King Fahd University of Petroleum and Minerals

Electrical Engineering Department

EE 420

Fiber Optics Communication

Laboratory Manual

July 2005

PREFACE

This manual contains ten laboratory experiments to be performed by students taking the optical fiber communication course (EE 420). The various experiments included in this manual are designed to enrich the student experience in the field of fiber optics communication and to compliment and improve understanding of the various concepts studied in the classroom lectures. The experiments range from introductory ones in which the student learns basic concepts such as optical power measurement to more advanced experiments, such as experiments that utilize the optical time domain reflectometer (OTDR) in fiber optics measurements.

The experiments are designed, whenever possible, to be theoretically verifiable. This is important not only for gaining practical experience, but also to give students confidence in the theory studied in the classroom lecture. In addition, in the design of those experiments, lengthy and repetitive procedures are avoided, whenever possible. Repetitive measurements are only done when such measurements are essential for theoretical interpretation and verification of the experimental results. A lot of effort has been made to simplify and clarify the experimental procedure and to insure smooth conduct of the experimental measurements.

The students are strongly encouraged to read the introductory part of each experiment ahead of time, before attending the laboratory. Each experiment contains an ample and clear introduction to the experiment, which should facilitate understanding, conducting and interpretation of the experimental work.

Students at the senior level are expected to submit professionally-written laboratory reports. To help the student prepare professional quality reports, a guide has been developed and included in Appendix A along with a sample report. The EE 420 students are strongly encouraged to read this guide and the sample report, because they stress and clarify a number of basic ideas that are frequently neglected or misunderstood by our students. Because a number of EE 420 laboratory experiments utilize laser sources, a laboratory safety procedure has been included at the end of this manual.

I would like to thank Mr. Hameed Frazi, Mr. Joey Espinosa and Mr. Ibrahim Al-Rashid of the EE department for providing invaluable help during the hardware setup of the various experiments found in this manual.

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EXPERIMENT 1
OPTICAL POWER MEASUREMENT

OBJECTIVES:

The objectives of this experiment are to understand the basic concepts of optical power measurements using optical power meters, the difference between calibrated and non-calibrated optical power meters, the proper use of the various optical power units and conversion between those units. In order to gain experience with optical power measurement, the optical power loss due to microscope glass slides will be determined experimentally using a non-calibrated optical power meter. The experimental results will be compared with theory.

EQUIPMENT:

1. Optical Power Meter: INFOS, Model # M100.
2. HeNe Laser: Coherent, Model # 31-2090-000.
3- One glass microscope slide, marked with 8 circles.
3. Five glass microscope slides, each marked with a single circle.
4. Glass slide holder.
5. Laboratory jack.
6. Short optical bench (about 1/4 meter long).
7. Horizontal and vertical translation stages assembled on a bench base.

PRELAB ASSIGNMENT:

Read appendices B and C thoroughly in order to prepare for this laboratory experiment. The information contained in appendices B and C provide basic background for optical power measurement, which is important for understanding this experiment and future experiments.

Before the experimental part of this experiment, the laboratory instructor will briefly explain appendix B and C, but it's your responsibility to fully understand their contents.

INTRODUCTION:

It is well-known that when an optical beam is incident *normally* from a medium with refractive index n_1 onto another medium with refractive index n_2, part of the beam is reflected and part of it is transmitted (see Figure 1). Note that the incident beam encounters a single interface only. The reflectivity R_1 and transmissivity T_1 in this case are given by:

$$R_1 = \frac{P_r}{P_i} = \left(\frac{n_1 - n_2}{n_1 + n_2}\right)^2 \qquad (1)$$

$$T_1 = \frac{P_t}{P_i} = 1 - R_1 = \frac{4n_1 n_2}{(n_1 + n_2)^2} \qquad (2)$$

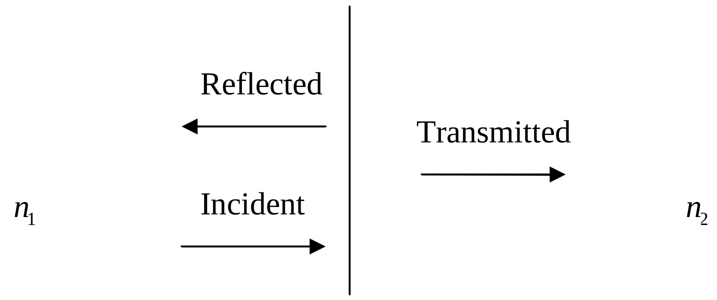

Figure 1: Reflection and Transmission of Light at a Single Interface.

Where P_i, P_r and P_t denote the incident, reflected and transmitted powers, respectively. The subscripts in R_1 and T_1 denote reflection and transmission through a single interface.

The situation becomes more involved when light passes through a slab of material with a non-zero thickness d, as shown in Figure 2. The refractive index of the slab is assumed to be n_2 and the refractive index of the surrounding material is assumed to be n_1. This type of problem is different from the single interface problem shown in Figure1, because in this particular case, the light beam encounters two parallel interfaces, leading to multiple reflections inside the slab.

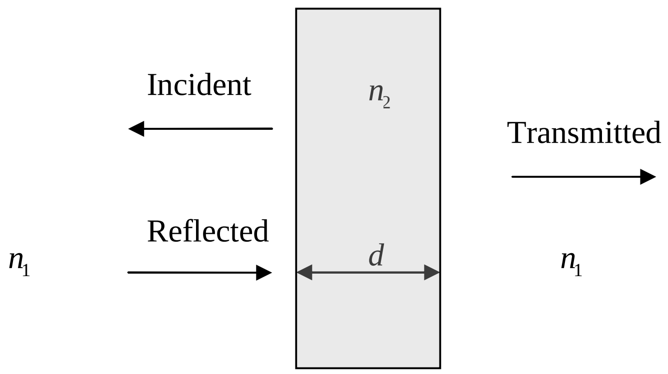

Figure 2: Reflection and Transmission of Light at Two Parallel Interfaces.

According to theory, the transmissivity T_2 of the slab shown in Figure 2 is given by:

$$T_2 = \frac{P_t}{P_i} = \frac{(1 - R_1)^2}{(1 - R_1)^2 + 4R_1 \sin^2 \delta} \qquad (3)$$

Where R_1 is the reflectivity of a single interface, which is given by equation (1), $\delta = k_o n_2 d = (2\pi/\lambda) n_2 d$ and λ is the free space wavelength. The subscript in T_2 indicates the presence of two parallel interfaces.

According to equation (3), when the parameter δ is a multiple of π (i.e. $\delta = k_o n_2 d = 0, \pi, 2\pi, 3\pi, ...$) the transmissivity reaches a *maximum* value of 1. However, when δ is an *odd* multiple of $\pi/2$ (i.e. $\delta = k_o n_2 d = \pi/2, 3\pi/2, 5\pi/2, ...$) the transmissivity reaches a *minimum* value of $(1-R_1)^2/(1+R_1)^2$. Thus the transmissivity T_2 of the slab *always* lies in the range:

$$(1-R_1)^2/(1+R_1)^2 \le T_2 \le 1 \qquad (4)$$

Let us assume that the slab is made of *glass* ($n_2 = 1.50$) and the surrounding medium is *air* ($n_1 = 1.00$). Using equation (1) results in $R_1 = 0.04$. Then using equation (4), it is easy to show that T_2 lies in the range:

$$0.852 \le T_2 \le 1.0 \qquad (5)$$

Using equation (5), we can calculate *range* of the power loss in dB that an optical beam encounters when passing through a slab of glass (see appendix B):

$$-10\log(0.852) \ge dB_{Loss} \ge -10\log(1.0)$$

$$0.696\ dB \ge dB_{Loss} \ge 0\ dB \qquad (6)$$

In this experiment, the power loss due to a glass slab in the form of a microscope slide will be measured in dB. Because the thickness d of the microscope slide is *not uniform* across the slide, the parameter δ changes value depending on the location where the light beam passes through the slide. This means that the power loss caused by the glass slide is also not uniform. However, according to theory this loss must always lie in the range given by equation (6). Also according to equation (6), the *mean* loss of the glass slide equals $(0+0.696)/2 = 0.348\ dB$.

The gain an insight into how the slide thickness effect the transmissivity, let us note that a $\pi/2$ *change* in the parameter δ can cause the transmissivity to change from maximum to minimum or vice versa. For $\Delta\delta = \pi/2 = k_o n_2 \Delta d$, we have $\Delta d = (\pi/2)/(k_o n_2) = \lambda/(4n_2) = 0.6328/(4\times1.5) \approx 0.11\mu m$. Thus a very small change in d can lead to large changes in the transmitted power.

This experiment consists of two main parts. In part A, the optical power loss experienced by a light beam as it passes through different locations of the same glass slide will be measured. In part B, the optical power loss due to a number of glass slides, separated by air gaps will be measured. Note that in part B, optical power readings will be repeated using different meter wavelength settings. One objective of part B is o find out if the meter setting has an effect on the optical loss measurements.

PROCEDURE:

PART A:

1- Turn on the optical power meter and the HeNe Laser. Wait for about 15 minutes in order for the HeNe laser output to stabilize.

2- In the optical power meter, select $\lambda = 0.85\,\mu m$ and the dBm scale. [*The optical power meter is clearly not calibrated, because the HeNe laser has a wavelength of* $0.633\,\mu m$].

3- Align the Laser and the power meter for maximum meter reading. This gives the value of P_i in dBm, record it in table 1. [*Take extra care not to move the laser source or the power meter after you take this reading*].

4- Insert the glass slide (the glass slide marked with 8 circles) between the laser source and the power meter (see Figure 3). The slide should be positioned so that the laser beam passes through circle number 1. [*The glass slide must be kept clean, by holding the slide on the sides only*].

5- Record the power meter reading in table 1 in the column marked P_o.

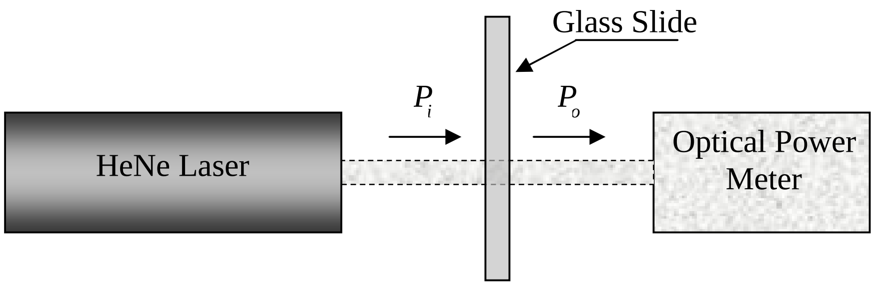

Figure 3: A Glass Slide Inserted between the Laser Source and the Optical Power Meter.

6- Repeat step 5, when the light passes through circles number 2 through 8.

7- Calculate and record the power loss in dB ($\mathrm{dB_{Loss}} = P_i - P_o$) for each of the 8 cases.

8- Calculate the average *experimental* dB loss and record its value in table 1.

9- Plot the $\mathrm{dB_{Loss}}$ versus circle number.

10- Compare the experimental results obtained in table 1 with the theoretical *range* of the dB power loss [as predicted by equation (6)]. Are the results within the predicted range?

11- Compare the average theoretical and average experimental dB power losses.

12- Discuss the results, write comments and some conclusions.

Circle Number	P_o (dBm)	dB_{Loss}	$P_i =$ dBm
1			
2			
3			
4			
5			
6			
7			
8			
	Theoretical Average dB loss	Experimental Average dB loss	
	0.348 dB		

Table 1: Input and Output Powers in dBm when Light Passes through Different Locations of the Microscope Glass Slide.

PART B:

1- Leave the optical power meter setting at $\lambda = 0.85\ \mu m$ and the dBm scale.
2- Remove the slide used in part A.
3- Align the Laser and the power meter for maximum meter reading. Record the meter reading in table 2.
4- Insert the glass slide # 1 between the laser source and the power meter. The slide should be positioned so that the laser beam passes through the circle.
5- Insure that the laser beam passes (as close as possible) through the *center* of the circle.
6- Record the power meter reading in table 2 in the column marked P_o.
7- Add slide # 2 (do not remove slide # 1). Record the meter reading in table 2.
8- Keep adding new slides, one at a time and record the meter reading in table 2, until you finish inserting all the five slides provided.
9- Calculate the dB loss in each case and record the values in table 2.
10- Plot the dB_{Loss} versus the total number of slides used.
11- Change the power meter setting to $\lambda = 1.310\ \mu m$.
12- Remove all the slides.
13- Repeat steps 3 through 10 using the new meter setting. *Add the slides in the same previous order, slide 1 first, followed by slide 2 and so on.*
14- Discuss and compare the results obtained in tables 2 and 3. Does the dB loss measurement depend on the power meter setting? Write some conclusions.

Slide Number	P_o (dBm)	dB_{Loss}	$P_i =$ dBm
1			
2			
3			
4			
5			

Table 2: Input and Output Powers in dBm when Light Passes through a Number of Microscope Glass Slides. The Optical Power Meter is Set at $\lambda = 0.85\,\mu m$.

Slide Number	P_o (dBm)	dB_{Loss}	$P_i =$ dBm
1			
2			
3			
4			
5			

Table 3: Input and Output Powers in dBm when Light Passes through a Number of Microscope Glass Slides. The Optical Power Meter is Set at $\lambda = 1.310\,\mu m$.

QUESTIONS:

Make sure you read Appendix B, before you answer these questions.

1- Convert 0dBm to: a) mW b) W & c) μW

2- Convert 0.1 mW to: a) dB b) dBm & c) dBμ

3- Convert $0.3\,\mu$W to: a) dB b) dBm & c) dBμ

4- A 2.5 mW optical beam passes through a lossy optical element. If the loss of the element is 10 dB, calculate the output power in mW and in dBm.

5- The input to a lossy element is $25dB\mu$ an the output power is $14dB\mu$. Calculate the dB element loss.

EXPERIMENT 2

THE HENE LASER INTENSITY PROFILE: THEORY AND EXPERIMENTAL VERIFICATION

OBJECTIVES:

The objectives of this experiment are to measure the transverse intensity profile of the HeNe laser, the angle of divergence as well as to measure the dependence of the spot size and the peak intensity on distance. The experimental results are to be compared with theoretical predictions.

EQUIPMENT:

1. Optical power meter: INFOS, Model # M100.
2. HeNe laser: Coherent, Model # 31-2090-000.
3- Horizontal and vertical stages assembled on a short optical bench (about 1/4 meter long). This assembly is required to hold the HeNe laser.
4- Approximately 2 meter long multimode fiber (core diameter $= 50\ \mu m$, Orange Color).
5. Mells Griot horizontal and vertical translation stages, (0.01 mm resolution) with a fiber holder assembled on a Mells Griot bench base.

PRE-LAB ASSIGNMENT:

Read the introduction to this laboratory experiment before you attend the lab. This introduction introduces important theoretical backgrounds which are necessary for understanding and interpreting the experimental results.

INTRODUCTION:

The light emitted by a HeNe laser source follows *approximately* a Gaussian intensity distribution in the transverse direction, which is given by:

$$I(r) = I_{\max} e^{-2r^2/w^2} \qquad (1)$$

Where r is the radial coordinate, w is the Gaussian beam *spot size* and $I_{\max}$ is the maximum intensity, which occurs at the beam center $r = 0$. The spot size w is also called the $1/e^2$ distance, because the intensity drops by a factor $1/e^2 = 0.135$ when we move a distance w from the beam center. Figure 1 shows a plot of the Gaussian intensity profile $I(r) = 10\exp(-2r^2/2^2)$. The maximum intensity $I_{\max} = 10$ and the spot size $w = 2$. The horizontal dashed line indicates the $1/e^2 = 0.135$ level, which clearly shows the spot size to be $w = 2$.

