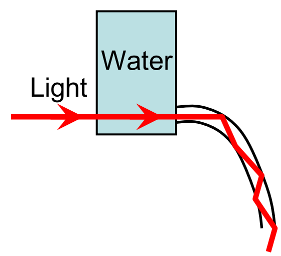
Photonics laboratory
Physics 472
Spring 2024

Experiment#7 Measuring the Numerical Aperture of an Optical Fibers.

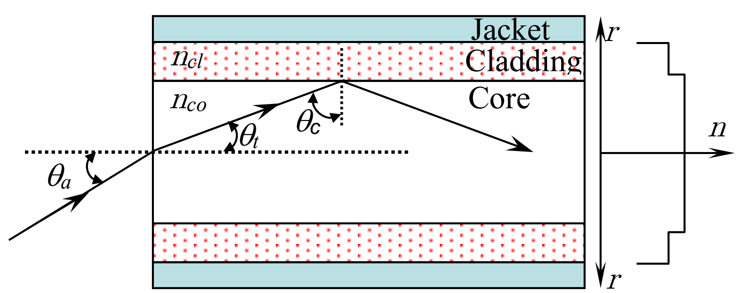
BACKGROUND

Light in Optical Fiber

Once you understand *total internal reflection*, you understand the illuminated stream shown in the figure. Light traveling through the water is reflected off of the surface of the water-air interface and trapped inside the stream. The same thing will happen to a glass rod or thread.



Optical fibers are a little more complicated than this, however. If one were to use a fiber consisting of only a single strand of glass or plastic, light could be lost at any point where the fiber touched a surface for support. Thus, the amount of light that could be transmitted would be dependent on the methods used for holding the fiber. The output of the fiber would also be affected by any movement of the fiber during its use. To eliminate these problems, the central light carrying portion of the fiber, called the core, is surrounded by a cylindrical region, called the *cladding* (see the figure below). The cladding is then covered with a protective *plastic jacket*. Since the refractive index difference between the core and the cladding is less than in the case of a core in air, the critical angle is much bigger for the clad fiber.



The index of the cladding, n_{cl}, is still less than the index of the core, n_{co}, because total internal reflection will occur only when $n_{co}>n_{cl}$. Looking at a cross-section of the fiber in the figure, one sees that the cone of rays that will be accepted by the fiber is determined by the difference between the refractive indices of the core and cladding. The *fractional refractive index difference* is given by

$$\Delta = \frac{n_{co} - n_{cl}}{n_{co}}$$

Because the refractive index of the core is a constant and the index changes abruptly at the core-cladding interface, the type of fiber in the figure is called a *step index fiber*.

The definition of the critical angle can be used to find the size of the cone of light that will be accepted by an optical fiber with a fractional index difference, Δ. In the figure above a ray is drawn that is incident on the core-cladding interface at the critical angle. If the cone (accepting) angle is θ_a, then by *Snell's Law* you can show that the *numerical aperture* of the fiber (*NA*) is given by

$$NA = \sqrt{n_{co}^2 - n_{cl}^2}$$

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.

$$NA = n_i \sin(\theta_{a-\max})$$

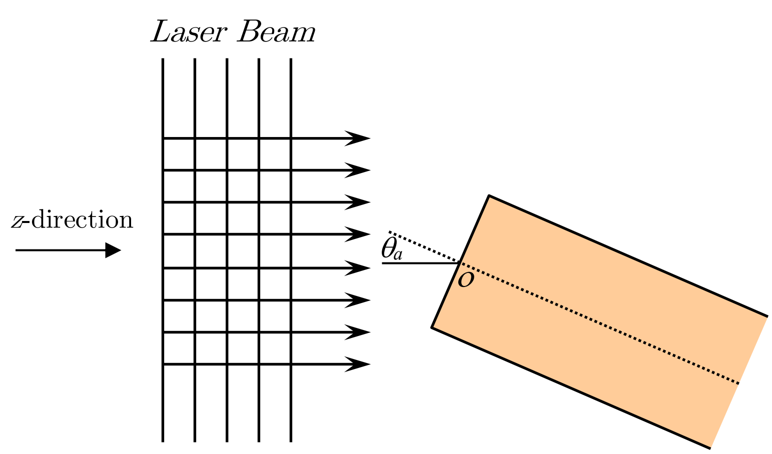
For the case of weakly-guiding approximation ($\Delta << 1$) and when the light is incident from air ($n_i = 1$) the numerical aperture of a step-index fiber is given by

$$NA = n_{co}\sqrt{2\Delta}$$

PROCEDURE

Measuring the Numerical Aperture

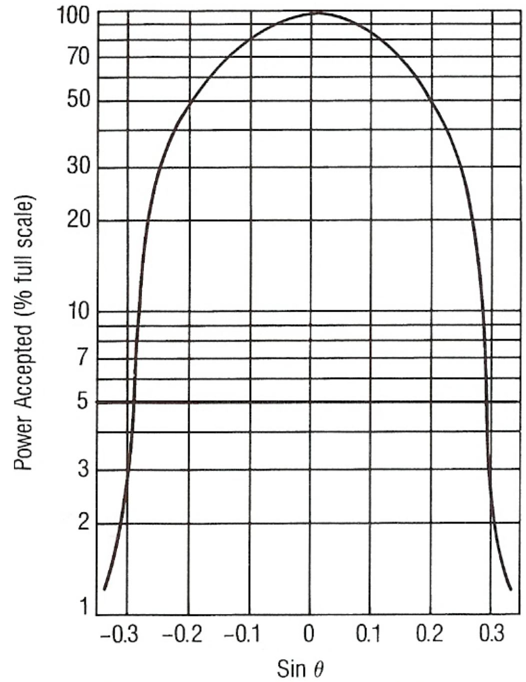
As an example, a typical multimode communications fiber may have $\Delta \approx 0.01$, in which case the weakly-guiding approximation, which assumes $\Delta << 1$, is certainly justified. For silica-based fibers, n_{co} will be approximately 1.46. Using the above equation, these values of Δ and n_{co} give *NA* = 0.2. This gives a value of 11.50 for the maximum incident angle in fiber figure above 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 figure. 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_a in the figure.

