2. Numerical Aperture Mesurement

(Dated: December 31, 2020)

I. OBJECTIVE

To determine the numerical aperture of given multi-mode and single mode fibers from the measurements on the far field.

II. APPARATUS

1. Optical breadboard
2. He-Ne Laser and Laser aligner
3. Microscopic objective (20X) and holder
4. xyz-translational stage
5. Pin hole photodetector with multimeter and holder
6. Two fiber chucks
7. 2 post bases and 3 posts
8. Single-mode and Multimode fiber of appropriate length
9. Fiber cleaver
10. Rotation stage

III. THEORY

Numerical Aperture is the measure of the ability of an optical fiber to collect or confine the incident light ray inside it. It is among the most basic property of optical fiber. We know light through an optical fiber is propagated through total internal reflection. Or we can say multiple TIR takes place inside the optical fiber for the light ray to get transmitted from an end to another through an optical fiber. It is defined as the sine of the acceptance angle, i.e. the largest angle an incident ray can have for total internal reflection in the core.

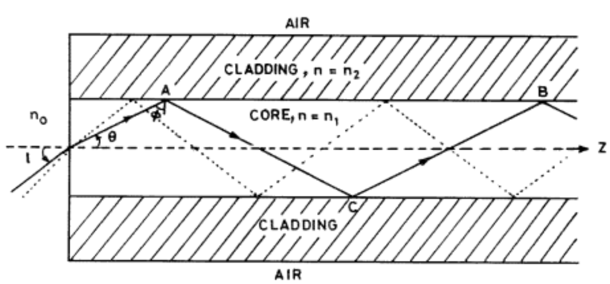

FIG. 1. Light path inside the fiber

In the figure let us consider a ray that is incident on the entrance aperture of the fiber making an angle i with the axis. Let the refracted ray make an angle θ with the fiber axis. Assuming the outside medium to have a refractive index n_0, we get

$$\frac{sin(i)}{sin(\theta)} = \frac{n_1}{n_0}$$

Now, if this ray suffers total internal reflection at the core-cladding interface,

$$sin(\phi)(= cos(\theta)) > \frac{n_2}{n_1}$$

Thus,

$$sin(\theta) < \left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2}$$

and we must have

$$sin(i) < \frac{n_1}{n_0}\left[1 - \left(\frac{n_2}{n_1}\right)^2\right]^{1/2} = \left[\frac{n_1^2 - n_2^2}{n_0^2}\right]^{1/2}$$

If $(n_1^2 - n_2^2) \geq n_0^2$, then for all values of i total internal reflection will occur at the core-cladding interface. Assuming $n_0 = 1$, the maximum value for $\sin(i)$ for a ray to be guided is given by

$$\sin(i_m) = \left(n_1^2 - n_2^2\right)^{1/2} \quad when \quad n_1^2 < n_2^2 + 1$$

$$= 1 \qquad when \quad n_1^2 > n_2^2 + 1$$

Thus, if a cone of light is incident on one end of the fiber, it will be guided through the fiber provided the semi-angle of the cone is less than i_m. This angle is a measure of the light-gathering power of the fiber and, as such, one defines the numerical aperture (NA) of the fiber by the following equation

$$NA = sin(i_m) = (n_1^2 - n_2^2)^{1/2}$$

In visual method, the following formula is used

$$NA = sin(i_m) = sin[tan^{-1}(D/2z)]$$

where, D/2 = radius of the circle obtained on the screen. And z = distance of fiber from screen.

IV. PROCEDURE FOLLOWED

Light was coupled into the multimode fiber in the similar manner as it was done in the previous experiment to obtain maximum coupling.
After obtaining maximum coupling, the photo detector was mounted on the rotation stage, and the rotation stage was fixed on the optical breadboard in such a way that the distance between the fibre end and the detector is about 3-4 cm, so that it is far enough to observe the far field but not too far as then detector would not have been able to detect much of the output.
After setting this up, the rotation stage was rotated upto small degree and then the reading of multimeter was recorded. This process wass repeated starting from multimeter reading of 0 to the maximum value and then again 0. Finally, the readings are plotted in a graph and at 5% of the total normalized power, we got the θ, from which NA was calculated.