When a Gaussian beam propagates in a homogeneous medium, such as air, the spot size w *increases* with distance and the peak intensity $I_{\max}$ drops. Electromagnetic theory actually predicts that the intensity of a Gaussian beam propagating in a homogeneous medium is given by (see Figure 2):

$$I(r,z) = I_{\max}(z)e^{-2r^2/w^2(z)} \quad (2)$$

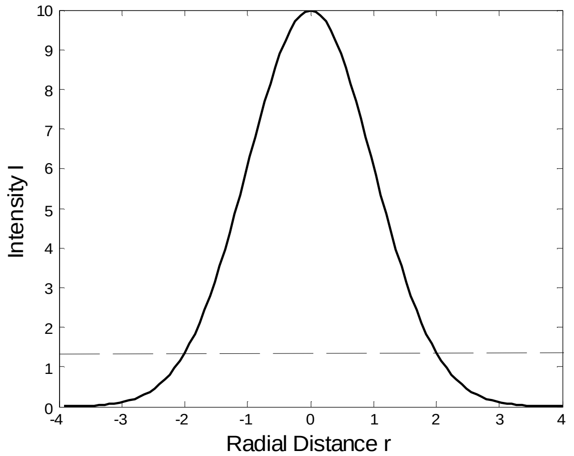

Figure 1: Gaussian Intensity Distribution in the Radial Direction.

Where the z- varying *peak intensity* $I_{\max}(z)$ and spot size $w(z)$ (in free space) are given by:

$$I_{\max}(z) = I_{\max}(0)w^2(0)/w^2(z) \quad (3)$$

$$w(z) = w(0)\sqrt{1+\left[\frac{\lambda z}{\pi w^2(0)}\right]^2} \quad (4)$$

Where λ is the wavelength and z is the direction of Gaussian beam propagation. $I_{\max}(0)$ and $w(0)$ are respectively, the peak intensity and spot size at $z = 0$ (see Figure 2). The spot size $w(0)$ is also known as the minimum or initial spot size. The *asymptotic* angle of divergence of the Gaussian beam is given by:

$$\theta = \frac{\lambda}{\pi w(0)} = \frac{\lambda}{\pi w_o} \quad (5)$$

For HeNe lasers, the angle of divergence θ is very small, much smaller than 1 degree. According to equation (3), *for large values of* z, i.e. $[\lambda z/\pi w^2(0)]^2 >> 1$, the spot $w(z)$ becomes a linear function of z:

$$w(z) = w(0)\sqrt{1+\left[\frac{\lambda z}{\pi w^2(0)}\right]^2} \approx \lambda z/\pi w(0) = \theta z \quad (6)$$

Also for *large values of* z, from equations (3) and (4), we can conclude that the peak intensity $I_{\max}(z)$ becomes proportional to $1/z^2$.

In this experiment, we will scan the laser beam emitted by a HeNe laser in order to measure its intensity profile in the transverse direction (across the beam). An optical fiber with a sufficiently small core diameter (much smaller than the measured beam spot size, i.e. $d_{fiber} << w$) will be used in order to insure that only a small portion of the beam power is detected by the power meter, as seen in Figure 3. This is done to insure high resolution of measurement. If we use a fiber whose diameter is comparable to the beam spot size, the results we obtain will be poor. In this experiment the fiber used has a core diameter of $50\,\mu m$, which is much smaller the spot size that we will be measuring.

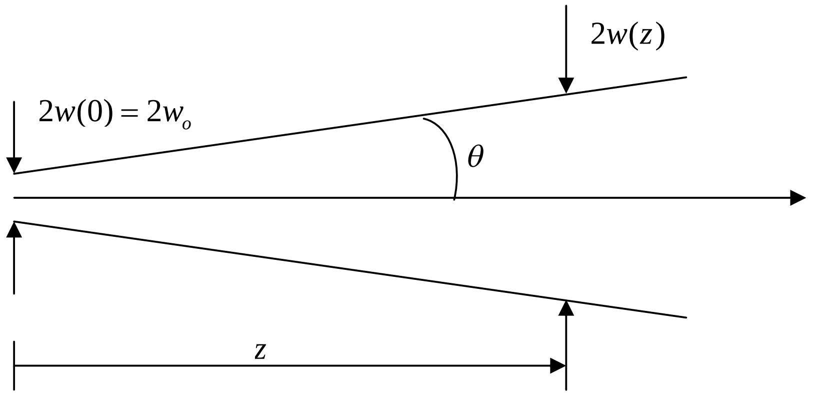

Figure 2: Illustration of Gaussian Beam Expansion, Showing the Initial Spot Size $w(0)$ and the Definition of the Distance z.

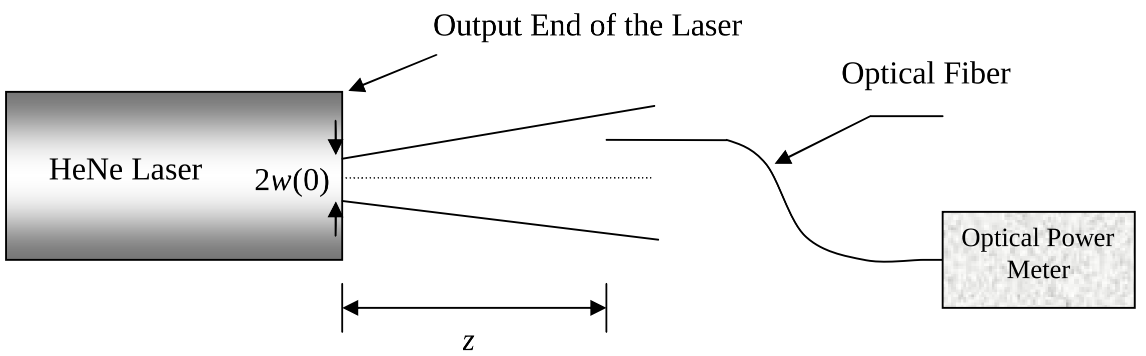

Figure 3: An Optical Fiber Used for Scanning the Laser Intensity Profile at a Fixed Distance z from the Laser Output End.

PROCEDURE:

[**IMPORTANT: INSURE THAT THE UNCONNECTED END OF THE FIBER HAS BEEN RECENTLY CLEAVED AND CLEANED BEFORE YOU BEGIN**].

1- Turn the HeNe laser source and leave it on for about 15 minutes in order for it to stabilize.

2- Connect optical fiber to the optical power meter. D*o not remove* the fiber from the power meter and do not move the optical power meter while taking measurements.
3- Set the optical power meter to the dBm scale and choose $\lambda = 0.85\ \mu m = 850\ nm$.
4- Attached the open end of the fiber to the fiber holder and position tip at a distance $z \approx 0.5\ cm$ or less from the laser output end. [*Be careful that the fiber's tip does not touch the laser, because that may break the fiber*].
5- Move the fiber's tip *both* in the *horizontal and vertical* directions until you obtain maximum power reading.
6- The fiber tip is now located at the beam's center ($r = 0$).
7- Record the maximum power in the second column of table 1 *in the row marked* $r = 0$. The meter is expected to register about $-15\,dBm$ (or a few dBms higher). [*If your meter registers much less power, consult with your laboratory instructor. This may be due to a poor connector which is used to connect the fiber to the optical power meter*].
8- Scan the beam *only in the* ***horizontal*** *direction* in the range ($-0.5 \le r \le +0.5\ mm$) using a step of 0.02 mm. [*For the Mells Griot translation stage micrometer, 1turn = 0.5 mm*]. This means that the distance between the individual marks of the Mills Griot translation stage is 0.01 mm. Record the power (in dBm) in the second column of table 1.
9- Repeat steps 4 through 8 for $z =$ 20, 40, and 80 cm and record the measured powers in the second column of tables 2, 3 and 4, respectively. [*Note that tables 2, 3 and 4 have different step sizes and different ranges*].

<u>REPORT REQUIREMENTS:</u>

1- Convert the powers recorded in the second column of tables 1 through 4 to mW and record the results in the third column of each table.
2- Normalize the powers calculated in column 3 of the each table by dividing by the maximum power in each case. Record the values in column 4 of each table. This column now contains the normalized power P_N (or equivalently the normalized intensity I_N).
3- Plot the *normalized intensity* I_N versus the radial distance for each of the four cases *on the same graph*. By definition, the maximum intensity seen in the resulting graphs should equal to unity.
4- Comment on and discuss the resulting graphs. How close to Gaussian is the normalized intensity profile for each case? Does the spot size appear to increase with the distance from the laser end?
5- Comment on and discuss the dependence of the peak power (in mW) on distance from the laser end.
6- In order to compare the experimental and theoretical results, we need first to accurately calculate the spot sizes w_0, w_1, w_2 and w_3 corresponding respectively to the distances $z_0 \approx 0.5\,cm \approx 0cm$, $z_1 = 20\ cm$, $z_2 = 40\ cm$ and $z_3 = 80\ cm$. Use a Gaussian function fit to calculate the spot size in each case. This can be done as follows, using **matlab**:

A - Plot the normalized intensity (column 4 of the table) versus the radial distance r.

B - Program and plot the *normalized* Gaussian function $\exp[-2(r-r_o)^2/w^2]$ (in the same figure) versus r.

C - *Initially* set the radial shift parameter r_o to *zero* and try several values of w to obtain the best possible *graphical* fit between the experimental data of column 4 and the normalized Gaussian function. If necessary, adjust the value of r_o to obtain the best possible Gaussian fit. The value of w which results in the best possible fit between the two graphs corresponds to the Gaussian spot size. If done correctly, this procedure gives accurate values of the spot size. *Accurate spot size is necessary for the consistent results.*

7- Plot the experimentally determined normalized intensity and the corresponding Gaussian fit on the same figure for each of the four cases.

8- Record the values of w_o, w_1, w_2 and w_3 obtained from the Gaussian fit procedure in table 5.

9- Use the measured value of $w(0)=w_o$ to theoretically predict the values of w_1, w_2 and w_3 using equation 4. Record the results in table 5. Compare the theoretical and measured values of w_1, w_2 and w_3. [use $\lambda = 0.633\,\mu m$].

10- Plot $w(z)$ versus z for $z \geq 0\,cm$ using the theoretical and experimental data on the same graph.

11- Plot the experimentally measured *peak power* (in linear units) versus z and comment on the resulting graph. Does the peak intensity increase or decrease with z?

12- Demonstrate that the measured peak power in mW (at the Gaussian beam center) is proportional to $1/w^2$.

13- Calculate θ in radians and in degrees using the known value of w_o and equation 5. Is θ much smaller than 1^o?

14- Discuss and comment on the results including the symmetry of the laser beam intensity profile and write some conclusions.

Radial Distance (mm) [Beam is Scanned Horizontally]	P (dBm)	P (mW)	$I_N = P_N$ (Unit-less)
-0.50			
-0.48			
-0.46			
-0.44			
-0.42			
-0.40			
-0.38			
-0.36			
-0.34			

-0.32			
-0.30			
-0.28			
-0.26			
-0.24			
-0.20			
-0.18			
-0.16			
-0.14			
-0.12			
-0.10			
-0.08			
-0.06			
-0.04			
-0.02			
0.00			
0.02			
0.04			
0.06			
0.08			
0.10			
0.12			
0.14			
0.16			
0.18			
0.20			
0.22			
0.24			
0.26			
0.28			
0.30			
0.32			
0.34			

0.36			
0.38			
0.40			
0.42			
0.44			
0.46			
0.48			
0.50			

Table 1: Optical Power Versus Radial Distance r. The Distance between the HeNe Laser Output End and the Fiber Input End is $z \approx 0.5\,cm \approx 0\,cm$.

Radial Distance (mm) [Beam is Scanned Horizontally]	P (dBm)	P (mW)	$I_N = P_N$ (Unit-less)
-0.50			
-0.48			
-0.46			
-0.44			
-0.42			
-0.40			
-0.38			
-0.36			
-0.34			
-0.32			
-0.30			
-0.28			
-0.26			
-0.24			
-0.20			
-0.18			
-0.16			
-0.14			
-0.12			

-0.10			
-0.08			
-0.06			
-0.04			
-0.02			
0.00			
0.02			
0.04			
0.06			
0.08			
0.10			
0.12			
0.14			
0.16			
0.18			
0.20			
0.22			
0.24			
0.26			
0.28			
0.30			
0.32			
0.34			
0.36			
0.38			
0.40			
0.42			
0.44			
0.46			
0.48			
0.50			

Table 2: Optical Power Versus Radial Distance r. The Distance between the HeNe Laser Output End and the Fiber Input End is $z = 20\,cm$.

Radial Distance (mm) [Beam is Scanned Horizontally]	P (dBm)	P (mW)	$I_N = P_N$ (Unit-less)
-0.72			
-0.69			
-0.66			
-0.63			
-0.60			
-0.57			
-0.54			
-0.51			
-0.48			
-0.45			
-0.42			
-0.39			
-0.36			
-0.33			
-0.30			
-0.27			
-0.24			
-0.21			
-0.18			
-0.15			
-0.12			
-0.09			
-0.06			
-0.03			
0.00			
0.03			
0.06			
0.09			
0.12			
0.15			

0.18			
0.21			
0.24			
0.27			
0.30			
0.33			
0.36			
0.39			
0.42			
0.45			
0.48			
0.51			
0.54			
0.57			
0.60			
0.63			
0.66			
0.69			
0.72			

Table 3: Optical Power Versus Radial Distance r. The Distance between the HeNe Laser Output End and the Fiber Input End is $z = 40\,cm$.

Radial Distance (mm) [Beam is Scanned Horizontally]	P (dBm)	P (mW)	$I_N = P_N$ (Unit-less)
-1.00			
-0.95			
-0.90			
-0.85			
-0.80			
-0.75			
-0.70			

-0.65			
-0.60			
-0.55			
-0.50			
-0.45			
-0.40			
-0.35			
-0.30			
-0.25			
-0.20			
-0.15			
-0.10			
-0.05			
0.00			
0.05			
0.10			
0.15			
0.20			
0.25			
0.30			
0.35			
0.40			
0.45			
0.50			
0.55			
0.60			
0.65			
0.70			

0.75			
0.80			
0.85			
0.90			
0.95			
1.00			

Table 4: Optical Power Versus Radial Distance r. The Distance between the HeNe Laser Output End and the Fiber Input End is $z = 80\,cm$.

z (cm)	$w(z)$ [mm] [Theoretical]	$w(z)$ [mm] [Experimental]
0	------------	
20		
40		
80		

Table 5: Theoretical and Measured Gaussian Spot Sizes.

QUESTIONS:

1- Based on the experimental data, what should be the spot size at a distance of 100 m from the laser output end?

2- Using the experimental data, estimate the distance at which the spot size equals 5 cm.

3- Does the angle of divergence increase or decrease when the wavelength increases?

4- Estimate the distance beyond which $w(z)$ becomes a linear function of z. Use the condition $[\lambda z / \pi w^2(0)]^2 \geq 10$.

5- Based on your answer to part 4, do you expect the values of $w(z)$ measured in this experiment to increase linearly with z? Justify your answer.

6- A Gaussian beam has a peak intensity of $200\,(V/m)^2$, calculate its intensity at $r = 2w$.

EXPERIMENT 3
LIGHT POLARIZATION AND FOCAL LENGTH OF THIN LENSES

OBJECTIVES:

This experiment consists of two separate parts, parts A and B. Part A has two objectives. The first objective is to determine whether or not a given beam of light is polarized. The second objective is to experimentally verify the angular dependence of the transmitted optical power when a beam of light passes through a polarizer/analyzer pair. The objective of part B is to experimentally verify the thin lens formula by experimentally finding the focal lens of a given thin lens by imaging.

PART A:

EQUIPMENT REQUIRED

1. Optical power meter: INFOS, Model # M100.
2. HeNe laser: Coherent, Model # 31-2090-000.
3. ¼ m optical bench.
4. Holder.
5. Laboratory Jack.
6. Two linear polarizers.

INTRODUCTION:

A linear polarizer is characterized by a pass axis with a block axis at 90 degree with respect to the pass axis as shown in Figure 1.

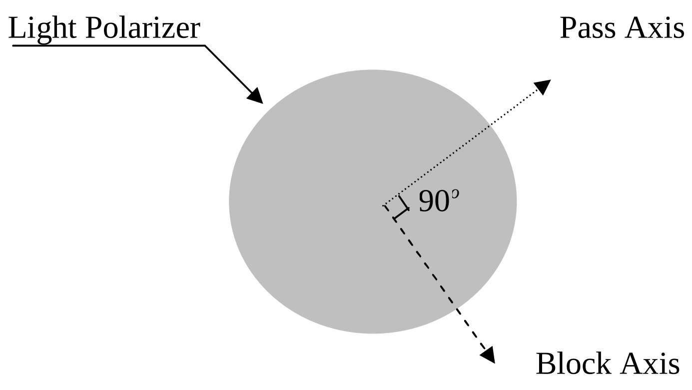

Figure 1: A linear Polarizer with Pass Axis at 90-Degree with Respect to the Block Axis.

