4. Refractive Index Profile of Multi-mode Fiber

(Dated: January 15,2021)

I. OBJECTIVE

To measure near-field intensity profile of a multimode fiber and hence its refractive index profile.

II. APPARATUS

1. Optical breadboard
2. He-Ne Laser and Laser aligner
3. Microscopic objectives (20X and 40X) and holders
4. xyz-translational stage
5. Pin hole photodetector mounted on micrometer translation stage with a connection to power meter
6. fiber chucks
7. Posts and post bases
8. Multimode fiber of appropriate length
9. Fiber cleaver
10. Rotation stage
11. Index matching liquid
12. V-Groove fiber mounts.

III. THEORY

A refractive index profile is the distribution of refractive indices of materials within an optical fiber. Some optical fiber has a step-index profile, in which the core has one uniformly-distributed index and the cladding has a lower uniformly-distributed index. Other optical fiber has a graded-index profile, in which the refractive index varies gradually as a function of radial distance from the fiber center. Graded-index profiles include power-law index profiles and parabolic index profiles.In this experiment, the fiber used is a graded index multimode fiber.

The power accepted at any point 'r' in the fiber core from source is directly proportional to the square of local Numerical aperture. Therefore, maximum power can be accepted by the fiber at position 'r' where Numerical aperture is maximum. We can define an equation such that:

$$\frac{P(r)}{P_m} = \frac{n^2(r) - n_{cl}^2}{n_m^2 - n_{cl}^2} \quad ....(1)$$

where,P(r) = Power accepted at point r.
P_m = maximum power accepted.
$n(r)$ = refractive index at r.
n_cl = refractive index of cladding.
n_m = maximum refractive index.

For small refractive indices:

$$\frac{P(r)}{P_m} \approx \frac{n(r) - n_{cl}}{n_m - n_{cl}} \quad ......(2)$$

The power distribution that is transmitted into the fiber will be received at the other end if the fiber is of short length and without any deformities or bends, i.e. the guided modes propagates without any mode conversion or attenuation. Therefore, the output can be measured using the photodetector and it will represent the distribution on the input end.

The nominal refractive index distribution is given by:

$$n(r) = n_m \left[1 - 2\Delta \left(\frac{r}{a}\right)^q\right]^{1/2}, \qquad r < a$$

$$n(r) = n_m[1 - 2\Delta]^{1/2} = n_{cl} \qquad r \geq a \quad ....(3)$$

The relative core cladding refractive index difference is given by:

$$\Delta = \frac{n_m^2 - n_{cl}^2}{2n_m^2} \approx \frac{n_m - n_{cl}}{n_m} \quad ......(4)$$

Now, using eq.(3) in eq.(2), we get

$$\frac{P(r)}{P_m} = 1 - \left(\frac{r}{a}\right)^q$$

$$log\left[1 - \frac{P(r)}{P_m}\right] = q * log(r/a) \qquad .....(5)$$

IV. PROCEDURE FOLLOWED

Light was coupled into the multimode fiber in the similar manner as it was done in the first experiment to obtain maximum coupling.
After obtaining maximum coupling, the other end of the fiber was also mounted on the V-Groove on a xyz translational stage. Then, the 40X microscope objective was placed in front of the output end of fiber at a distance of approx. 2mm, which is the focal length of the MO. Then the fiber was adjusted using the x,y and z screws in order to get a sharp magnified image on the screen placed on the other side of MO.
After that, the screen was removed, and a translation

stage with Micrometer attached to it was fixed on optical breadboard. Then, the pinhole detector was mounted on the translation stage and aligned such that it can measure power of the output spot along the diameter of the spot.
After that, using the micrometer screw, the detector was moved to extreme right of the spot, such that the power reading is 0. Then it was slowly moved to the left and readings were taken as shown in the following section.