V. EXPERIMENTAL DATA

A. Single Mode (NA = 0.1)

TABLE I. Scanning method for Single-mode fiber with NA = 0.1

Reading on the rotation stage (degrees)	Voltage of multimeter (mV)	Normalized Power
-10	0	0
-9	0	0
-8	0	0
-7	0	0
-6	0	0
-5	0	0
-4.8	0	0
-4.6	0.1	0.04028
-4.4	0.1	0.04028
-4.2	0.1	0.04028
-4.0	0.1	0.04028
-3.8	0.1	0.04028
-3.6	0.2	0.161121
-3.4	0.2	0.161121
-3.2	0.2	0.161121
-3.0	0.2	0.161121
-2.8	0.3	0.360771
-2.6	0.3	0.360771
-2.4	0.3	0.360771
-2.2	0.3	0.360771
-2.0	0.3	0.360771
-1.8	0.4	0.642732
-1.6	0.4	0.642732
-1.4	0.4	0.642732
-1.2	0.4	0.642732
-1.0	0.5	1
-0.8	0.5	1
-0.6	0.5	1
-0.4	0.5	1
-0.2	0.5	1
0	0.5	1
0.2	0.5	1
0.4	0.5	1
0.6	0.5	1
0.8	0.5	1
1.0	0.5	1
1.2	0.4	0.642732
1.4	0.4	0.642732
1.6	0.4	0.642732
1.8	0.4	0.642732
2.0	0.4	0.642732
2.2	0.4	0.642732
2.6	0.3	0.360771
2.8	0.3	0.360771
3.0	0.3	0.360771
3.2	0.3	0.360771
3.4	0.3	0.360771
3.6	0.2	0.161121
3.8	0.2	0.161121
4.0	0.2	0.161121
4.2	0.1	0.04028
4.4	0.1	0.04028
4.6	0.1	0.04028
4.8	0.1	0.04028
5.0	0.1	0.04028
5.2	0.1	0.04028
5.4	0	0
5.6	0	0
5.8	0	0
6	0	0
7	0	0
8	0	0
9	0	0
10	0	0

B. Single Mode (NA = 0.14)

TABLE II. Scanning method for Single-mode fiber with NA = 0.14

Reading on the rotation stage (degrees)	Voltage of multimeter (mV)	Normalized Power
0	0	0
1.2	0.2	0.000213
2.2	0.4	0.000852
9.4	1	0.005328
10	1.2	0.007672
20	1	0.005238
23.6	1.1	0.006447
23.8	1.5	0.011988
24	2	0.021312
25	2.5	0.0333
27.8	3	0.047951
29.2	4.3	0.098514
29.6	5.2	0.144067
30	6.6	0.232085
30.2	7.6	0.307741
30.4	9.3	0.460814
30.8	10.2	0.554318
31.8	12.8	0.872928
35.6	13.7	1
36.6	9.5	0.480845
37.8	6.4	0.218232
41.9	4.8	0.122755
42.8	3.8	0.076935
44.6	1.6	0.01364
46.2	1	0.005328
61	0	0

.

C. Multimode (NA = 0.20)

TABLE III. Scanning method for multimode fiber with NA = 0.20

Reading on the rotation stage (degrees)	Voltage of multimeter (mV)	Normalized Power
-15	0	0
-14	0	0
-13	0	0
-12.2	0	0
-12	0.1	0.04
-11	0.1	0.04
-10	0.2	0.16
-9	0.2	0.16
-8	0.2	0.16
-7	0.3	0.36
-6	0.3	0.36
-5.6	0.3	0.36
-5	0.4	0.64
-4	0.4	0.64
-3	0.5	1
-2	0.5	1
-1	0.5	1
0	0.5	1
1	0.5	1
2	0.5	1
3	0.5	1
4	0.4	0.64
5	0.4	0.64
5.4	0.3	0.36
6	0.3	0.36
7	0.3	0.36
8	0.2	0.16
9	0.2	0.16
10	0.1	0.04
11	0.1	0.04
11.2	0	0
12	0	0
13	0	0
14	0	0
15	0	0

.

VI. GRAPHS AND CALCULATIONS

A. Single Mode (NA=0.1

Using appropriate values from Table I, graph between normalized power and angle obtained from rotation stage is plotted as below:

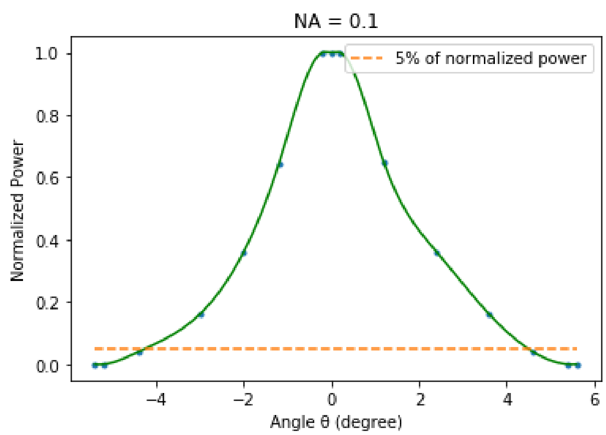

FIG. 2. Normalized Power vs Angle

Now, from the graph, we get i_m using the formula: $i_m = \frac{(\theta_2 - \theta_1)}{2}$. Where θ_2 and θ_1 are the value of angle at which the normalized power drops by 95% . As seen from the graph,

$$i_m = \frac{(4.6 - (-4.4))}{2}$$

$$i_m = 4.5$$

Now,

$$NA = sin(i_m) = sin(4.5)$$

$$NA = 0.078$$

So, value of NA of the single mode fiber obtained through experiment is 0.078 which is close to 0.1. .

B. Single Mode (NA=0.14

Using appropriate values from Table II, graph between normalized power and angle obtained from rotation stage is plotted as below:

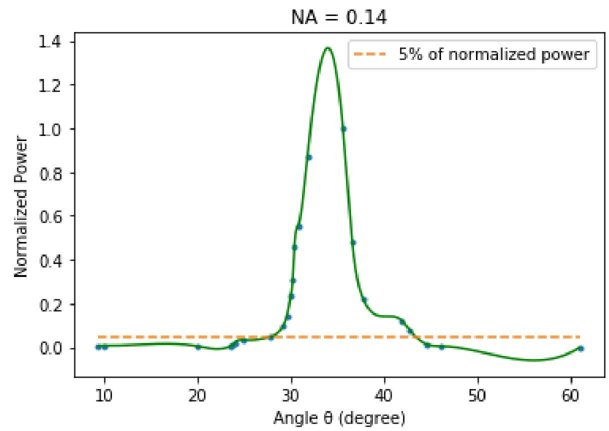

FIG. 3. Normalized Power vs Angle

Now, from the graph, we get i_m using the formula: $i_m = \frac{(\theta_2 - \theta_1)}{2}$. Where θ_2 and θ_1 are the value of angle at which the normalized power drops by 95% . As seen from the graph,

$$i_m = \frac{(43.5 - 27.8)}{2}$$

$$i_m = 7.85$$

Now,

$$NA = sin(i_m) = sin(7.85)$$

$$NA = 0.1366$$

So, value of NA of the single mode fiber obtained through experiment is 0.1366 which is close to 0.14.

C. Multimode (NA=0.2

Using appropriate values from Table III, graph between normalized power and angle obtained from rotation stage is plotted as below:

Now, from the graph, we get i_m using the formula: $i_m = \frac{(\theta_2 - \theta_1)}{2}$. Where θ_2 and θ_1 are the value of angle at which the normalized power drops by 95% . As seen from the graph,

$$i_m = \frac{(10.6 - (-10.4))}{2}$$

$$i_m = 10.5$$

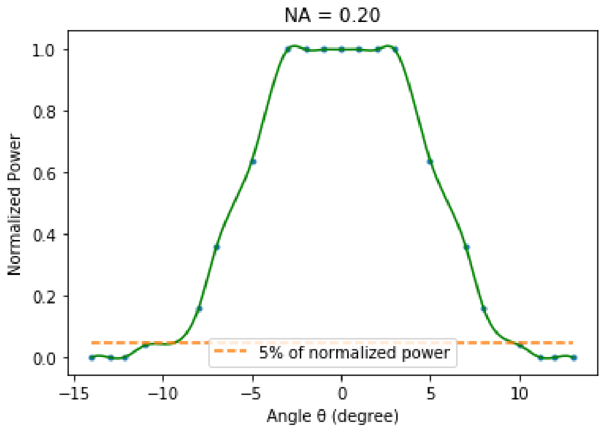

FIG. 4. Normalized Power vs Angle

Now,

$$NA = sin(i_m) = sin(10.5)$$

$$NA = 0.1822$$

So, value of NA of the multi mode fiber obtained through experiment is 0.1822 which is close to 0.2.

VII. RESULT

The following values of numerical aperture were observed in the experiment for different fibers:
For two Single mode fibers, the value for NA are 0.078 and 0.1366 respectively.
For the multimode fiber, the value of NA is 0.1822.

[1] Solid state Physics Lab Manual,*School of Physical Sciences,NISER*

[2] `https://circuitglobe.com/numerical-aperture-of-optical-fiber.html`

[3] `https://www.newport.com/t/fiber-optic-basics#:~:text=The%20Numerical%20Aperture%20(NA)%20of,radiation%0modes%20of%20the%20fiber.`