When light beam pass through an *ideal* linear polarizer, the electric field vectore component parallel to the pass axis passes through the polarizer without loss. However, the beam's electric field vector component parallel to the block axis does not pass at all through the ideal linear polarizer. In this experiment we use a linear polarizer and assume that it approximates the operation of the ideal linear polarizer.

Now consider a linearly polarized light beam propagating in air in the z-direction, with an electric field given by:

$$\vec{E} = \vec{E}_i = \vec{a}_x E_x e^{-jk_o z} + \vec{a}_y E_y e^{-jk_o z} \qquad (1)$$

Where E_x and E_y are the field amplitudes in the x and y directions, respectively and k_o is the free space phase constant. This beam will be used as input to the polarizer. Let us situate the polarizer in the $x-y$ plane (normal to the beam's direction of propagation z) and rotate the polarizer such that its pass axis becomes parallel to the y- axis (see Figure 2). The Block axis is not shown, because we know it is always at 90^o with respect to the pass axis.

As shown in Figure 2 (a), the input electric field vector makes an angle θ with respect to the pass axis of the polarizer. The output electric field vector is shown in Figure 2(b), after the beam passes through the linear polarizer. It is clear that only the y- component of the field vector passes through the polarizer, while the x-component is blocked, resulting in the output electric field:

$$\vec{E}_o = \vec{a}_y E_y e^{-jk_o z} \qquad (2)$$

This represents a beam linearly polarized in the y- direction.

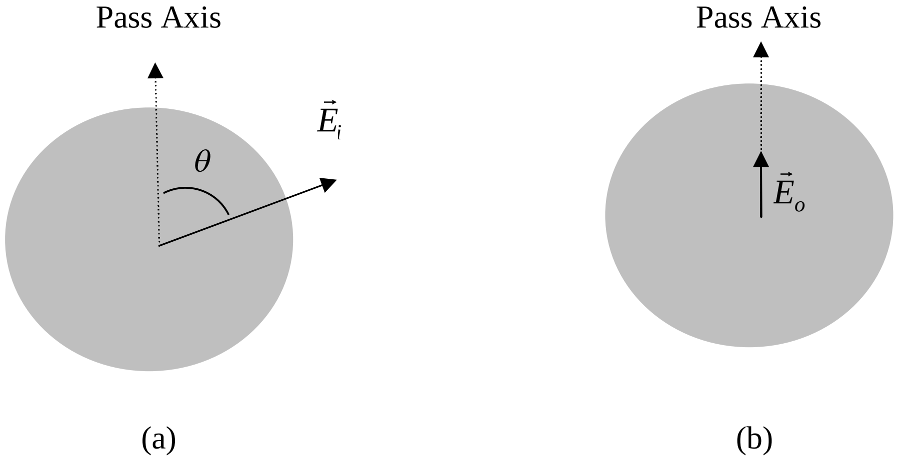

Figure 2: Input and Output Electric Field Vectors when a Linearly Polarized Light Beam Passes Through a Linear Polarizer. The Input Electric Field Vector is at Angle θ with Respect to the Pass Axis of the Polarizer.

For the case considered above, the amplitude of the input electric field and output electric fields are respectively given by: $E_i = \sqrt{E_x^2 + E_y^2}$ and $E_o = E_y$ which are related by the simple relationship:

$$E_o = E_i \cos\theta \qquad (3)$$

Since the electromagnetic power is proportional to the square of the electric field, we can easily predict the ratio of the output to input power:

$$(\frac{E_o}{E_i})^2 = \frac{P_o}{P_i} = \cos^2\theta \qquad (4)$$

Equation (4) is valid only for the ideal linear polarizer shown in Figures 1 and 2. However, we can still use equation (4) for practical linear polarizers provided we interpret P_i to be the maximum output power $P_{o,\max} = P_o(\theta = 0)$ that can pass through the polarizer (i.e. when $\theta = 0$). Thus for a practical linear polarizer, we have:

$$\frac{P_o(\theta)}{P_o,\max} = P_N = \cos^2\theta \qquad (5)$$

Where P_N is the *normalized* output power. In this part of the experiment (part A), we will perform optical power measurements to verify the validity of equation (5).

From the point of view of polarization, there are two types of lasers. Either they are linearly polarized or randomly polarized. A linearly polarized laser means that the electric field vector of the laser has a specific and fixed direction. In the case of a randomly polarized laser, the electric field vector continually and rapidly changes direction in a random manner. Sunlight is another example of a randomly polarized light. In this experiment, we will find out whether the HeNe laser source in the EE 420 laboratory is linearly or randomly polarized.

During this part of the experiment, it is important to distinguish between the two angles θ and θ_p. The angle θ = angle between the *input* electric field vector and the pass axis of the polarizer, exactly as defined in Figure 2 (a). However, θ_p simply represents the *reading* of the polarizer dial. The polarizer dial used in the EE 420 laboratory has the following range $0 \le \theta_p < 360^\circ$.

PROCEDURE:

[IMPRTANT: FOR THIS PART OF THE EXPERIMENT, THE LASER MUST BE TURNED ON FOR AT LEAST ONE HOUR BRFORE RELIABLE MEASUREMENTS CAN BE TAKEN].

1- Place a polarizer between the HeNe laser source and the optical power meter as shown in Figure 3. Adjust the polarizer orientation so that the beam passes normal to the polarizer and as close as possible to the center of the polarizer.

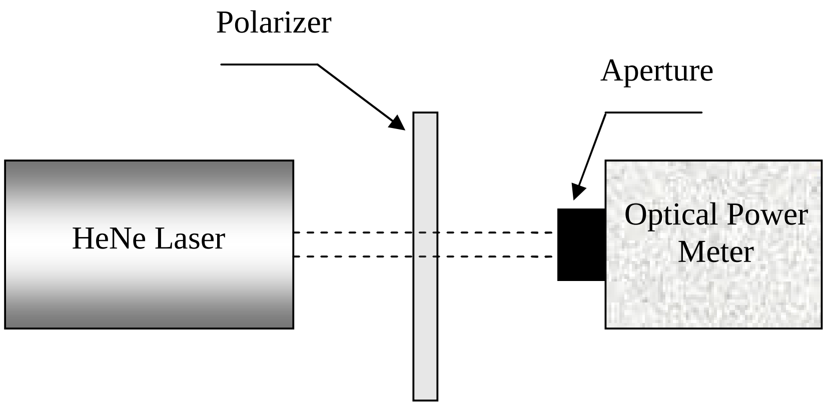

Figure 3: Setup Used for Examining the Polarization of the HeNe Laser Source Using a Linear Polarizer Placed Between the Laser and an Optical Power Meter.

2- Turn on the power meter and select the dBm scale and $\lambda = 0.85\mu m$.

3- Insure that an appropriate aperture is used at the input end of the power meter to minimize the effect of the ambient light. The power meter cover can be used an aperture.

4- Set the polarizer angle θ_p to zero degrees.

5- Adjust the position of the power meter for maximum meter reading.

6- Record the optical power in dBm in the second column of table 1.

7- Set the polarizer dial to $\theta_p = 10^o$ and record the dBm power in table 1.

8- Repeat step 7 for $\theta_p = 20^o, 30^o, \ldots\ldots, 90^o$.

9- Covert the dBm power to mW and record the values in the third column of table 1.

10- Calculate the corresponding normalized power P_N and record its value in column 4 of table 1.

11- Plot a graph that shows the variation of P_N with θ_p. At this point the distinction between θ_p and θ is not important.

12- Using this graph, comment on the variation of P_N with θ_p. Is the HeNe laser linearly polarized or randomly polarized?

13- Place another polarizer between the HeNe laser source and the optical power meter as shown in Figure 4. The polarizer on the right-hand-side is now called *analyzer*, because it is used to analyze the linearly polarized light that emerges from the polarizer.

14- Insure that the light beam passes as close to the center of both the polarizer and analyzer.

15- Set the *analyzer angle* θ_p to 90^o.

16- Rotate the dial of the *polarizer* until the power received is minimum. The reading of the polarizer angle is not important, so we do not need to record it. *Since the power received by the meter is minimum, we are now sure that the linearly polarized light makes an angle $\theta = 90^o$ with respect to the analyzer pass axis*.

17- Record the dBm meter reading in the third column of table 2 (use the bottom row, which corresponds to $\theta = \theta_p = 90^o$).

18- Rotate the analyzer dial to $\theta_p = 80^o$ and record the meter reading in the third column of table 2. [*Do not change the polarizer angle*].

θ_p (Degrees)	P (dBm)	P (mW)	P_N (Unit-less)
0			
10			
20			
30			
40			
50			
60			
70			
80			
90			

Table 1: Measured Optical Power Variation with the Polarizer Angle θ_p when a Single Polarizer is Used.

19- Repeat step 18, for $\theta_p =$ 70, 60, 50, …., 10, 0, 350, 340, 330, …., 270 and 280 degrees. [*Note that the angle* $\theta_p = 350^o$ *is equivalent to* $\theta = -10^o$, $\theta_p = 340^o$ *is equivalent to* $\theta = -20^o$ *and so on*].

20- Convert the meter reading recorded in column 3 to mW and record the values in column 4 of table 2.

21- Divide by the maximum power to convert the data of column 4 to normalized power and record the resulting normalized power P_N in column 5 of table 2.

22- Plot P_N versus θ.

23- Plot equation (5) [$P_N = \cos^2\theta$] in the *same* figure.

24- Calculate the relative error between the experimental and theoretical values of P_N.

25- Discuss and comment on the results. Write some conclusions.

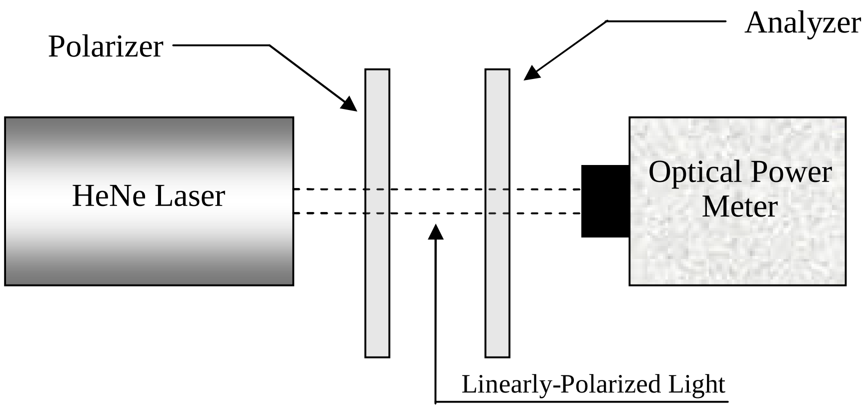

Figure 4: Polarizer/Analyzer Pair Placed between the HeNe Laser Source and the Optical Power Meter. The Laser Light is Linearly Polarized by the Polarizer Before it Passes Through the Analyzer.

θ_p (Degrees)	θ (Degrees)	P (dBm)	P (mW)	P_N (Unit-less)
270	-90			
280	-80			
290	-70			
300	-60			
310	-50			
320	-40			
330	-30			
340	-20			
350	-10			
0	0			
10	10			
20	20			
30	30			
40	40			
50	50			
60	60			
70	70			
80	80			
90	90			

Table 2: Measured Optical Power with θ for the Polarizer/Analyzer Pair Arrangement.

PART B:

EQUIPMENT REQUIRED

1- White light source.
2- 1 m optical bench.
3- White Screen.
4- Lens Holder.
5- Lens (focal length $f = 10\,cm$).
6- Lens (unknown focal length).
7- Object with holder.

INTRODUCTION:

In this part of experiment we will use the well-known thin lens formula:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i} \qquad (6)$$

to experimentally measure the focal length of a thin lens, where f, d_o and d_i are respectively the focal length of the lens, the object distance and the image distance (see Figure 5 in the procedure section). After forming an image, we will measure the distances d_o and d_i, from which the focal length of the lens can easily be determined, using equation (6). We will do two separate measurements. The first measurement will be done using a lens having a focal length of 10 cm. The measured value of f will then be compared with the known value. In the second measurement, the focal length of the thin length is unknown and we are expected to determine it experimentally. In doing this experiment, it is helpful to recall that a real image can be formed only if $d_o > f$.

PROCEDURE

1- Insert a lens of focal length $f = 10\,cm$ between the object and the screen, as shown in Figure 5.
2- Adjust the intensity of the white light source in order to reduce glare.
3- Set the object distance to $d_o = 12\,cm$.
4- Change the distance d_i until a *sharp* image is formed on the screen.
5- Record the value of d_i in table 3.
6- Calculate the value of the focal length using equation (6) and record it in table 3. Comment on how close this value is to $f = 10\,cm$. Comment on the sources of error if any. Discuss the results and write some conclusions.
7- Using the above procedure, determine the focal length of the lens supplied to you by the laboratory instructor and record the experimental value in table 3. Write a conclusion.

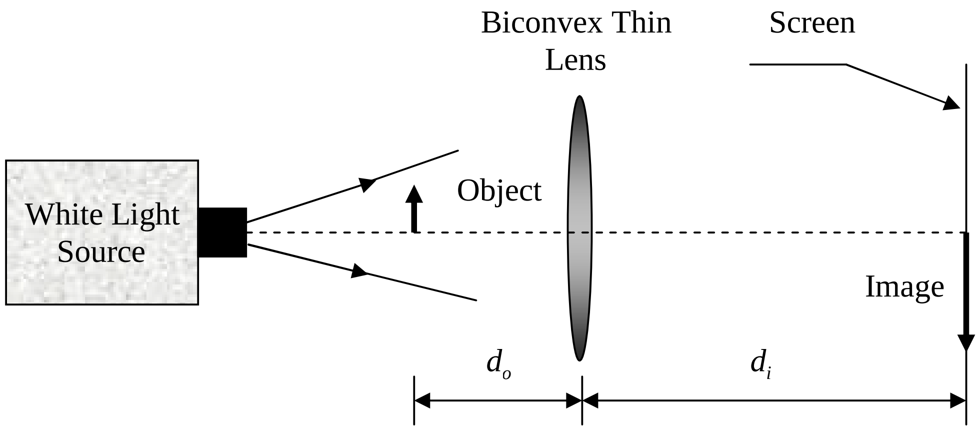

Figure 5: Image Formation Using a Thin Biconvex Lens.

Lens Focal Length	d_o (cm)	d_i (cm)	$f_{\text{experimental}}$ (cm)
10 cm	12		
Unknown			

Table 3: Imaging Data for the Known and Unknown Lenses.

QUESTIONS:

1- For the polarizer/analyzer arrangement, calculate (theoretically) the angle θ such that the transmitted power is 50% of the maximum power.

2- For the polarizer/analyzer arrangement, calculate (theoretically) the angle θ such that the transmitted power is 6 dB below the maximum power.

3- For the polarizer/analyzer arrangement, calculate (theoretically) the ratio of the transmitted electric field (for $\theta = 30^o$) to the maximum possible electric field.

4- Briefly suggest a simple method that can be done to show that sunlight is not linearly polarized. You can use only one polarizer.

5- A thin lens having a known focal length of $5\,cm$ is used for the formation of a real image on a screen. If you want to form an image at 45 cm from the lens, how far from the lens must the object be placed? What is the resulting magnification?

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 μm graded-index fiber (Orange Color). NA = 0.220.
8- Approximately 5m long, 62.5 μm 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.

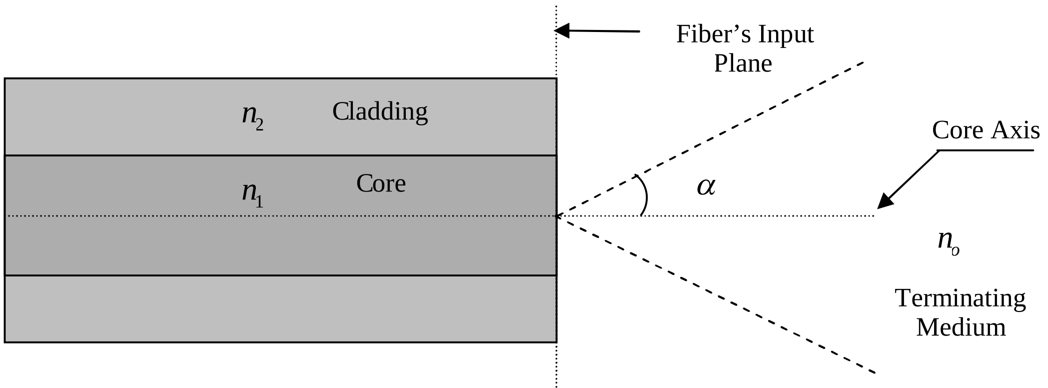

Figure 1: The Acceptance Angle α of an SI Optical Fiber.