V. EXPERIMENTAL DATA

A. Multi-mode fiber (NA = 0.2)

TABLE I. Near field Scanning for Multimode Fiber

Reading of the micrometer (cm)	Voltage of multimeter (mV)	Normalized Power
0.974	0	0
0.979	0.001	0.0000089
0.998	0.002	0.000036
1.013	0.003	0.00008
1.025	0.004	0.00014
1.036	0.005	0.00022
1.095	0.01	0.00089
1.145	0.015	0.002
1.186	0.02	0.00356
1.23	0.03	0.00802
1.255	0.041	0.01498
1.274	0.051	0.02318
1.285	0.06	0.03208
1.295	0.071	0.04492
1.307	0.081	0.05846
1.317	0.091	0.07379
1.327	0.1	0.08911
1.338	0.123	0.13481
1.345	0.142	0.17967
1.348	0.166	0.24554
1.349	0.181	0.29192
1.351	0.204	0.37083
1.354	0.224	0.4471
1.358	0.24	0.51325
1.362	0.26	0.60236
1.370	0.282	0.70861
1.377	0.300	0.80196
1.384	0.311	0.86185
1.386	0.315	0.88416
1.391	0.320	0.91245
1.397	0.327	0.95281
1.400	0.330	0.97037
1.401	0.331	0.97626
1.406	0.332	0.98217
1.408	0.333	0.9881
1.414	0.334	0.99404
1.420	0.335	1
1.427	0.334	0.99404
1.453	0.333	0.9881
1.457	0.331	0.97626
1.459	0.330	0.97037
1.471	0.321	0.91816
1.477	0.315	0.88416
1.486	0.299	0.79662
1.494	0.278	0.68865
1.502	0.255	0.57942
1.511	0.213	0.40427
1.513	0.191	0.32507
1.519	0.153	0.20589
1.523	0.141	0.17715
1.534	0.120	0.12831
1.550	0.098	0.08558
1.555	0.091	0.07379
1.564	0.081	0.05846
1.571	0.073	0.04748
1.583	0.062	0.03425
1.595	0.051	0.02318
1.610	0.043	0.01648
1.634	0.030	0.00802
1.675	0.020	0.00356
1.707	0.015	0.002
1.747	0.010	0.00089
1.793	0.005	0.00022
1.803	0.004	0.00014
1.814	0.003	0.00008
1.828	0.002	0.000036
1.846	0.001	0.0000089
1.869	0	0

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TABLE II.

$log(\frac{r}{a})$	$log\left(1-\frac{P(r)}{P_m}\right)$
-0.61059	-1.92428
-0.55867	-1.62456
-0.4143	-1.08706
-0.36461	-0.93615
-0.29934	-0.6917
-0.24857	-0.50675
-0.20311	-0.37615
-0.17694	-0.30147
-0.15708	-0.22495
-0.14748	-0.17074
-0.1199	-0.1016
-0.10244	-0.08468
-0.05775	-0.05964
1.9E-16	-0.03885
0.01658	-0.03329
0.04491	-0.02616
0.06574	-0.02113
0.09927	-0.01514
0.1304	-0.01018
0.16641	-0.00721
0.21846	-0.0035
0.29507	-0.00155
0.3467	-0.00087
0.40365	-0.00039

TABLE III. Measurement of $n^2(r)$

r	$n^2(r)$
0.0055	4.71571
0.0315	4.71103
0.0355	4.70968
0.0375	4.70895
0.0495	4.70362
0.0555	4.70037
0.0645	4.69475
0.0725	4.68901
0.0805	4.68255
0.0855	4.67815
0.0895	4.67443
0.0915	4.67250
0.0975	4.66644
0.1015	4.66217
0.1125	4.64949
0.1285	4.62858

VI. GRAPHS AND CALCULATIONS

A. Power Profile

Using appropriate values from Table I, graph between normalized power and r obtained by subtracting the mean value of 1^{st} and last reading of micrometer:

From this graph, we get two values at which the Normalized Power drops by 95% , taking mean of those values, we get the radius of fiber core:

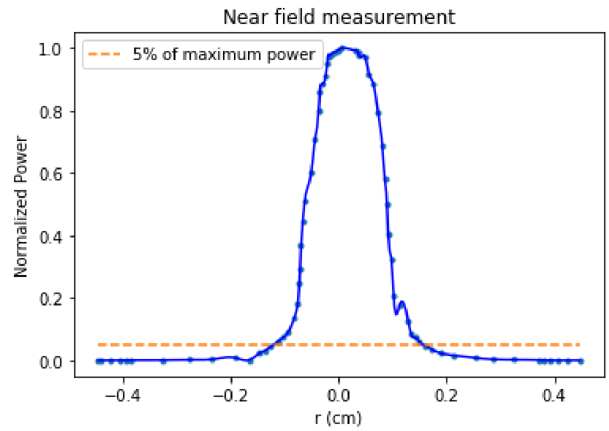

FIG. 1. Normalized Power vs Angle

$$a = \frac{(0.1425-(-0.1145))}{2} = 0.1285cm$$

But a should be in order of μm. This happened because we are measuring the magnified image, on calculating the actual radius, we get:

$$Magnification = \frac{a_{image}}{a_{actual}}$$

$$40 = \frac{0.1285}{a_{actual}}$$

$$a_{actual} = \frac{0.1285}{40} = 0.00321cm = 32.1\mu m$$

So, we got radius of core as = 32.1 μm
But in the calculations further, we consider a = 0.1285 cm as all the values of r is also calculated from the magnified image.

B. Determination of q

Now, using the values from Table II, the following graph is plotted and value of q is determined from this graph:

From the graph, we can see the log vs log graph of eq.(5). The straight line represents the straight fit of the graph with intercept 0. So the equation of line become y = mx. And from the graph it is clear that m = q.
We got q = 2.0603, which indicates that the RIP should be parabolic in nature.

C. Refractive Index Profile

From the previous graph, we got the value of q = 2.0603. Now, since we know NA of the fiber from 2^{nd}

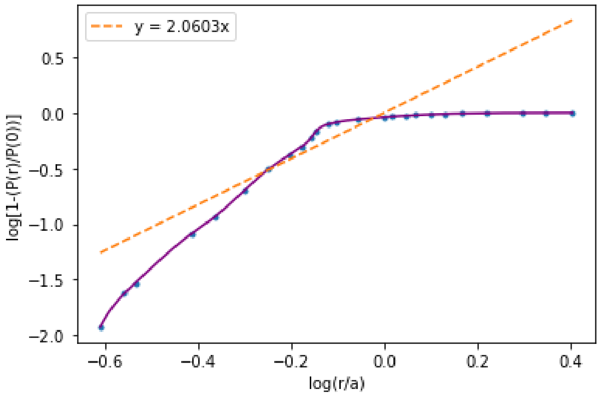

FIG. 2. Log vs Log Graph

experiment. We can calculate n_m:

$$(NA)^2 = (n_m)^2 - (n_{cl})^2$$

$$(0.18)^2 = (n_m)^2 - (1.46)^2$$

$$n_m = 1.4736$$

Now, using eq.(4) we can calculate Δ

$$\Delta = \frac{n_m^2 - n_{cl}^2}{2n_m^2} \approx \frac{n_m - n_{cl}}{n_m}$$

$$\Delta = 0.009229$$

Now Using all these values in eq.(3), we can plot the following graph:

$$n(r) = 1.4736\left[1 - 2 * 0.009229\left(\frac{r}{a}\right)^2 .0603\right]^{1/2}$$

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Now, we can conclude the result.

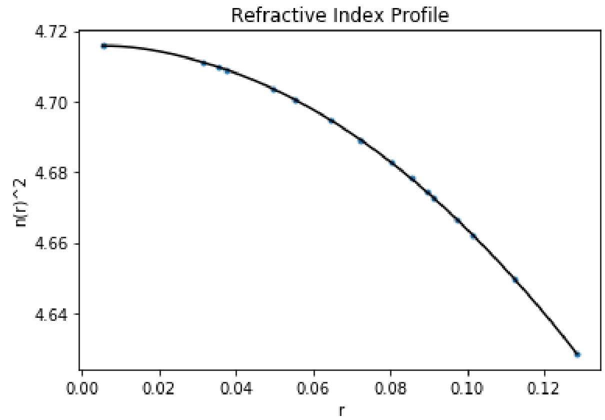

FIG. 3. Refractive Index Profile

VII. RESULT AND DISCUSSION

Using the near field scanning, power was recorded from the magnified image of the output profile of the multimode fiber and graph was plotted (Normalized Power vs r), which came out as expected.
From the graph, radius of fiber core was calculated, which came out to be a = 32.1 μm
Then from the Log vs Log graph of eq.(5), index exponent was calculated, q = 2.0603.
Then using all the values calculated from these graphs, refractive index profile of the fiber was plotted, which came out to be Parabolical. That means that the given multimode fiber is a Parabolically graded index fiber.

[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.