using an equation from Gaussian optics,

$$d = d_0 \sqrt{1+(z\theta/d_0)^2}.$$

In this equation, d_0 is the diameter of the laser beam at the output of the laser, 0.63 mm for the laser being used, z is the laser-to-lens distance, and θ is the beam divergence of 1.4 mrad or .0014 in the equation.)

3. If the calculations in Steps 1 and 2 show that $d_1 = 2w_0$, then optimized coupling should be obtained when the input beam is focused on the fiber core, as shown in **Fig. 3.5**. If $d_1 \neq 2w_0$, then the value of d_1 must be adjusted by changing the distance between the F-916 coupler and the laser. For example, moving the laser further from the objective lens causes the input beam diameter, d, to become larger due to the beam divergence of the laser. This, in turn, causes d_1 to become smaller.

4. Mount the HeNe laser and the F-916 Fiber Coupler, with the 20X objective lens, so that the laser beam is parallel to the lens axis and strikes the lens at its center, as is illustrated in **Fig. 3.5**. Be sure to place the lens/fiber positioner assembly, which forms the top of the coupler, so that the rear focal plane of the microscope objective lens is directly over the pivot of the tilt platform. The rear focal plane of the M-20X objective lens is 1/2" in front of the lens, as shown in **Fig. 3.6**.

5. Cut a segment of F-SV fiber ~ 2m in length and cleave both ends as was done in **Project #1 (Section 1.6.1, Steps 1-3)**. Mount one end of the fiber in the fiber holder from the F-916 coupler and insert it into the F-916. Use the microscope slide cover glass to monitor the Fresnel reflection from the fiber end face, as was done in **Project #2 (Section 2.5, Step 3)**, and bring the end of the fiber into the focal plane of the objective lens by rotating the coarse adjustment knobs on the FP-1A positioner of the F-916 coupler. This will assure that the z-axis fiber alignment is approximately correct and will assure 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.*

6. Adjust the x and y components of the fiber alignment, using the fine adjustment knobs on the tilt stage of the F-916 Fiber Coupler, to achieve the maximum coupling of the laser beam into the fiber. *You may wish to refer again to the F-916 instruction sheet to understand the principle of operation of the tilt stage adjustment.*

Monitor the output power using the Power Meter. For one who has never done single-mode coupling before, a total loss (from laser output to fiber output) of 3 dB (50% loss; see **Section 2.1**) would be considered to be a good result, but with experience one should be able to consistently achieve losses of less than 2 dB (< 37% loss).

3.6.2 GAUSSIAN APPROXIMATION

1. Mount the far end of the fiber on the RSP-1T Rotation Stage in exactly the same way that the front end of the fiber was mounted in **Project #1 (Section 1.6.2, Steps 3, 4)**. The experimental set-up is shown in **Fig. 3.7**. This time, however, the actual far-field distribution of the fiber output will be measured. (The far-field of a fiber is usually said to start at a distance $z_0=(2a)^2/\lambda$ from the end of the fiber. The far field is effectively the region where the fact that the core diameter is non-zero plays no role in the energy distribution.) *Note that at 632.8 nm with a 4 micron fiber, this implies a far-field distance of under 1 mm.*

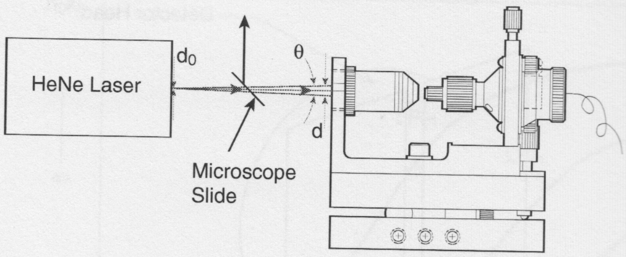

Figure 3.5. Coupling of HeNe laser light into a single-mode fiber.

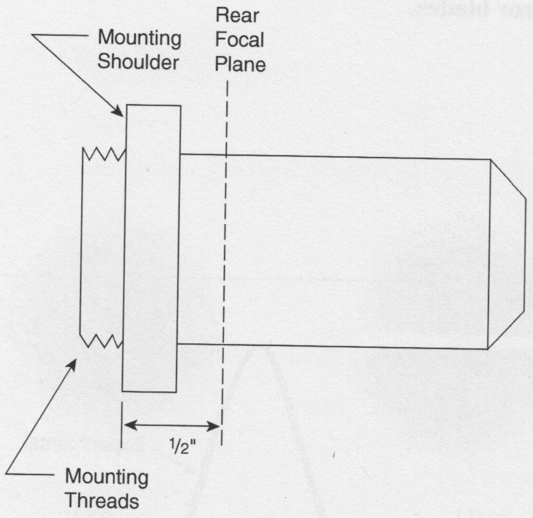

Figure 3.6. Microscope objective lens, showing the rear focal plane.