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.

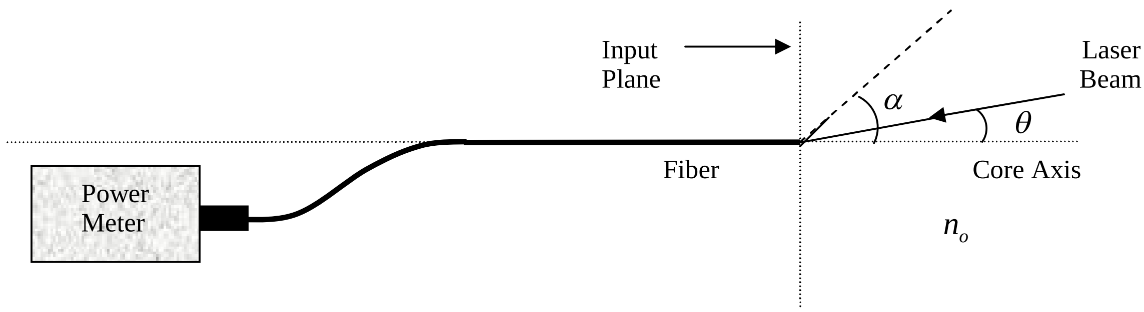

Figure 2: Method Used for Measuring the Acceptance Angle α of an Optical Fiber.

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.

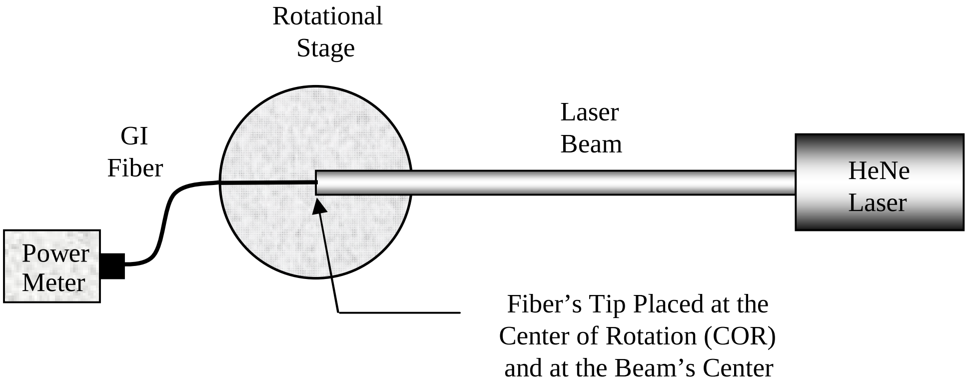

Figure 3: Basic Experimental Setup Used for Measurement of the Acceptance Angle.

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 μm 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^o. 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^o. 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 μm 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 ($n_{water} = 1.33$).

EXPERIMENT 5
LIGHT COUPLING TO MULTIMODE GRADED INDEX FIBERS

OBJECTIVES:

The objective of this experiment is to couple HeNe laser light to a multimode grade index fiber. Both direct and lens coupling will be done. The coupling efficiency is to be measured in each case and the experimental results are to be compared with theoretical prediction.

EQUIPMENT REQUIRED

1- Optical power meter: INFOS, Model # M100.
2- HeNe laser: Coherent, Model # 31-2090-000 on a horizontal and translation stage, all assembled on a ¼ m bench.
3- Mells Griot horizontal and vertical translation stages, (0.01 mm resolution) with a fiber holder assembled on a Mells Griot bench base.
4- GI $50\mu m$ optical fiber [Orange]. About 2 meter long.
5- Thin lens ($f = 5\,cm$).
6- Lens holder.
7- Translation stage assembled on ¼ m bench: Ealing Electro-Optics.

PRELAB ASSIGNMENT:

Read the introduction to this experiment before attending the laboratory.

INTRODUCTION:

In this experiment HeNe laser light will be first coupled *directly* to a $50\mu m$ GI optical fiber. This will be followed by *indirect* coupling by focusing the laser light into the GI fiber using a thin lens.

Let us turn our attention first to the direct coupling of a laser beam to a highly multimode GI fiber of core radius a, as shown in Figure 1. Electromagnetic theory predicts that the coupling efficiency η in this case is given by the simple relationship:

$$\eta = (a^2 / w^2) \qquad \text{for} \qquad a \le w \qquad (1)$$

Where w is the laser spot size (assumed to be Gaussian) and a is the core radius of the fiber. The corresponding dB loss in this case is given by:

$$dB_{loss} = -10\log\eta = -10\log(a/w)^2 = -20\log(a/w) \qquad (2)$$

In this experiment we will verify the theoretical prediction of equation (2), by coupling a laser beam of known power and measure the resulting dB loss in the case of *direct* laser/ fiber coupling. This method tends to couple part of the light power into the *cladding modes* of the fiber. Cladding modes are *very lossy* modes, which decay after few meters or few tens of meters depending on the type of fiber and method of excitation. The fiber used in this experiment is relatively short, so there is a strong possibility that the measured fiber transmission efficiency, in the case of direct coupling, will be somewhat higher than the prediction of equation (1). This also means that the experimental dB loss may be somewhat smaller than the prediction of equation (2). We can use the theoretical and experimental coupling efficiencies to *roughly estimate* the optical power coupled to the cladding modes (*and ultimately reaching the power meter*) in the case of direct coupling.

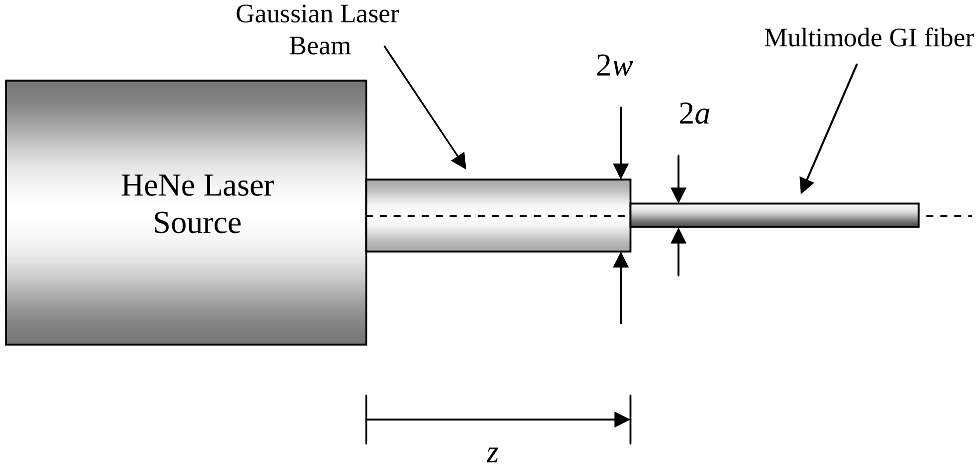

Figure 1: Direct Coupling of the HeNe Laser Source to a Multimode GI Fiber of Core Radius a.

LASER/FIBER LENS COUPLING:

Based on equation (1), when the laser spot size w is reduced, the coupling efficiency η increases. One way to reduce w is by focusing the laser beam using a lens, before the light is coupled into the fiber input end, as shown in Figure 2.

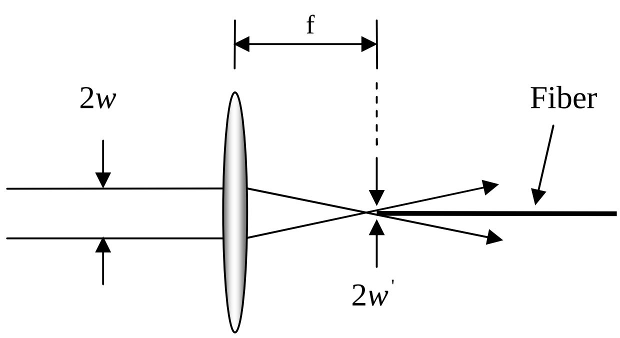

Figure 2: Laser/Fiber Lens Coupling.

In theory, we can obtain a maximum efficiency of $\eta \approx 1$ if we reduce the laser spot size from w to w' and *match it* to the radius $a = 25\mu m$ of the GI fiber (i.e. $w' = a = 25\,\mu m$). To successfully achieve this task, we need first to design the lens coupling system. The Gaussian spot size w' at the focal point (see Figure 2) is given by the well-known relationship:

$$w' = \frac{\lambda f}{\pi w} \quad (3)$$

From experiment 2, we have measured the minimum spot size w_o (at $z = 0$) of the HeNe laser and found it to be $w_o \approx 0.28\,mm$. Using this spot size, along with equation (3), we can find the focal length of the lens required to focus this spot size into $w' = 25\,\mu m$, as follows:

$$f = \pi w' w / \lambda = \pi \times (25 \times 10^{-6}\,m) \times (0.28 \times 10^{-3}\,m) / (0.633 \times 10^{-6}\,m) = 3.47\,cm$$

The nearest available lens has a focal length $f = 5\,cm$. Thus, we will use this lens in this experiment. However, if we use this lens, the focused spot size w' will be larger than the target spot size $w' = 25\,\mu m$ (see equation 3). What should be the value of w that can be focused into $w' = 25\,\mu m$ when a lens of focal length $f = 5\,cm$ is used? Using equation (3), the answer is $w = 0.4\,mm$. This spot size can be obtained if we increase the distance z from the laser output end to the lens, since the Gaussian beam emitted by the laser expands with z. Previous *experimental* results show that at $z \approx 37\,cm$, the spot size is $w = 0.4\,mm$ (see experiment 2).

This method of excitation *tends not* to excite the cladding modes, provided the beam is properly focused directly into the fiber's core and the spot size is reduced to match the core radius.

<u>PROCEDURE:</u>

HENE LASER TOTAL POWER MEASUREMENT:

1- Turn on the HeNe laser and wait for it to stabilize.
2- Remove the cover of the optical power meter.
3- Measure the *total power* emitted by the laser source. Because the sensor of the power meter has a smaller area than the laser beam, you need to first *partially focus* the laser light into the light sensitive area of the power meter. *Do not overly focus the light into the light sensitive area of the meter, because this causes sensor saturation and leads to meter readings that are less than the actual power*. To measure the total power emitted by the laser, use the following procedure (Refer to Figure 3):

- Place the lens at about 20 cm from the laser output end.
- Place the light sensitive area of the meter at about $L \approx 9\,cm$ from the lens. [Insure that the laser beam size is *slightly smaller* than the dimension of the light sensitive area. *The light sensitive area must capture all the laser light*].
- Turn the power meter on and set it to dBm and $\lambda = 0.85\,\mu m$ and record the meter's reading in table 1.

- Repeat the above for $L \approx 8, 7, 6$ and $4cm$. Record the values in table 1

4- Take the *maximum* of the five readings in table 1 and call it P_l and record its value in table 1. *Also record the same value of P_l in table 2.*

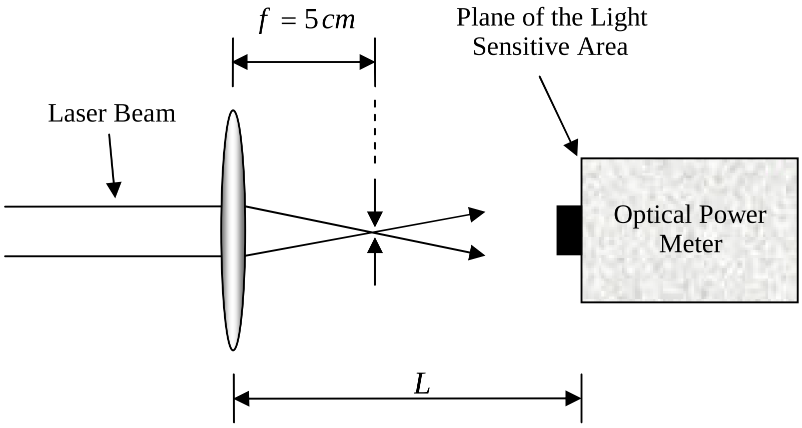

Figure 3: Arrangement Used to Measure The Total Power of the HeNe Laser Source.

Total Laser Power (dBm)	
$L \approx 9cm$	
$L \approx 8cm$	
$L \approx 7cm$	
$L \approx 6cm$	
$L \approx 4cm$	
Maximum (P_l)	

Table 1: Total Laser Power Measurement.

LASER/FIBER DIRECT COUPLING:

[IMPORTANT: INSURE THAT THE FIBER HAS BEEN RECENTLY CLEAVED AND CLEANED BEFORE YOU BEGIN. IF THE FIBER IS NOT PROPERLY CLEAVED, EXTREMELY LARGE EXPERIMENTAL ERRORS WILL RESULT].

1- Connect the fiber to the fiber's holder on the horizontal/vertical translation stage (Stage XY) and adjust the distance between the laser to the fiber's tip to $z = 37cm$ (see Figure 4).
2- Connect the other end of the fiber to the power meter and insure it is set to the same previous setting.
3- Move stage XY in both the horizontal and vertical directions until you obtain maximum meter reading (as you did in experiment 2). The fiber now should be

located at the beam's center. Record the maximum measured power value in table 2 and call it P_{direct}. [*You should obtain a value of about* $-15\,dBm$ *or higher by a few dBms. If the received power is much lower than* $-15\,dBm$, *consult your laboratory instructor, because the fiber may not be properly cleaved, or it may be dirty. Another possible reason is that the connector used to connect the fiber to the power meter is either dirty or not well prepared*].

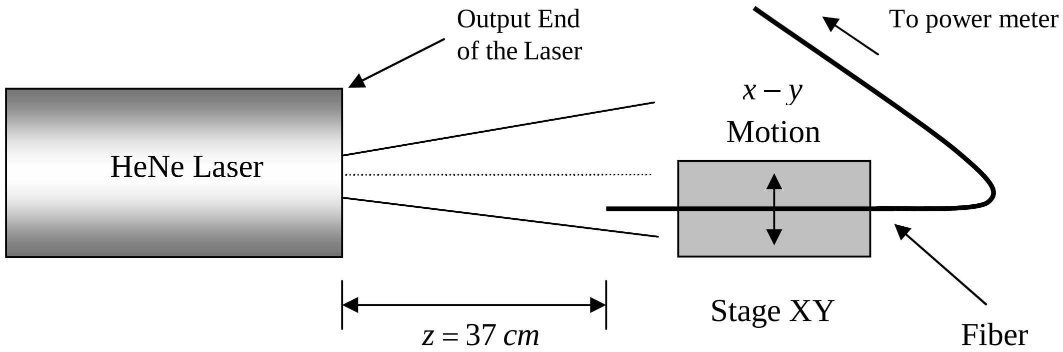

Figure 4: Direct Light Coupling Setup.

LASER/FIBER LENS COUPLING:

[<u>WARNING</u>: WHEN MAXIMUM COUPLING IS ACHIEVED USING THE PROCEDURE YOU ARE ABOUT TO DO, ALMOST ALL THE LASER POWER WILL BE COUPLED INTO THE FIBER. DO NOT REMOVE THE FIBER FROM THE POWER METER, BECAUSE THIS MAY CAUSE SERIOUS EYE INJURY].

1- Setup the lens coupling arrangement shown in Figure 5.
2- Attach one end of the test fiber to the fiber holder and connect the other end to the power meter.
3- Turn the laser on.
4- Now you need to accurately align your setup. Use the following procedure experimental setup and laser alignment:

- Use the holes on the optical table to insure the ¼ m optical bench (that carries the laser) and the Mills Griot optical bench (that carries stage XY) are *parallel* to each other.
- Using a meter stick to align the laser in order to insure that it is *parallel* to the optical table. Bring the meter stick close to the laser and record the *exact height* where the laser hits the meter stick (A height $h = 25-30\,cm$ is recommended). Repeat this step at a distance of about 1 meter. If the *laser beam's center* hits the meter stick at a different height, then adjust the vertical tilt of the laser until the laser hits the stick at the same height.
-Now confirm your alignment by moving the stick in the horizontal direction to insure that the laser hits the stick at the same height h regardless of distance from the laser (see Figure 6).
- Finally, align the laser with respect to the fiber to insure that it is perfectly *perpendicular* to the fiber.