If the fiber end face is then rotated about the point *o* in the figure above, we can then measure the amount of light accepted by the fiber as a function of the incident angle, θ_a.

The near figure 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.

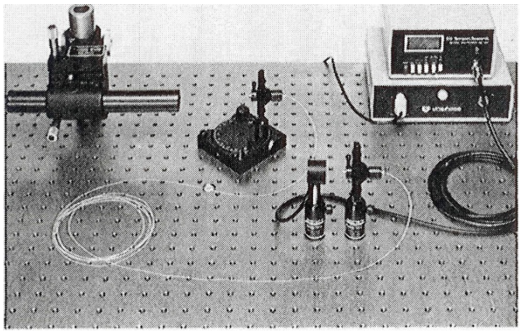


Note that the radiation levels were measured for both positive and negative rotations of the fiber and the *NA* was determined using one half of the full angle between the two 5%-intensity points. This eliminates any small errors resulting from not perfectly aligning $\theta_a = 0$ to the plane wave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

EXPERMENTS

Task#1: Numerical Aperture of a Fiber

1. Bolt the Model 807 Laser Mount to the Model 340C Clamp, using 1/4-20 bolts from the SK-25 Screw Kit. Place the 340C Clamp on the Model 41 Short Rod. Mount this on the LS-22 Breadboard. Place the Model U-1301P HeNe Laser into the 807 Mount. Tighten the set screw. Do not over tighten as this will damage the laser. Plug the laser power supply into a 1l0V 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. 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 41 Short Rod is properly mounted on the table. Check the laser alignment with the line of bolt holes and adjust the Model 41 Short Rod, if necessary.



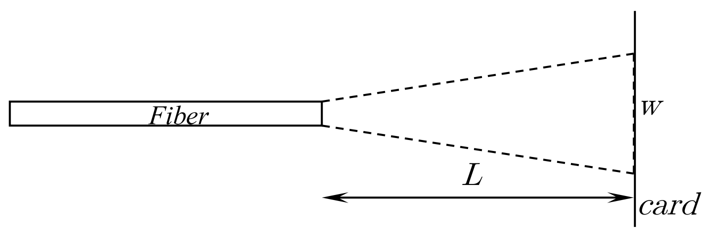
2. Mount the *Rotation Stage* to the breadboard so that the beam from the He-Ne laser passes over the center hole of the rotation stage. The Rotation Stage will have to be placed at an angle to the line of bolt holes in order to bolt it into place as instructed, as shown in the figure. Mount the MPH-l Micro-Series Post Holder on the rotation stage. Use an 8-32 screw to mount the MPH-I. The 1/4-20 threaded hole in the bottom of the MPH-l is used only as a through hole. Place the MSP-l Micro Series Post in the MPH-l, as shown in the figure. ***Make sure that the laser beam passes over the center of the rotating stage and hits the center of the post on the post-holder. Otherwise, you will never be able to align the system.***
3. Prepare a fiber segment, ~ 1/2 meters long, with a good cleave at each end face (Use the procedure done in **lab #7**). The FPH-S Fiber Holder comes as part of the FP-l Fiber Positioner. Insert one end of the fiber into an FPH-S Fiber Holder (you will need to have stripped at least 2" - 3" of the jacket 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 RSX-2 rotation stage, using the MPH series post holder and the MSP series post.
4. **Extend the tip of the fiber and orient the FP-1 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 set up 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-1 Fiber Positioner) and the FP-1 Fiber Positioner. Now, mount the detector head of the Power Meter so that the output beam from the fiber is incident on the detector head, as shown in

above figure. Make a hood of aluminum foil or black tape 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.

7. 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. Enter you date in a table.
8. Plot the power received by the detector as a function of the sine of the acceptance angle. Semi-log scale is recommended. Measure the full width of the curve at the points where the received power is at 5% of the maximum power. The half-width at this power is the experimentally determined numerical aperture of the fiber.

Task#1: Numerical Aperture of a Fiber: A Quick Approximate Measurement

You can get a quick approximate measure of the fiber's *NA*. Rotate the translational stage in order to get maximum power received by the detector. Now, remove the power detector and place a 3×5 card at a distance, L, away from the fiber in a darkened room, as shown in the figure below. 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 θ_a of the fiber is approximately $\sin^{-1}(w/2L)$. This is a quick method which is used when only an approximate measurement of a fiber's *NA* is needed.



Task#1: Comparison of the NA Result of both Methods

Compare your results obtained using the results of Step 9 and the results of step 8.

QUESTIONS

1. Show that NA for a step-index fiber is given by $NA = \sqrt{n_{co}^2 - n_{cl}^2}$. You need to derive this expression. Show clearly all the steps with diagrams.

2. Show that for $\Delta << 1$ $NA = n_{co}\sqrt{2\Delta}$.

3. Find the maximum acceptance angle θ_{max} of a multimode step index fiber whose fractional refractive index difference Δ=1%. Consider the fiber in air.

4. A step index fiber has a core diameter of 100μm and a refractive index of 1.480. The cladding has a refractive index of 1.460. Calculate the numerical aperture of the fiber, and the acceptance angle from air.