EXPERIMENT 4
DETERMINATION OF THE ACCEPTANCE ANGLE AND NUMERICAL APERTURE OF OPTICAL FIBERS

OBJECTIVES:

The objective of this experiment is to measure the acceptance angle in air (from which the numerical aperture can be determined) of two types of multimode graded index (GI) optical fibers. The axis of the optical fiber will be rotated with respect to an incident laser beam for this purpose.

EQUIPMENT REQUIRED

1- Optical power meter: INFOS, Model # M100.
2- HeNe laser: Coherent, Model # 31-2090-000.
3- Optical bench (¼ m).
4- Horizontal and vertical stages (Used to carry and align the HeNe laser).
5- Laboratory jack.
6- Rotational stage with aluminum adapter plate.
7- Approximately 2m long, $50\,\mu m$ graded-index fiber (Orange Color). NA = 0.220.
8- Approximately 5m long, $62.5\,\mu m$ graded-index fiber (Gray Color). NA = 0.275.
9- Optical fiber holder.
10- Meter stick.

PRELAB ASSIGNMENT

Read the introduction to this experiment, before you attend the laboratory.

INTRODUCTION:

Consider a step-index (SI) optical fiber with a core and cladding refractive indices n_1 and n_2, respectively. Also assume that the SI fiber terminates at a medium of refractive index n_o, as shown in Figure 1.
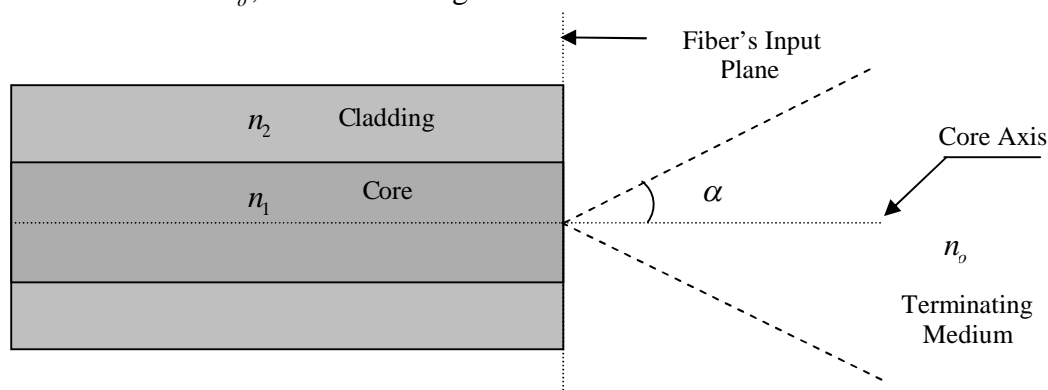

Figure 1: The Acceptance Angle α of an SI Optical Fiber.

The acceptance angle α and numerical aperture (NA) of the SI fiber are given by (see Figure 1):

$$NA \equiv n_o \sin \alpha = \sqrt{n_1^2 - n_2^2} \qquad (1)$$

This well-known relation however, does not apply to graded-index (GI) optical fibers, because the core refractive of GI fibers *decreases* with the distance r from the fiber core axis. For a GI fiber, with an non-uniform (graded) core refractive index $n^2(r)$ and uniform cladding index n_2, equation (1) is modified to:

$$NA \equiv n_o \sin \alpha = \sqrt{n^2(r) - n_2^2} \qquad (2)$$

Which means that for GI fibers, both NA and α are decreasing functions of r. The refractive index $n(r)$ has a maximum value of n_1 at the core axis ($r = 0$) and the minimum value of n_2 at the core-cladding boundary ($r = a$). Thus the core refractive index has the following range:

$$n_1 \leq n(r) \leq n_2 \qquad (3)$$

Thus the numerical aperture and the acceptance angle have the following ranges:

$$0 \leq NA \leq \sqrt{n_1^2 - n_2^2} \qquad (4)$$

$$0 \leq \alpha \leq \sin^{-1}(\sqrt{n_1^2 - n_2^2} / n_o) \qquad (5)$$

The definition of the acceptance angle [given either by equations (1) for SI fibers or (2) for GI fibers] is based on *ray theory*, which is an approximate theory. Equations (1) and (2) also do not tell us how to *directly* measure the acceptance angle experimentally. How can we then measure the acceptance angle of a given fiber? A possible direct method is illustrated in Figure 2. A laser beam is coupled to an optical fiber an angle θ with respect to the core axis of the fiber.
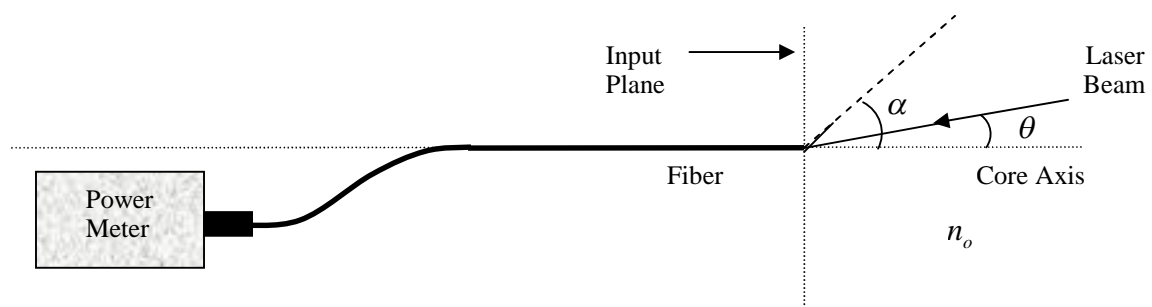

Figure 2: Method Used for Measuring the Acceptance Angle α of an Optical Fiber.

When $\theta = 0^o$, *maximum* power is coupled the fiber. When θ increases beyond zero, the coupled power start to decrease. The acceptance angle α is reached when the power is reduced by 13 dB with respect to the maximum.

The experimental setup is shown in Figure 3. A $50 \, \mu m$ multimode GI fiber will be used in this experiment. As shown in the figure, the fiber's tip needs to be placed *as close as possible* to the center of rotation of the rotational stage. If the fiber's tip is misplaced, the experimental measurements will be poor, as will be explained later. The fiber holder and the stainless adapter plate are not shown in Figure 3.
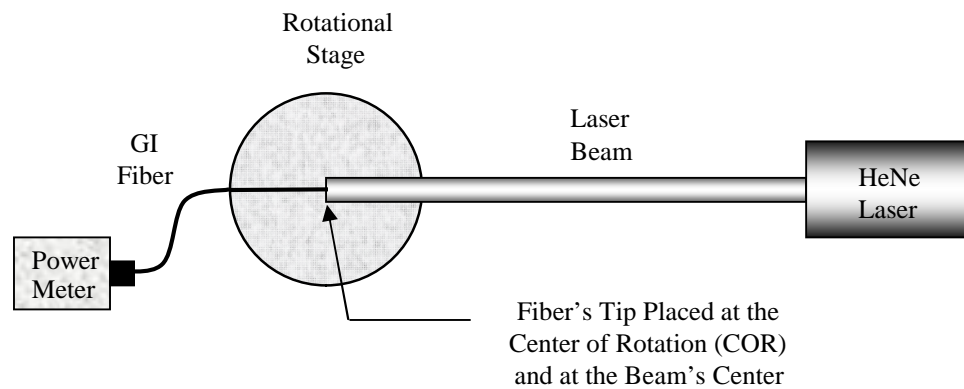

Figure 3: Basic Experimental Setup Used for Measurement of the Acceptance Angle.

In this experiment, it is important to make sure of the following:

1) The fiber's tip should be in the exact center of the laser beam (see Figure 3).
2) The fiber's tip should be located exactly at the center of rotation of the rotational stage. If this is not done accurately, then when the stage is rotated, the fiber's tip will move away from the beam's center, resulting in erroneous results, because the laser intensity profile is non-uniform. By keeping a sufficiently long separation between the fiber's tip and the laser beam, results in laser beam expansion, which tends to reduce the error due to dislocating the fiber's tip.
3) The laser beam must be properly aligned. The means that the laser beam's and the fiber's axes must coincide with each other.

In this experiment, we will measure the acceptance angle of two GI optical fibers, which both of which have a variable the acceptance angle in the radial direction r. The experimental method explained above can be used to estimate the *average* acceptance angle of a GI fiber. It *cannot* be used to measure $\alpha(r)$, the variation of the acceptance angle as a function of r.

PROCEDURE:

[IMPORTANT: INSURE THAT BOTH ENDS OF THE TWO FIBERS HAVE BEEN RECENTLY AND PROPERLY CLEAVED, OTHERWISE LARGE EXPERIMENATL ERRORS MAY OCCUR].

1- Turn the laser on and place its output end approximately 1m from the rotational stage.
2- Align the laser. For laser alignment use the following simple procedure:

- Establish a convenient reference straight line axis on the optical table.
- Move the meter stick along the *reference axis* and bring it close to the laser beam output end. Mark the position where the laser beam *center* hits the meter stick.
- Move the stick away from the laser and again mark the position where the laser beam center hits the stick. [*When the laser is aligned the laser should hit the stick in the same position*].
- If necessary rotate the laser in the plane *parallel* to the optical table and in the plane *normal* to the optical table, until the laser beam hits the meter stick at the same position, regardless of its position *along the reference axis.*

3- Connect the $50\,\mu m$ optical fiber (orange color) to the optical power meter. Turn the power meter on and set it to the dBm scale and $\lambda = 0.85\,\mu m$.