5- Place the lens at a distance $z = 35\,cm$ (less the target value $z = 37\,cm$ for a reason that will be clear shortly) from the laser.
6- Adjust the position of the lens until the laser hits the *exact center* of the lens. To insure this, use the following procedure:

- Remove the lens from the lens holder.
- Use a meter stick and place it about 1 meter from the laser and mark the *exact point* where the laser hits the stick. *Keep the meter stick in its exact place, don't move it*.
- Place the lens in the lens holder. Insure that the laser beam is perpendicular to the beam.
- Adjust the lens *both in the horizontal and vertical* directions until the *center* of the *expanded laser spot* hits the meter stick at *exactly the same previous point*. (see Figure 7).

7- Now you need to *exactly* place the fiber's tip at the focal point of the lens. This procedure requires a little patience because of the small spot size of the focused beam spot size ($w' \approx 25\,\mu m$). This can be done using the following procedure:

- *Initially,* place the fiber's tip at $7\,cm$ from the lens (larger than $f = 5\,cm$). At this position, the laser beam being focused by the lens is relatively wide and therefore easier to locate (see Figure 7).
- Adjust stage XY in the horizontal and vertical directions and monitor the meters reading until you obtain maximum power reading.
- Adjust Stage Z to move the lens *towards* the fiber's tip, and monitor the meter's reading until you obtain maximum meter reading.
- Again, adjust stage XY in the horizontal and vertical directions and monitor the meters reading until you obtain maximum power reading.
- If necessary repeat the above steps until you obtain the *maximum possible* meter reading. When successfully done, the fiber's tip should be at the focal point of the lens. Make a final *visual* check to see if the fiber's tip is at the focal point of the lens, 5 cm away from the lens. Record the maximum power reading in table 2 and call it P_{lens}.

[*When the above procedure is successfully done, the power meter should register a dBm power slightly less than the total laser power you measured in the first part of the experiment*].

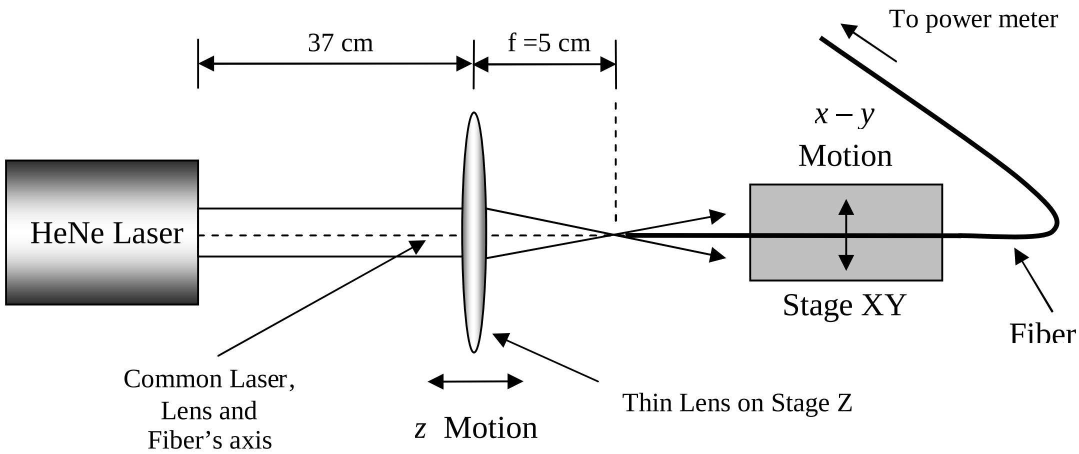

Figure 5: Thin Lens Light Coupling Setup.

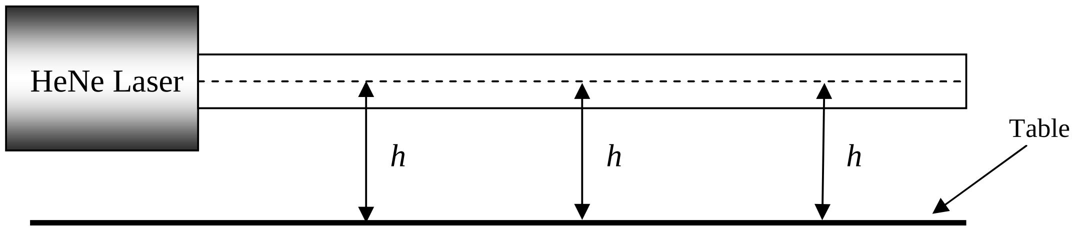

Figure 6: Illustration of Laser Alignment with Respect to the Optical Table.

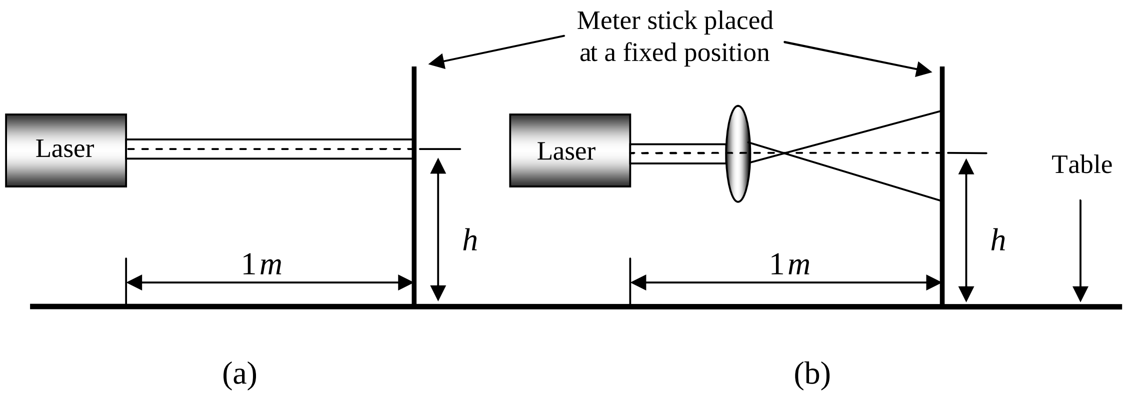

Figure 7: Illustration of Laser Alignment with Respect to the Lens Center. (a) Without Lens. (b) With Lens.

P_l (dBm)	
P_{direct} (dBm)	
P_{lens} (dBm)	

Table 2: Summary of Power Measurements.

REPORT REQUIREMENTS:

1- Calculate the optical power loss in dB when direct laser/fiber coupling is used. In dB, this loss is given by $dB_{loss} = P_l - P_{direct}$. Record the value in table 3.
2- Calculate the theoretical loss in dB using equation (2) and write down the result in table 3.
3- Repeat the above for the laser/fiber *lens* coupling. Write the results in table 3.
4- Compare the theoretical and experimental measurements of the dB loss in table 3 and suggest some possible sources of error.
5- To identify some of the sources of error, think of the additional loss due to light reflection from the lens surfaces (Fresnel reflection) and the variation of the NA of the GI fiber with distance from the core axis. In addition, the connector from the fiber to the optical power meter may give additional loss. Is the laser spot size at $z = 37\,cm$ exactly equal to $0.4\,mm$? What about coupling to the cladding modes in the case of direct coupling?
6- Discuss how far away your result (for the lens coupling method) is from optimal efficiency (i.e. how far it is from the zero dB loss).
7- In the case of direct coupling, use the theoretical and experimental coupling efficiencies to *estimate* the dBm power coupled to the lossy claddings modes that reaches the optical power meter. This can be done as follows: theoretically *estimate* the power (in mW) that is coupled to the fiber's core using equation (1). Then find the total power (in mW) that has actually been coupled to the fiber (including core and cladding). Take the difference between the two powers in mW. This gives an estimate of the power (in mW) coupled to the cladding modes in the case of direct coupling. Finally, convert this power to dBm. Do you expect this power to be reduced if the fiber is much longer?
8- Discuss the overall experimental results. Write some comments and conclusions.

dB_{loss} (dB)	Theoretical	Experimental
Laser/Fiber (Direct)		
Laser/Fiber (Lens)		

Table 3: Theoretical and Measured Coupling Losses in dB.

QUESTIONS:

1- It is easier to *optimize* lens coupling using a highly multimode fiber or a single mode fiber. Discuss the experimental difficulties that you expect to face if you try to lens couple light into a single mode fiber having a *diameter* of $5\,\mu m$.

2- You are given a set of lenses, with the following *standard* focal lengths:

$f = 3.06\,cm$, $f = 1.674\,cm$, $f = 0.855\,cm$, and $f = 0.4488\,cm$

Suppose you want to achieve *maximum* coupling efficiency from the HeNe laser into the single mode fiber presented in question 1. You can achieve this by focusing the laser light into a spot size that equals the core radius of the single mode fiber. Which lens is the most appropriate to use? [*The distance from the laser to the lens should not exceed 40 cm*]. Sketch the experimental setup showing the lens that you have selected and the distance from the laser to the lens.

3- Estimate the loss in dB due the lens in the last part of this experiment.

EXPERIMENT 6

FIBER MISALIGNMENT LOSS MEASUREMENT

OBJECTIVES:

The objective of this experiment is to measure the dB power loss due to longitudinal and lateral misalignments of two identical multimode GI fibers.

EQUIPMENT REQUIRED

1- Optical power meter: INFOS, Model # M100.
2- Mells Griot horizontal and vertical translation stages, (0.01 mm resolution) with a fiber holder assembled on a Mells Griot bench base.
3- Laboratory jacks for raising the Mells Griot bench base [Two].
4- HeNe laser: Coherent, Model # 31-2090-000 on a horizontal and translation stage, all assembled on a ¼ m bench.
5- Approximately 2m long, $50\,\mu m$ core diameter, GI fibers (Orange Color), NA = 0.22 [Two].
6- Additional optical fiber holders [Two].
7- Horizontal and vertical stages assembled on a (½ m) bench base: Ealing Electro-Optics.
8- Translation stage assembled on a (¼ m) optical bench [Two Sets]: Ealing Electro-Optics.
9- Bench base: Ealing Electro-Optics.
10- General purpose holders [Two].
11- Thin lens holder.
12- Magnifying lens.
13- Thin lens, focal length 5 cm.
14- Meter stick.
15- Plate (black).
16- Black screen.

PRELAB ASSIGNMENT

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

INTRODUCTION:

Examples of optical fiber misalignments include longitudinal, lateral and angular misalignments. Longitudinal and lateral misalignments of two *identica*l fibers are illustrated in Figure 1. Longitudinal misalignment (see Figure 1a) refers to the fibers' end separation z. Lateral misalignment refers to the separation x of the fibers' axes (see Figure 1b). Large optical power loss can occur when the two fibers are misaligned. The degree of loss due to fiber misalignment is a function of the core diameter, the refractive index profile and to a lesser degree on the operating wavelength.

Generally, in the case of longitudinal misalignment ($z > 0$), a millimeter and sometimes *a fraction of a millimeter* can cause large optical power loss. However, in the case of lateral misalignment ($x > 0$), the degree of loss depends mostly on the core diameter. When the fiber's core size is small, a few *micrometers* can result in a large power loss. The fibers used in this experiment have small core diameters. Thus, large losses are expected to occur for x in the micrometer range and therefore, one has to be *extremely careful* in aligning the two fibers in the lateral direction and also in measuring fibers' separation in this direction. When x exceeds the *core diameter* of the fiber, almost no optical power is coupled from one fiber into the other.

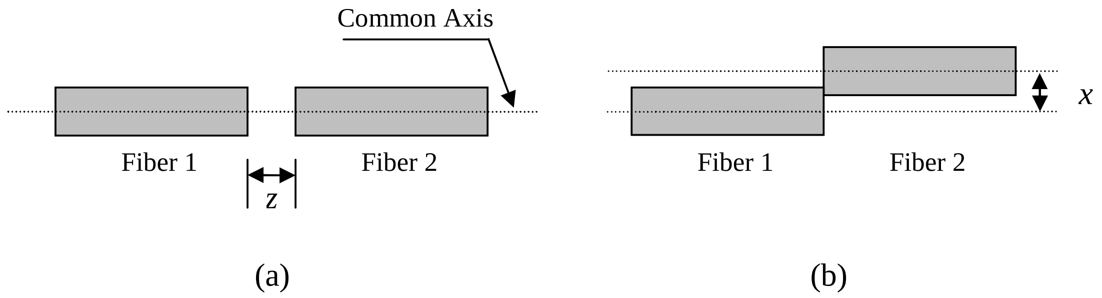

Figure 1: **(a)** Longitudinal Misalignment ($z > 0$). **(b)** Lateral Misalignment ($x > 0$).

In this experiment, the longitudinal and lateral misalignment losses of two identical GI fibers will be measured. Light from a HeNe laser will be coupled into the input end of fiber 1 and an optical power meter will be connected to the output end of fiber 2. The misalignment loss can be found from the optical power reading.

The following expression can be used to estimate the longitudinal misalignment loss L_z (**in dB**) between two identical fibers:

$$L_z \approx 3(NA/a)z, \text{ for } z >> a \qquad (1)$$

Where NA is the numerical aperture of the fiber, a is the *core radius* and z is the longitudinal serration of the two fibers. For multimode GI fibers with a parabolic refractive index profile, the lateral misalignment loss L_x (**in dB**) can be estimated theoretically using the following simple expression:

$$L_x \approx -10\log[1-0.75(\frac{x}{a})], \text{ for } 0 < x < 0.4a \qquad (2)$$

Where a is the core radius and x is the lateral separation. Notice that equation (1) has a limited, but very practical range of applicability.

Determination of the fiber misalignment loss should be straight forward to do experimentally. However, there are two difficulties. First, two fibers with relatively small cores (i.e. $2a = 50\mu m$) have to be well-aligned, which needs patience and accuracy. The experimental procedure details a possible method for doing this task. The second difficulty arises because the optical power meter has a finite sensitivity. It cannot measure optical power below a certain level. For the HeNe light, the readings of the optical power meter used in this experiment becomes unreliable below about

$-62\,dBm$ (using the $\lambda = 0.85\mu m$ setting). In addition, since the fiber misalignment introduces additional power losses, the optical power reaching the optical power meter can become too small to measure when the HeNe laser light is coupled directly to fiber 1. For this reason, the light from the HeNe laser source is first focused into fiber 1 using a thin lens in order to maximize the input power.

PROCEDURE:

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

[WARNING: DO NOT LOOK DIRECTLY AT THE FIBER'S END WHEN THE FIBER CARRIES LASER LIGHT. THIS MAY CAUSE SERIOUS EYE DAMAGE].

1- Turn the HeNe laser source.
2- Connect one end of fiber 1 to the first z stage (Z1), as shown in Figure 2 (main experimental setup).
3- Connect one end of fiber 2 to the first $x-y$ (XY1, Mills Griot) and the other end to the optical power meter.
4- Align the fibers ends. The two fibers must be first *visually* aligned. Use the following procedure for the visual alignment:

- Use the magnifying glass as an aid, because the fibers' tips may be hard to see and use a *black background* for much improved visibility. Use the black plate and screen to produce a black background.
- Adjust the Z1 translation stage until the fibers' tips are very close to each other ($z \approx 1mm$). [*Do not allow the tips to touch each other*].
- Adjust the horizontal stage (x- direction) while *looking from above* to bring the fibers' tips closer until they are aligned in the horizontal direction.
- Adjust the vertical stage (y- direction) while *looking from the side* to bring the fibers' tips closer until they are aligned in the vertical direction.
- Repeat the above two steps as necessary until the fibers axes are aligned.
- Reduce z further until the gap between the two tips is almost invisible and the two fibers appear almost a single continuous fiber, while taking care that the two tips don't touch.