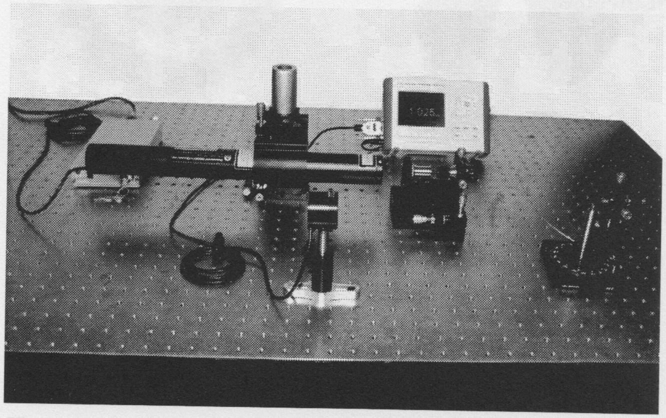

Figure 3.7. Laboratory set-up for examining the Gaussian approximation for a single-mode fiber.

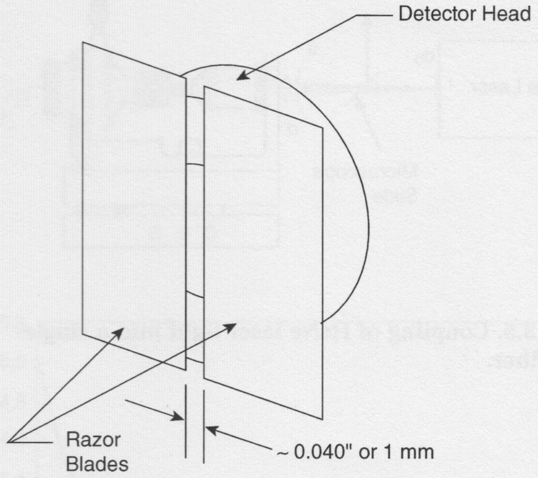

Figure 3.8. Masking of the detector with a slit made from two razor blades.

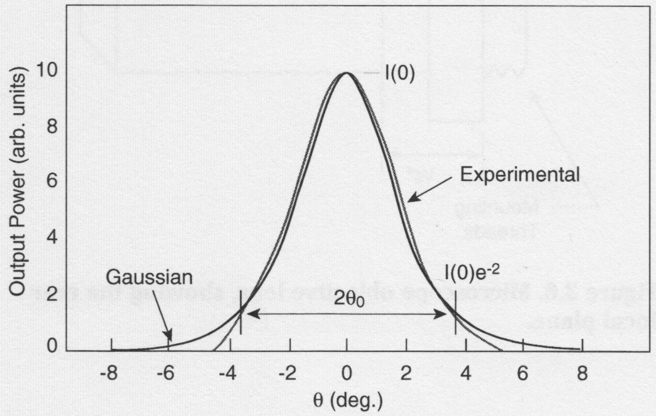

Figure 3.9. Plot of experimental data taken in Newport's laboratory. I(0) and θ_0 found from this data are indicated.

2. Mask the detector head, as shown in **Fig. 3.8**, and post-mount it on the table a few inches away from the fiber end face. Two razor blades taped together with a spacing of about .040" between the blade edges makes a good mask. Be sure that the tape that is used is not transparent to the laser light.

3. For the best continuity, 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. (The results should subtend an angle of about 15 degrees).

4. Plot the far-field distribution of the fiber as a function of angle. **Fig. 3.9** shows a plot of data taken in Newport's laboratory. 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 as shown in **Fig. 3.9**. Take half of that full width and call it θ_0. Plot a Gaussian curve on the same graph with your experimental data. Use Eq. 3.2, substituting θ for r, and θ_0 for r_0. Compare the two plots and assess the validity of the Gaussian approximation for this fiber at this wavelength.

Note: *Most single-mode fibers have a step-index profile. In that case, the near-field distribution (scanning as a function of position across the end face of the fiber) and the far-field distribution (scanning as a function of angle far away from the fiber end face) will have the same form, when scaling to the appropriate conversion factors. We are then able to examine the Gaussian approximation by looking at the far-field distribution of the fiber output, since it will mimic the distribution as a function of position within the fiber.*