Experiment 7:

Measuring the Numerical Aperture of an Optical Fiber

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Abstract

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1 Experiments

1.1 Numerical Aperture of a Fiber

Task:

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

Task:

Mount the Rotation Stage to the breadboard so that the beam from the *HeNe* 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.*

Task:

Prepare a fiber segment, $\tilde{1}/2$ 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.

Task:

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.

Task:

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

Task:

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.

Task:

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.

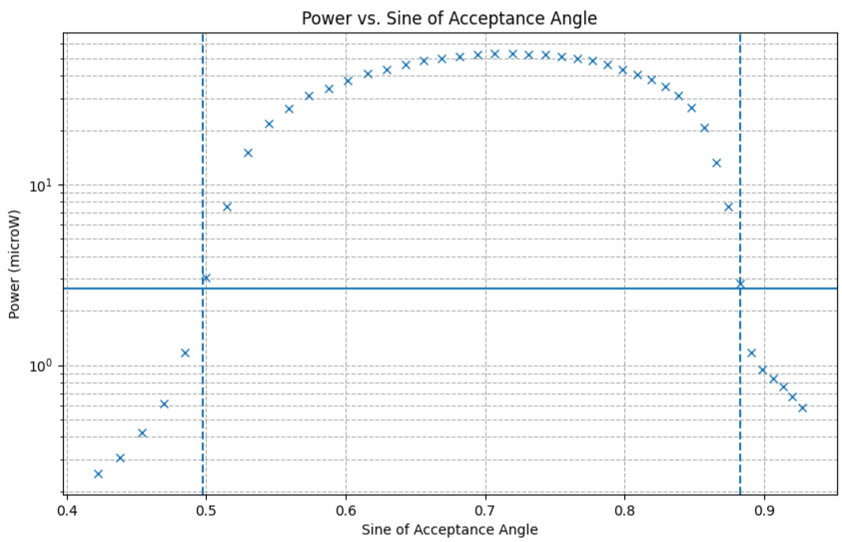
Here is the data table obtained experimentally at the laboratory:

Degrees	Data (microW)	Degrees	Data (microW)
46	53.10	47	52.48
45	52.90	48	52.34
44	52.3	49	51.32
43	51.00	50	50.04
42	49.66	51	48.27
41	48.3	52	45.90
40	46.35	53	43.41
39	43.50	54	40.52
38	41.05	55	38.04
37	37.70	56	34.96
36	34.13	57	31.00
35	31.02	58	26.60
34	26.41	59	20.75
33	21.69	60	13.26
32	15.03	61	7.58
31	7.58	62	2.84
30	3.04	63	1.18
29	1.18	64	0.95
28	0.61	65	0.84
27	0.421	66	0.76
26	0.308	67	0.67
25	0.251	68	0.58

Task:

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.

On the plot we can see the blue contiguous horizontal line representing the 5% of the maximum power, which was 53.1 mW. The vertical dashed lines represent the points at which the line crosses the data, making a window between 0.498 and 0.883. This distance is then divided by 2 and outputs the numerical aperture, $NA = 0.1925$.



1.2 A quick Approximate Measurement

Task:

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 3x5 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 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.

By doing this approach we obtained this data: 7.6, 9.6, 11.1, 13.2 from which 0.41 cm has to be substracted for each datapoint. The diameters used were 2, 3, 4 and 5 cm respectively. The calculated numerical aperture was 0.1182, which is in the same order of magnitude.

This approximation is close but the error is quite big. We got an error (assuming that the previous method was the true one) of 39%, which is quite inaccurate although the method is way faster and easier to implement, so it still has its place

2 Questions

Task:

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.

The derivation of this formula is based on Snell's law and the concept of total internal reflection. Snell's law states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the ratio of the velocity of light in the original medium to the velocity of light in the refracting medium. This can be written as:

$$n_{co} \cdot \sin(\theta_{co}) = n_{cl} \cdot \sin(\theta_{cl})$$

where θ_{co} is the angle of incidence in the core, and θ_{cl} is the angle of refraction in the cladding. For total internal reflection to occur in the fiber, the light must be incident at an angle greater than the critical angle (θ_c). The critical angle is given by:

$$\sin(\theta_c) = \frac{n_{cl}}{n_{co}}$$

The numerical aperture is defined as the sine of the acceptance angle (θ_a), which is half the cone angle within which incident light is totally internally reflected. It can be shown that the acceptance angle is equal to the critical angle, so:

$$NA = \sin(\theta_a) = \sin(\theta_c) = \frac{n_{cl}}{n_{co}}$$

Substituting Snell's law into this equation gives:

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

Task:

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

The Numerical Aperture (NA) of a step-index fiber can also be expressed in terms of the relative refractive index difference, Δ, which is defined as:

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

where n_{co} is the refractive index of the core, and n_{cl} is the refractive index of the cladding.

For $\Delta << 1$, we can derive the expression for NA as follows:
We start with the formula for NA and substitute the expression for Δ:

$$NA = \sqrt{n_{co}^2 - n_{cl}^2} = n_{co}\sqrt{1 - \left(\frac{n_{cl}}{n_{co}}\right)^2} = n_{co}\sqrt{1 - (1 - \Delta)^2}$$

Since $\Delta << 1$, we can use the binomial approximation $(1 - \Delta)^2 \approx 1 - 2\Delta$:

$$NA \approx n_{co}\sqrt{1 - (1 - 2\Delta)} = n_{co}\sqrt{2\Delta} \tag{1}$$

So, for $\Delta << 1$, the Numerical Aperture (NA) of a step-index fiber can be approximated as $NA = n_{co}\sqrt{2\Delta}$.

Task:

Find the maximum acceptance angle $\theta_{textmax}$ of a multimode step index fiber whose fractional refractive index difference $\Delta = 1\%$. Consider the fiber in air.

The maximum acceptance angle, $\theta_{\max}$, of a multimode step index fiber can be found using the formula for the Numerical Aperture (NA):

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

where n_{co} is the refractive index of the core, and Δ is the fractional refractive index difference. The acceptance angle is then given by:

$$\theta_{\max} = \sin^{-1}(NA)$$

Given that the fiber is in air, we can assume that the refractive index of the core is approximately equal to the refractive index of silica, which is about 1.5. Also, given that $\Delta = 1\% = 0.01$, we can substitute these values into the formula to find the NA:

$$NA = 1.5\sqrt{2 \cdot 0.01} = 0.212132$$

Finally, we can substitute the NA into the formula for the acceptance angle to find $\theta_{\max}$:

$$\theta_{\max} = \sin^{-1}(NA) = \sin^{-1}(0.212132) = 4.74959^\circ$$

Task:

A step index fiber has a core diameter of $100\mu m$ 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.

The Numerical Aperture (NA) of a step-index fiber is given by the formula:

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

where n_{co} is the refractive index of the core, and n_{cl} is the refractive index of the cladding.
Given that $n_{co} = 1.480$ and $n_{cl} = 1.460$, we can substitute these values into the formula to find the NA:

$$NA = \sqrt{(1.480)^2 - (1.460)^2} = 0.242487$$

The acceptance angle, $\theta_{\max}$, is then given by:

$$\theta_{\max} = \sin^{-1}(NA) = 0.244929^\circ$$

3 Addenda

LaTeX code that generates this document

PHOTONICS-LabRep3:aperture.tex

Python code that generates the plots and contains the data

PHOT-E7.py