5- Now, refer to the HeNe lens laser/fiber setup shown in Figure 3. Adjust the distance from the laser output end to the thin lens to about $20-40cm$. The laser light must pass through the center of the lens (exactly) and should be perpendicular to the lens. [*Refer to the laser/fiber lens coupling procedure done in experiment 5*].
6- Adjust the distance from the tip of fiber 1 to the thin lens initially to about $7cm$.

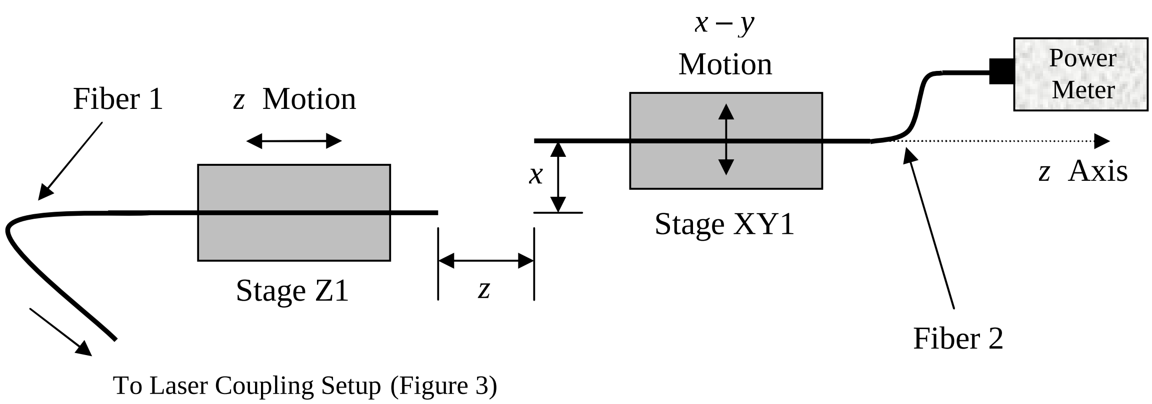

Figure 2: The Main Experimental Setup.

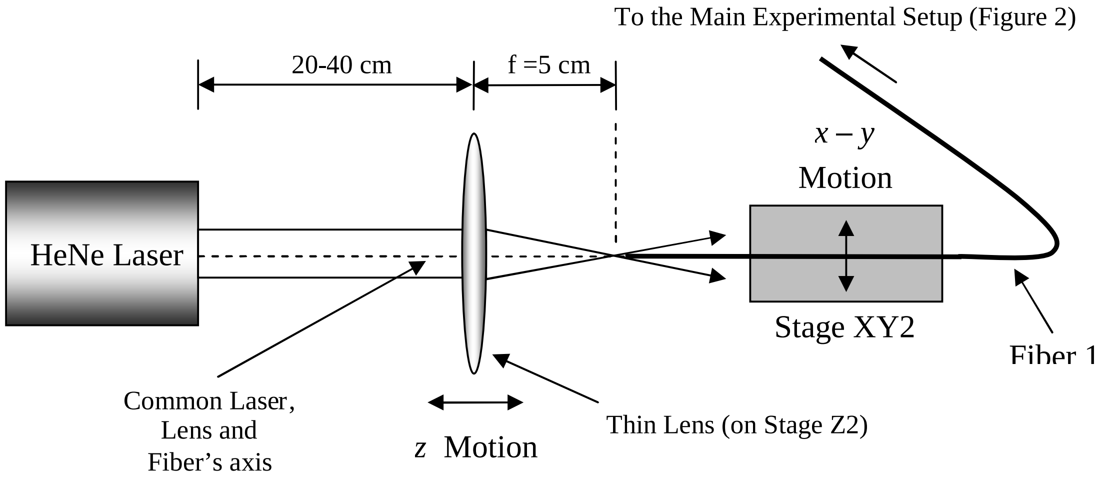

Figure 3: Laser Coupling Setup.

7- Move stage XY2 in the horizontal and vertical directions until the focused laser light hits the tip of fiber 1. *[You will see somewhat faint light leaving the other end of fiber 1 when this occurs*].
8- Adjust the XY2 stage until maximum amount of light is seen leaving fiber 1.
9- Adjust stage Z2 to bring the fiber's tip closer to the focal point and visually monitor the level of scattered light from the output end of fiber 1 (remember the fiber's tip must be at 5 cm for absolute maximum power coupling).
10- Repeat steps 8 and 9 iteratively until the level of scattered light from the output end of fiber 1 is sufficiently high.
11- Turn the power meter on and set it to the dBm scale and $\lambda = 0.85 \mu m$.
12- The power meter should show a substantial reading (much more than -60 dBm). If the meter's reading is too low, visually check the fibers' alignment (Figure 2) or the location of fiber 1 tip with respect to the focused laser light (Figure 3). You may also need to check the connection to the power meter.
13- Again move the XY2 stage in the horizontal and vertical directions and this time monitor the power meter until you get maximum meter reading.
14- Move the second z translation stage (Z2) slightly backward and forward to fine tune the laser power coupling to fiber 1 by observing the power meter reading, until

you obtain maximum power coupling. [*Fiber 1 must be exactly at the focal point for maximum power coupling*].

15- Use the power meter's reading to also fine tune the fibers' alignment (Figure 2), until you obtain maximum power reading [*Do not change the value of* z *while you are doing this step*].

16- Record the maximum power in the *second row* of table 1.

17- Rotate the z stage *knob clockwise* to increase z and the take the meter's reading every 0.2 mm. [*One full rotation of Ealing translation stage equal 1.00 mm*]. Record the results in table1.

18- Reduce z as much as possible by rotation the stage counterclockwise until the gap is almost invisible again.

19- Adjust the $x-y$ stage again for maximum power reading and record the result in the *bottom* row of table 2.

20- Move the horizontal stage in steps of $\Delta x = \pm 5\mu m$ and record the optical power meter readings in table 2. [*The separation between the individual marks of the Mills Griot micrometer corresponds to* $10\mu m$ *and a full turn = 0.5 mm, use the magnifying lens for a better view of the markings on the micrometer*].

z (mm)	P (dBm)
0	
0.2	
0.4	
0.6	
0.8	
1.0	
1.2	
1.4	
1.6	
1.8	
2.0	

Table 1: Variation of the Received Optical Power in dBm Versus the Longitudinal Displacement z.

$x(\mu m)$	P (dBm)	$x(\mu m)$	P (dBm)
-65		5	
-60		10	
-55		15	
-50		20	
-45		25	
-40		30	
-35		35	
-30		40	
-25		45	
-20		50	
-15		55	
-10		60	
-5		65	
0		-	

Table 2: Variation of the Received Optical Power in dBm Versus the Lateral Displacement x.

<u>REPORT REQUIREMENTS:</u>

1- Plot the longitudinal misalignment loss [$L_z \equiv P(z) - P(0)$] versus z in millimeter, where $P(z)$ is the dBm powers recorded in table 1 and L_z is longitudinal alignment loss in dB. [*Recall: the difference between dBm powers results in dB power loss. There is no such thing as dBm power loss*].

2- On the same figure, plot the theoretical longitudinal loss using equation (1). Compare the theoretical and experimental results.

3- Comment on the experimental longitudinal loss versus longitudinal separation and comment on the linearity of the resulting plot. How critical is the longitudinal separation?

4- Plot the lateral misalignment loss $L_x \equiv P(x) - P(x)\big|_{\max}$ versus x in micrometer. Where $P(x)$ is the dBm powers recorded in table 2, $P(x)\big|_{\max}$ is the maximum measured dBm power that appears in table 2 and L_x is the lateral alignment loss in dB. [*Note: if* $P(x)\big|_{\max}$ *is not the same as* $P(0)$*, then reset the x-axis, so that the maximum received dBm power occurs at* $x = 0$].

5- On the same graph, plot the theoretical results using equation (2), keeping in mind that equation (2) has a limited range of applicability. Compare the theoretical and experimental results.

6- Comment on the experimental lateral loss versus lateral separation including symmetry. How critical is the lateral separation?

7- Discuss and comment on the experimental results and the experiment in general. Is the experiment easy to do? What precautions do you have to observe for accurate measurements? Write a summary and some conclusions.

<u>**QUESTIONS:**</u>

1- Based on the experimental data, which displacement is more critical, the lateral or the longitudinal? Explain briefly.

2- Do you think this experiment will be easier or harder to do if the fibers used are single mode? Explain briefly. Give at least two reasons to justify your answer.

3- Briefly explain why it was necessary to use the thin lens?

4- Given two types of multimode GI optical fibers: Fiber 1 has a numerical aperture of 0.22 and a core radius of $50\,\mu m$ and fiber 2 has a numerical aperture of 0.275 and a core radius of $62.5\,\mu m$. Use equations (1) and (2) to answer the following questions:

a) For which fiber is the longitudinal misalignment more critical?

b) For which fiber is the lateral misalignment more critical?

EXPERIMENT 7
FIBER SPLICING AND INTRODUCTION TO THE OTDR

OBJECTIVES:

The objectives of this experiment are to observe the steps used in making a fiber splice and to introduce the Optical Time Domain Reflectometer (OTDR).

EQUIPMENT REQUIRED

1- Fiber splicing machine.
2- Two short lengths of single fiber cables (multimode $50\,\mu m$ GI fiber cables, Orange).
3- Jacket stripers for fiber outer jacket, inner and buffer layer.
4. Heat shrink tube.
5- A 100m long multimode $50\,\mu m$ GI fiber (Orange).
6- OTDR: Agilent Technologies E6000 Mini OTDR Main Frame with E6005A Module (850/1300 nm High Performance Multimode Module).

PRELAB ASSIGNMENT:

Read the introduction to this experiment before attending the laboratory.

INTRODUCTION:

The first part of this experiment shows a demonstration of fiber splicing. In order to understand the steps involved in making a fiber splice, you need to know more about the structure of the optical fiber cable used in this experiment. The structure of the fiber cable is shown in Figure 1. The cladding surrounds the core and together they form a unit that cannot be separated. The fiber used in the demonstration has a standard cladding diameter of $125\,\mu m$ and a core diameter of $50\,\mu m$. The cladding is surrounded by a primary coating layer $250\,\mu m$ in diameter. The primary coating is surrounded by a protective inner jacket (blue) and the inner jacket is surrounded by textile fibers (kevlar) in order to strengthen the fiber cable. Kevlar is the strength member of the cable. Finally, the kevlar strength member is surrounded by the outer cable jacket (orange).

All the layers are designed to give protection to the fiber, starting from the fiber buffer layer up to the outer jacket. When the buffer layer is removed, the core/cladding combination becomes fragile and can easily break. Bare core/cladding combination is also very thin and sharp and can cause injuries (it is as sharp as broken glass). Protect yourself, specially your eyes when the fiber is cleaved.

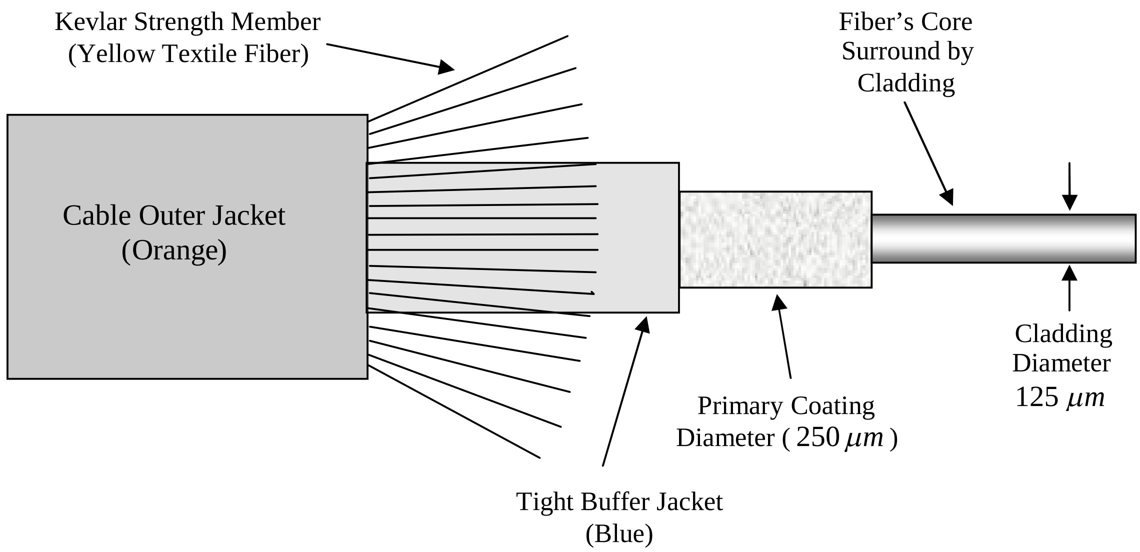

Figure 1: Structure of a Tight Jacket Single Fiber Cable with Kevlar Strength Member.

The Time Domain Reflectometer (OTDR) is a specialized piece of equipment used to test and diagnose optical fibers. It can be used to measure fiber attention and to locate splices, connectors, fiber's fault and fiber ends. The test is done from one end of the fiber with no need for measuring equipment on the output end of the fiber. The principle of operation of the OTDR is quite simple. However, actual implementation is quite complicated, leading to highly advanced piece of equipment.

The OTDR sends a narrow pulse of light into the fiber under test and then it measures the reflected light as a function of time, which is then converted to distance along the fiber and shows it graphically on the screen. This function is identical to the operation of the RADAR. Figure 2 shows a narrow pulse of light being launched by the OTDR at $t = 0$. Figure 2 also shows a fiber connector located a distance L along the fiber. A connector is known to cause part of the light energy to reflect back towards the OTDR. The launched pulse takes $t = L/v$ seconds in order to reach the connector, where v is the light velocity *inside the fiber*. When the pulse reaches the connector, a small portion of the light energy is reflected backwards towards the OTDR and most of the pulse energy continues to travel along the fiber. Figure 3, shows the reflected and transmitted light pulses in the time interval $L/v < t < 2L/v$ (i.e. after the light is reflected from the connector and before the reflected light reaches the OTDR). At $t = 2L/v$ the reflected light reaches the OTDR and the OTDR sensors measure the amount of reflected pulse power and the time of arrival. Using $t = 2L/v$, the OTDR then converts the time of arrival to length along the fiber (i.e. $L = vt/2$). The refractive index n of the fiber must be programmed into the OTDR, because $v = c/n$. If the refractive index is not entered correctly, then the OTDR obviously will display the wrong location of the connector.

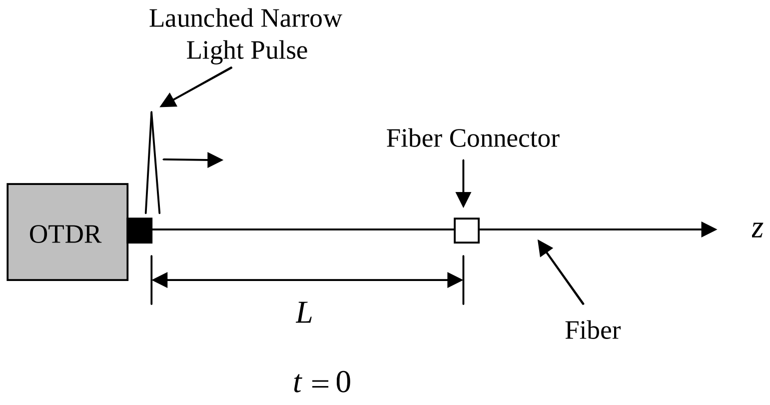

Figure 2: Launched Narrow Light Pulse at $t = 0$.

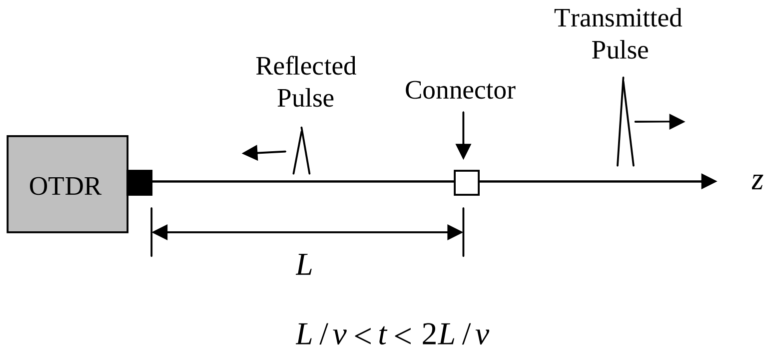

Figure 3: Reflected and Transmitted Light Pulses in the Time Interval $L/v < t < 2L/v$.