4- Place the fiber into the fiber holder and insure that the fiber's tip is as close as possible to the COR of the rotational stage (white dot) before you tighten the screws the fiber holder to the adapter plate. *Take extra care to do this. It helps if you look from above.*

5- Release the stopper of the rotational stage. Then rotate the stage so that the fiber's axis is approximately parallel to the beam (or parallel to the reference axis).

6- Move the horizontal and vertical stages until the laser hits the fiber's tip.

7- Adjust the *horizontal and vertical* stages for maximum meter reading in order to insure that fiber's tip is located *exactly* at the center of the laser beam.

8- To insure that the fiber's tip is located at the center of rotation, rotate the stage clockwise and counterclockwise to and check if the fiber's tip stays at the beam's center regardless of the angle of rotation.

9- Adjust the angle of rotation for maximum meter reading. Now, this means that $\theta = 0^o$. Record the meter reading in at the bottom of column 2 of table 1.

10- Turn the rotational stage clockwise using a step of 2°. Record the meter's reading in the second column of table 1.

11- Rotate the stage back to the position of maximum power. Then repeat step 10 using counterclockwise rotation with a step of 2°. Record the values in the forth column of table 1.

12- Convert the meter readings to mW and then calculate the normalized power P_N and record the values in table 2.

13- Plot a graph showing P_N versus θ.

14- Comment on the resulting graph including symmetry.

15- As discussed in the introduction, the acceptance angle is reached when the received power is 13 dB below the maximum. Thus, for the normalized power P_N, the acceptance angle corresponds to $P_N = 0.05$, since by definition, the maximum value of P_N is unity. Using the same graph, estimate the values of the acceptance angle α^+ and α^-, which correspond to positive and negative angles, respectively. Then find the final estimate of the acceptance angle α, using $\alpha = (\alpha^+ + \alpha^-)/2$.

16- Use the result obtained in the previous step to estimate the numerical aperture of the fiber. Compare the resulting value with the fiber's manufacturer's data.

17- Repeat steps 3-16 for the $62.5\,\mu m$ fiber (Gray Color). Record the results in tables 3 and 4.

18- Compare the acceptance angles and the numerical apertures of the two types of fibers. Discuss the experimental results; write appropriate comments and some conclusions.

θ (Degrees)	P (dBm)	θ (Degrees)	P (dBm)
-40		2	
-38		4	
-36		6	
-34		8	
-32		10	
-30		12	
-28		14	
-26		16	
-24		18	
-22		20	
-20		22	
-18		24	
-16		26	
-14		28	
-12		30	
-10		32	
-8		34	
-6		36	
-4		38	
-2		40	
0		-	

Table 1: Variation of the Received Optical Power in dBm Versus Angle for the 50 μm GI Optical Fiber.

θ (Degrees)	P (mW)	P_N	θ (Degrees)	P (mW)	P_N
-40			2		
-38			4		
-36			6		
-34			8		
-32			10		

-30			12		
-28			14		
-26			16		
-24			18		
-22			20		
-20			22		
-18			24		
-16			26		
-14			28		
-12			30		
-10			32		
-8			34		
-6			36		
-4			38		
-2			40		
0			-		

Table 2: Variation of the Normalized Optical Power versus Angle for the $50 \, \mu m$ GI Optical Fiber.

θ (Degrees)	P (dBm)	θ (Degrees)	P (dBm)
-40		2	
-38		4	
-36		6	
-34		8	
-32		10	
-30		12	
-28		14	
-26		16	
-24		18	
-22		20	
-20		22	
-18		24	
-16		26	
-14		28	
-12		30	

-10		32	
-8		34	
-6		36	
-4		38	
-2		40	
0		-	

Table 3: Variation of the Received Optical Power in dBm Versus Angle for the 62.5 μm GI Optical Fiber.

θ (Degrees)	P (mW)	P_N	θ (Degrees)	P (mW)	P_N
-40			2		
-38			4		
-36			6		
-34			8		
-32			10		
-30			12		
-28			14		
-26			16		
-24			18		
-22			20		
-20			22		
-18			24		
-16			26		
-14			28		
-12			30		
-10			32		
-8			34		
-6			36		
-4			38		
-2			40		
0			-		

Table 4: Variation of the Normalized Optical Power versus Angle for the 62.5 μm GI Optical Fiber.

QUESTIONS:

1- Using the experimental data for the $50\,\mu m$ GI optical fiber, find the angle at which the power drops to 20 dB below the maximum. Use the average of the positive and negative angles to find the answer.

2- Suppose we had a *uniform* laser beam, instead of the non-uniform laser beam used in this experiment. Does this complicate or simplify the experimental setup? Explain.

3- Given an optical fiber with $NA = 0.15$. Calculate the acceptance angle of the fiber when it is terminated in water ($n_{water} = 1.33$).