Actually, the OTDR can also sense the backscattered light due to Rayleigh scattering and uses it to display the reflected light power and the amount of optical power remaining in the fiber and a function of distance along the fiber. A typical OTDR trace is shown in Figure 4. The bold curve is called the OTDR trace, which shows the *reflected* light power in dB as a function of distance from the OTDR. The line is continuous because of the continually scattered light which travels backwards to the OTDR sensor.

The vertical axis is a dB scale which shows the dB level of the reflected power and the horizontal scale represent the distance along the fiber in meters or kilometers. All the sudden *discontinuities* in OTDR trace are called *events*, which can be caused by splices, connectors, fiber breaks or fiber ends. Events can be reflective ($z = L_2$ and $z = L_3$) or non-reflective ($z = L_1$). Reflective events are characterized by spikes (sudden *increase* in the dB power level). The height of the spike is related to the amount of the reflected power. Reflective events may be due to a *poor splice*, fiber connector, fiber break or fiber end. Non-reflective events are characterized by a sudden *decrease* in the power level. Non-reflected events may be due to a *good splice* or fiber *bends*.

The slope of the straight line segments between any two events gives the fiber attenuation in dB per unit length. For instance, we know that the dB power level at

$z = L_1$ is P_1 and the dB power level at $z = L_2$ is P_2 . We can then calculate the fiber attenuation per unit length using:

$$\propto_{dB} = \frac{P_1 - P_2}{L_2 - L_1} = \frac{|\Delta P|}{|\Delta L|} \qquad (1)$$

Thus lines with high slopes have large fiber attenuations in dB per unit length and vice versa. Non-reflective events can be caused by fiber splices. The splice loss can be calculated by taking the difference in the dB power level. For instance, the non-reflective event immediately to the left of $z = L_1$ causes a dB loss of $\Delta P = P_o - P_1$. The fiber end ($z = L_3$) can be reflective or non-reflective. The fiber end is typically followed by background noise trace.

The OTDR is a very sophisticated piece of equipment that needs care, cleaning and sufficient training to operate it correctly. There are many parameters that must be correctly set in order to obtain a reliable and correct trace. For instance, the OTDR must be given information about the fiber, particularly the refractive index and the operating wavelength. An error in the refractive index leads to error in the display of distance. The OTDR can be run either in manual or automatic modes. It has a number of facilities such as trace printing and storage. In this experiment you will learn how to generate a trace and measure the fiber's length and attenuation from the generated OTDR trace.

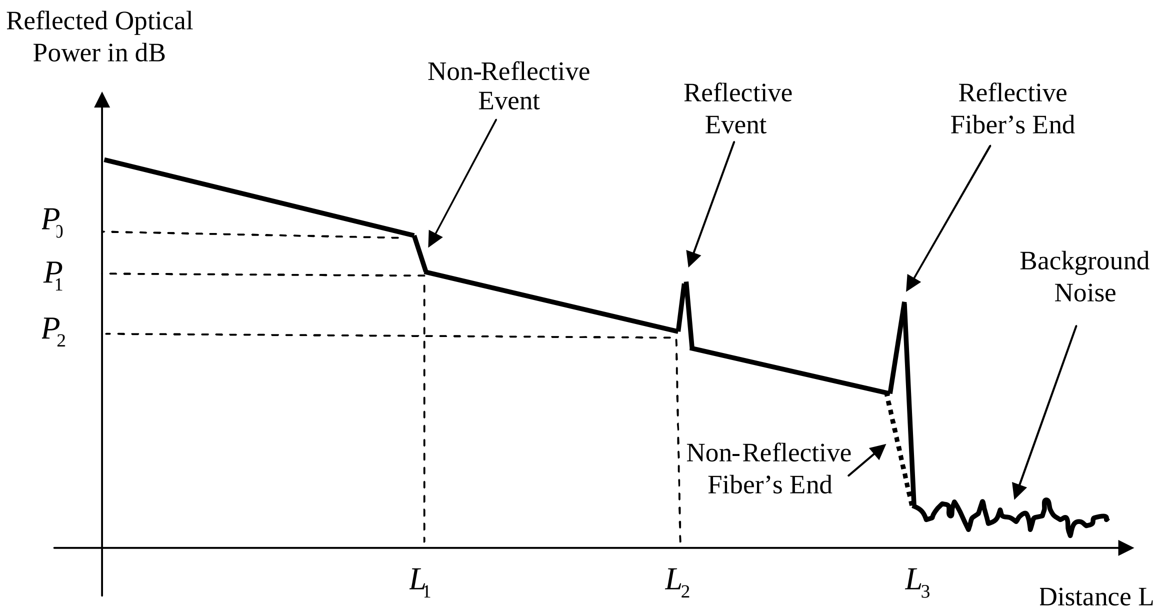

Figure 4: Typical OTDR Trace Showing the Locations of Reflective Events, Non-Reflective Events and Fiber's End.

The spectral loss in dB/Km of the fiber used in this experiment is shown in Figure 5.

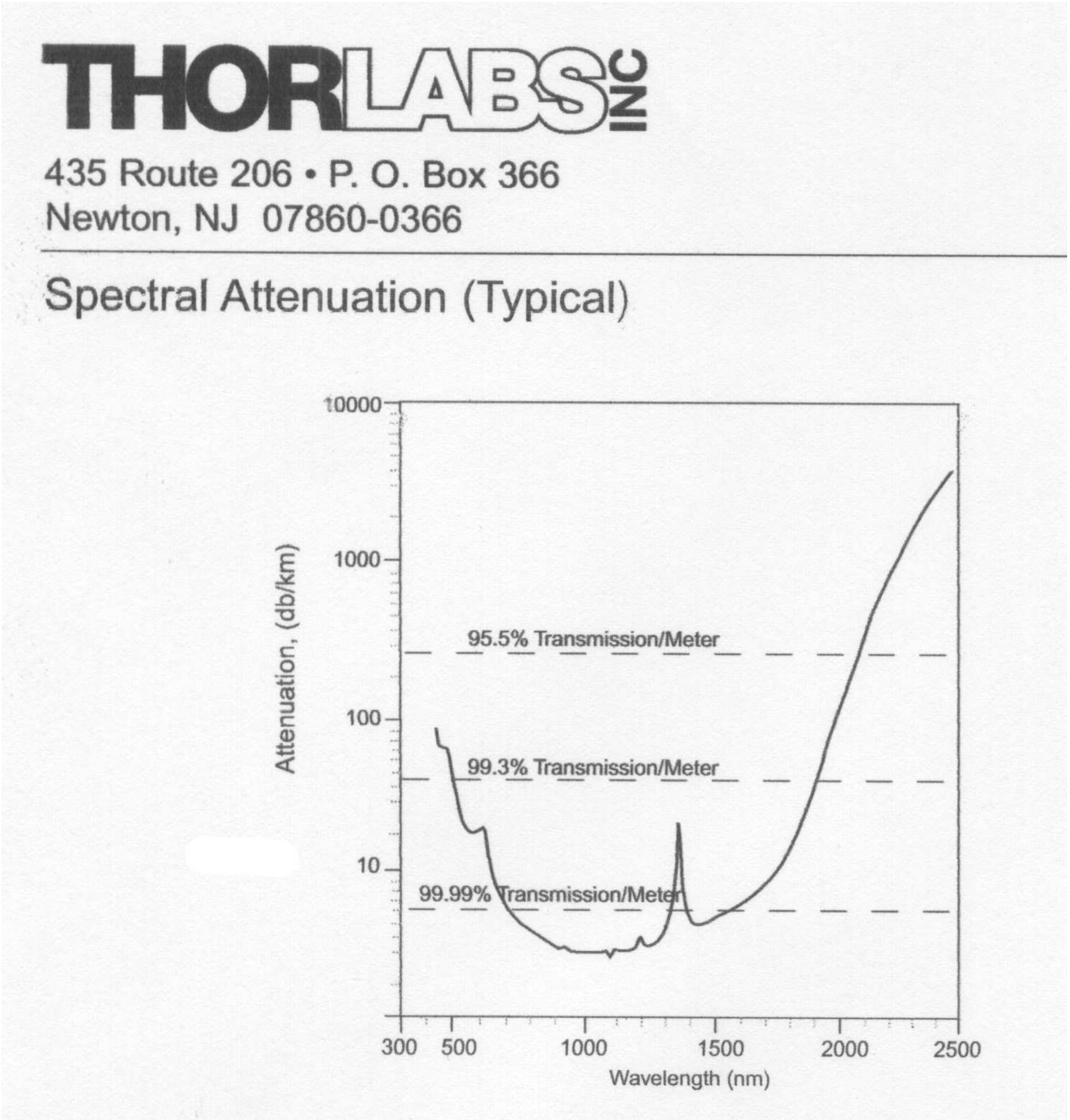

Figure 5: Spectral Loss in dB/Km for the Test Fiber (Manufacturer's Data).

<u>PROCEDURE:</u>

PART A: **FIBER SPLICING (DEMONSTARATION ONLY).**

1- Before the fiber is spliced, the layers surrounding the cladding must be removed and the fiber must be properly cleaved. The laboratory instructor will demonstrate the steps involved in the removal of the various layers, which are briefly summarized below:

- Cut and remove the outer jacket (orange) with the outer jacket remover tool.
- Cut and remove the extra kevlar with sharp scissors.
- Cut and remove the inner jacket (blue) with the inner jacket remover tool.
- Cut and remove *part* of the primary coating with the primary coating removal tool.
- Cleave the fiber end with the fiber cleaving tool.
- Clean the fiber with an appropriate chemical.

- Repeat the above steps for the second fiber.

2- Now the two fibers are ready to be inserted into the fiber splicing machine. The splicing machine is largely automatic. The machine uses precession optics and precession movements to insure that fiber misalignment losses are minimal, before the two fibers are fused together. The fibers ends are permanently spliced by application of heat using highly controlled electric discharge. Observe the procedure used to make the fiber splice. The splicing machine gives a reading of the splice loss after the splice is formed. [**Read and record the splice loss. Include the splice loss in your report**].

3- After the fibers are successfully spliced, a special tube is inserted around the spliced section of the fibers and heat shrunk in order to protect the recently formed splice.

PART B: INTRODUCTION TO THE OTDR.

[**The following is an introductory OTDR practice session that you should perform with the help of your laboratory instructor. If you have any difficulties consult with your instructor or refer to the appropriate page in the OTDR manual. This practice session is necessary to successfully do the next experiment (experiment 8). Pages 39-54 of the OTDR manual contain all you need to know to run this practice session. Ask the laboratory instructor to give you a copy].**

1- The 100 m long fiber (orange) reel should only be connected to the OTDR by the laboratory instructor or the laboratory technician. The fiber connector and the input end of the OTDR are very sensitive, especially to dirt, even by a small amount. They should be both cleaned before the fiber is connected to the OTDR. There is a special cleaning procedure, which the laboratory instructor or the laboratory technician should do before connecting the fiber to the OTDR. ***Do not remove the fiber from the OTDR***.

2- Turn the OTDR on and wait for the self test to end.

3- You should see the “OTDR Application Screen”, which provides a number of selections.

4- Select the “OTDR MODE”. Use the “CURSOR” key to highlight the “OTDR MODE” and press the “SELECT” key. [*To learn how to use the “CURSOR” key and the “SELECT” key, refer to pages 46-48 of the OTDR manual*].

5- You should now see an *empty* trace window. Push the “POPUP MENU” key.

6- You should now see the “POUP PANEL”. [*To learn more about the “POUP PANEL”, refer to pages 48-49 of the OTDR manual*].

7- Use the “CURSOR” key to highlight “SETTINGS”, and then press the “SELECT” key.

8- You should now see the OTDR “SETTINGS MENU”, including wavelength. The wavelength should be set to 855 nm for the first part of this session. If the wavelength already reads 855 nm, then don’t change it. If it is set to 1310 nm, change it to 855 nm.

9- Use the “CURSOR” key to highlight “AUTO” near the bottom left hand side of the screen. Then press the “SELECT” key.

10- Highlight “OK” and press “SELECT”.

11- You should now see the blank trace window again. You are now ready to run your first OTDR measurement.

12- Press the blue (RUN/STOP) key to start the trace and wait until it ends or the trace is free of noise. [*This may take sometime, so be patient*].
13- You should now see an OTDR trace similar to the one shown in Figure 6, which has been generated using a 100m long fiber (the same type of fiber you are using) at $\lambda = 855\,nm$. The OTDR trace shown in Figure 6 has been annotated for clarity.
14- In Figure 6, the *current vertical scale* is set to 5 dB/division and the *current horizontal scale* is set to 19.99 meter/division.
15- Push the *upper* "CURSOR" key to select "MARKER A" and move it the fiber's start (at z = 0), using the "CURSOR" *right/left* keys. [*Don't move it if it is already there*].

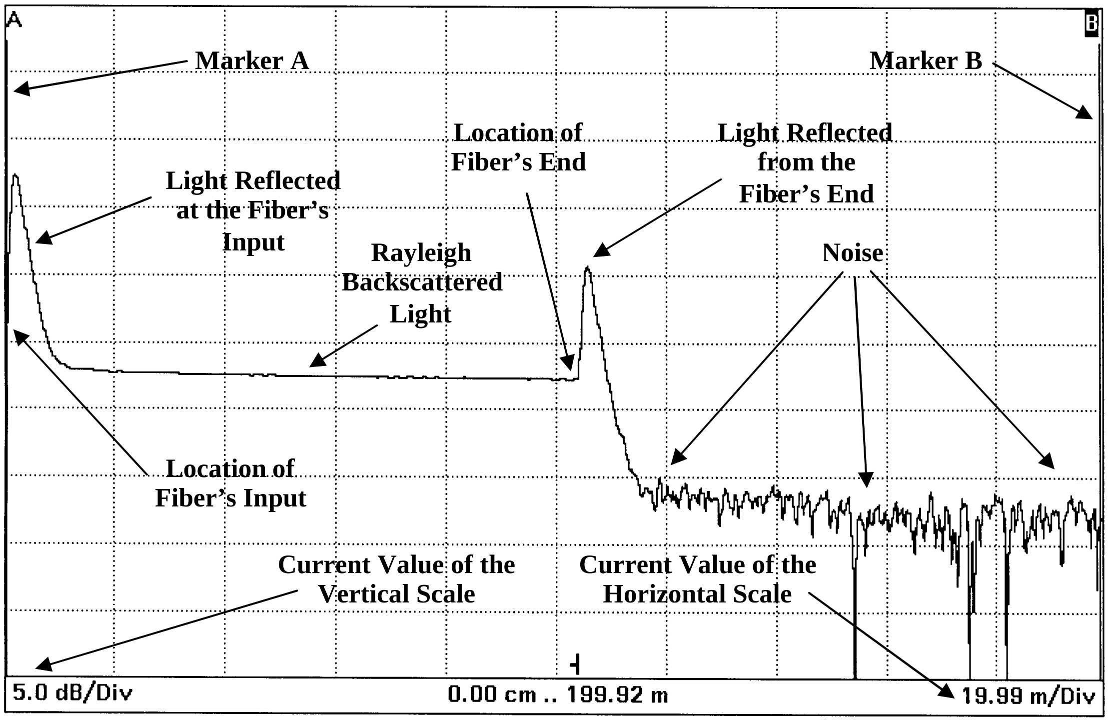

Figure 6: OTDR Trace for a 100 Meter long $50\,\mu m$ GI fiber Showing Reflected Light from both the Input and Output Fiber's Ends and the Current Locations of Markers A and B. The Trace was Generated at $\lambda = 0.855\,\mu m$.

16- Push the *upper* "CURSOR" key to select "MARKER B" and move it the location of the fiber's end, using the "CURSOR" *right/left* keys. [*To learn how to select and move a marker, consult the OTDR manual, page 46*].
17- Read the A-B distance in the "PARAMETER WINDOWS" *below the trace* (not shown in Figure 6). This gives the length of the fiber. Record the value in the first row of table 1.
18- The straight line between the fiber's start and fiber' end is due to Rayleigh backscattered light. The *slope* of this line gives the loss in dB per unit length.
19- In Figure 6, the line *appears* to have a zero slope (i.e. horizontal). In reality it has a non-zero slope. Use the "ZOOM" feature of the OTDR to decrease the vertical scale down to 0.1 dB/division for better details. The generally decreasing nature of this line should be very clear now. [*To learn how to change the vertical as well as the horizontal scale, read about ZOOMING, on page 49 of the OTDR manual*].

20- Move marker A to about 20 m.
21- Move marker B to about 90 m.
22- Read and record the distance (distance A-B) between the two markers in the 2nd row of table 1.
23- In the OTDR "PARAMETER WINDOWS", read the value of the "**2pt.L**" (i.e. two point loss or the loss in dB between markers A and B). Record the value in the 3rd row of table 1.
24- Calculate the fiber's attenuation in dB/Km (using equation 1) and record its value in the 4th row of table 1. Compare the result with the manufacturer's data (see Figure 5).
25- **Print the OTDR trace and include the printout in your experimental report.**
26- Go to the "SETTINGS" menu again and change the wavelength to 1310 nm. Highlight "AUTO" and select "OK". [*To learn how to change the wavelength, refer to pages 48-52 of the OTDR manual*].
27- Repeat steps 12-25. Of course, this time the trace should be generated at $\lambda = 1310\,nm$. [*Make sure that the printed trace to be included in your experimental report indicates the correct wavelength*].
28- Compare the fiber lengths measured using $\lambda = 855\,nm$ and $\lambda = 1310\,nm$.
29- Compare the fiber loss in dB/Km at the two different wavelengths.
30- Discuss the experimental results and make appropriate comments and conclusions.

Fiber's Length (m)	
Distance A-B (m)	
Fiber's Attenuation Over Distance A-B (dB)	
Fiber's Loss (dB/Km) [Measured]	
Fiber's Loss (dB/Km) [Manufacturer's Data]	

Table 1: Summary of OTDR Measurements for $\lambda = 855\,nm$.

Fiber's Length (m)	
Distance A-B (m)	
Fiber's Attenuation Over Distance A-B (dB)	
Fiber's Loss (dB/Km) [Measured]	
Fiber's Loss (dB/Km) [Manufacturer's Data]	

Table 2: Summary of OTDR Measurements for $\lambda = 1310\,nm$.

QUESTIONS:

1- The fiber used in this experiment is 100m long. Suggest two reasons for why the OTDR measurements of the fiber's length is not exactly 100 m. [Hint: $v = c / n$].

2- Estimate how long (in seconds) it takes (from the moment of pulse launch) before the reflected light from the fiber's end reaches the OTDR detector. [Hint: first estimate the speed of light inside a silica fiber. The refractive index of silica glass is *approximately* 1.5].

3- The OTDR has a feature for changing the pulse width. OTDR pulses range from nanosecond to microseconds. Estimate the spatial length (in meter) of a 5 nanosecond pulse inside the fiber.

4- Repeat question 3 for a 5 microsecond pulse.

5- Briefly explain why the *slope* of the Rayleigh backscattered light changes when λ changes? Why is it important to know the slope?

EXPERIMENT 8

OTDR MEASUREMENT OF FIBER LENGTH, ATTENUATION AND SPLICE LOSS

OBJECTIVES:

In this experiment, the fiber's length, fiber's attenuation and splice loss of a relatively short unknown optical fiber link will be measured using the OTDR at two different operating wavelengths.

EQUIPMENT REQUIRED

1- OTDR: Agilent Technologies E6000 Mini OTDR Main Frame with E6005A Module (850/1300 nm High Performance Multimode Module).
2- Unknown length of *two different types* of fibers connected together with *three* splices (two *fusion* splices and one *mechanical* splice). The fiber types are: $50\,\mu m$ multimode GI (orange) and $62.5\,\mu m$ multimode GI (gray).

PRELAB ASSIGNMENT:

Read the introduction to this laboratory and review the previous experiment and the OTDR manual to prepare for this experiment.

INTRODUCTION:

Figure 1 shows an imaginary OTDR trace of an optical fiber link in which three different types of fibers are connected together to form the entire link. This arrangement is not very common in practice, but some existing links use more than one fiber type. The reason we know that three different types of fibers exist in the link (whose OTDR scan is shown in Figure 1) is because there are three distinct straight lines (due to Rayleigh scatter) with *different* slopes. The first line segment has a slightly larger slope than the second straight line segment. This means fiber 1 is slightly lossier than fiber 2. Therefore, they must be different types of fibers.

From the trace, we also know that the lengths of fibers 1, 2 and 3 are L_1, $L_2 - L_1$ and $L_3 - L_2$, respectively. We already know how to find the fiber's attenuation in dB per unit length by finding the slope of each straight line segment, since we did this in the previous experiment. The splice between fibers 1 and 2, located at $z = L_1$, is non-reflective because of the sudden *decrease* in the reflected power without a spike. Non-reflective event can be due to either a good splice, fiber break or fiber bends. We can find the loss of this splice, simply by calculating the difference in the power levels before and after the splice (i.e. $P_1 - P_1^{'}$).

The joint between fibers 2 and 3, located at $z = L_2$, is reflective because of the sudden *increase* (*with a spike*) in the reflected power (if the sudden increase has no spike, then it must be interpreted as a non-reflective event). The joint between fibers 2 and 3 could be due to either a poor splice or a connector. The loss due to this joint can be calculated as before (i.e. $P_2 - P_2^{'}$). The trace also shows a reflective fiber's end at $z = L_3$. This is due to light reflection at the glass/air interface (Fresnel reflection) at the fiber's end. If desired, the fiber's end can be made non-reflected. This can be done by immersing the fiber's end into *an index-matched fluid* (a fluid that has the same refractive index as glass) to minimize Fresnel reflection. Alternatively, it is also possible to wrap the fiber's end several times around a tight bend to produce a non-reflective end. The tight bend causes large power loss, without reflection. In this manner, the light reaching the un-terminated fiber's end becomes too weak to detect.

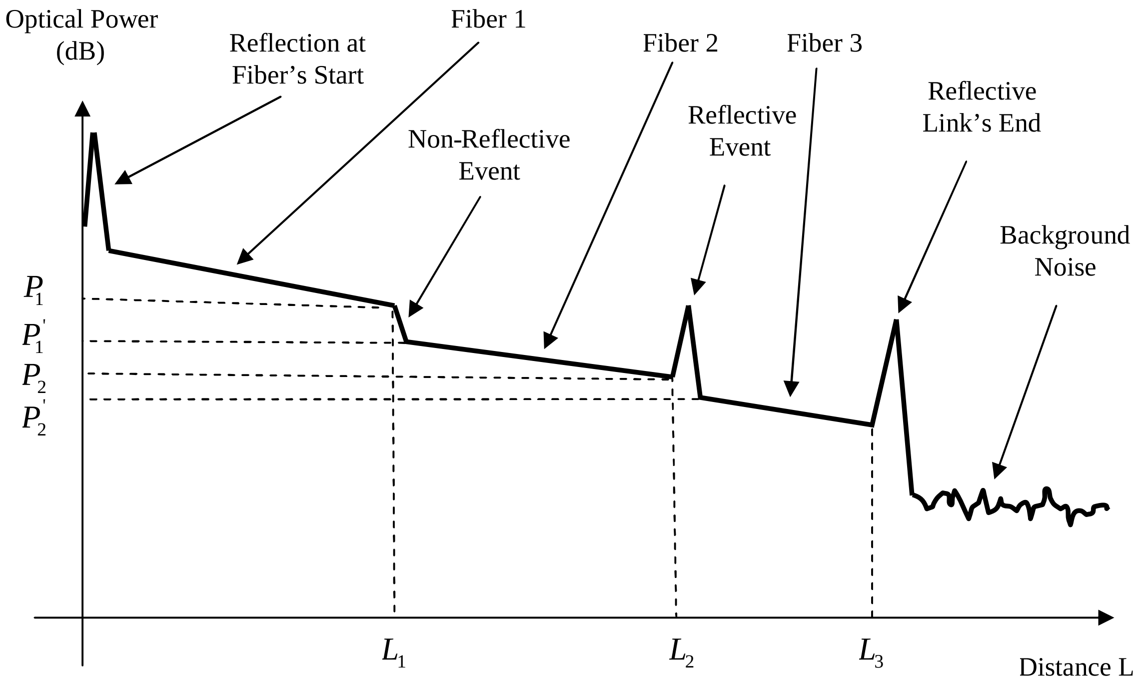

Figure 1: An Imaginary OTDR Trace of an Optical Fiber Link Consisting of Three Different Fiber Types Spliced Together. The OTDR Trace Shows the Locations of the Reflective Events, the Non-Reflective Events and the Link's End.

The OTDR trace shown in Figure 1 assumes that the three fibers used in the link have the same *Rayleigh scattering coefficients*. Rayleigh scattering coefficient is related to the *fraction of power scattered due to Rayleigh* scatter. For instance, suppose fiber 2 has a significantly higher Rayleigh scattering coefficient than fibers 1 and 3, then the OTDR scan of Figure 1 may be modified to the one shown in Figure 2. The OTDR trace due to Rayleigh scatter from fiber 2 appears as *power gain*. In this link, it is impossible to have optical power gain, because the system does not have optical amplifiers. The sudden rise in power is simply due to the higher percentage of power scattered from fiber 2. In reality the optical power in fiber 2 is less than the optical power in fiber 1.

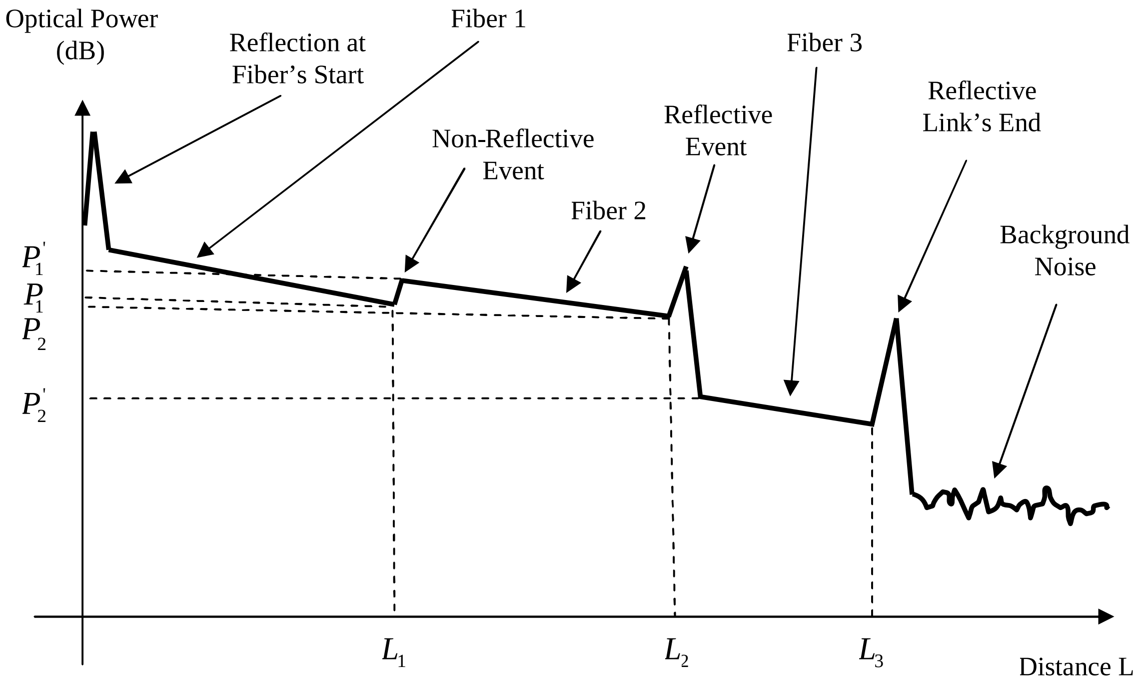

Figure 2: Sudden Rise in the Scattered Power when Fiber 2 has a higher Rayleigh Scattering Coefficient than Fiber 1 and Fiber 3.

When two fibers with different Rayleigh scattering coefficients are joined together, the joint loss *cannot be calculated* using the difference in power $P_1 - P_1'$ and $P_2 - P_2'$. The only way to compute the joint loss in this case is by first knowing the Rayleigh scattering coefficient of the two fibers. Unfortunately, we do not know the values of the Rayleigh scattering coefficients for the fiber types used in the experimental link. To summarize: when two different fiber types are joined together, the joint loss cannot be computed from the OTDR trace, unless the Rayleigh scattering coefficients of the two fibers are known.

The optical fiber link that you are going to examine in this experiment consists of two fiber types joined together using three joints. The first and second joints are fusion splices between two dissimilar fibers. The last joint is a *homemade mechanical splice* between two identical fibers. Thus, only the loss of this third joint can be computed, because it connects two identical fibers. In addition, because this splice is mechanical, its dB loss is expected to be relatively high.

PROCEDURE:

[**The test fiber should be connected by the laboratory instructor or the laboratory technician.** ***Do not remove the fiber from the OTDR. DO NOT LOOK DIRECTLY AT THE OUTPUT END OF THE FIBER***].

INVETIGATING A FIBER OPTIC LINK.

1- Read the fiber reel *letter* (e.g. A, B, C, etc.) and record it in the top row of table 1.
2-Turn the OTDR on and wait for the self test to end.
3- Select $\lambda = 855\,nm$ from the SETTINGS menu.

4- Select AUTO.
5- Press the RUN/STOP to generate an OTDR trace and wait for the averaging to end or the trace to be free of noise.
6- Print the trace. [*The printed trace should be included in your experimental report. The printed trace must show the correct wavelength*].
7- Find the distance from the fiber's start to the first splice (splice 1). Record the distance in table 1.
8- Zoom around splice 1 until you see it clearly and print the magnified OTDR trace. [*Change both the horizontal and vertical scales to see the details. Include the magnified trace in your report*].
9- Determine if the splice is reflective or non-reflective and record the result in table 1.
10- Repeat steps 7 - 9 for the second splice.
11- Repeat steps 7 - 9 for the third splice. In addition, compute the splice loss and record it in table 1.
12- Find the total link length and record it in table 1.
13- Find the total link loss in dB and record it in table 1. The total link loss can be found by finding the difference in dB *just to the right of the fiber's start* and *just to the left of the fiber's end.*
14- Find the loss in dB/Km for the first link segment and record it in table 1 (*Determine the slope of the straight line segment from just to the right of the fiber's start till the very beginning of splice 1, i.e. the left hand side edge*).
15. Repeat step 14 for link segments 2, 3 and 4.
16- Repeat steps 3-15 at $\lambda = 1310\,nm$. Record the result in table 2.
17- Compare the fiber lengths measured at $\lambda = 855\,nm$ and $\lambda = 1310\,nm$. Discuss.
18- Compare the losses (in dB/Km) of the four fiber segments at $\lambda = 855\,nm$ and indicate if the four segments are made of the *same* fiber type or *different* fiber types.
19- Compare the fiber losses (in dB/Km) and at $\lambda = 855\,nm$ and $\lambda = 1310\,nm$. Are those losses expected to be dependent or independent of λ ? Discuss.
20- Compare the measured loss of the third splice at $\lambda = 855\,nm$ and $\lambda = 1310\,nm$.
21- Discuss the over all experimental results and make appropriate comments and conclusions.

FIBER REEL LETTER ( )	
Location of splice 1 (m)	
Type of splice 1 (Reflective/Non Reflective)	
Location of splice 2 (m)	
Type of splice 2 (Reflective/Non Reflective)	
Location of splice 3 (m)	
Loss of splice 3 (dB)	
Type of splice 3 (Reflective/Non Reflective)	
Total link length (m)	
Total Link Loss (dB) [Including splice loss]	
dB Loss/Km of segment 1	
dB Loss/Km of segment 2	
dB Loss/Km of segment 3	
dB Loss/Km of segment 4	

Table 1: Summary of OTDR Measurements at $\lambda = 855\,nm$.

Location of splice 1 (m)	
Type of splice 1 (Reflective/Non Reflective)	
Location of splice 2 (m)	
Type of splice 2 (Reflective/Non Reflective)	
Location of splice 3 (m)	
Loss of splice 3 (dB)	
Type of splice 3 (Reflective/Non Reflective)	
Total link length (m)	
Total Link Loss (dB) [Including splice loss]	
dB Loss/Km of segment 1	
dB Loss/Km of segment 2	
dB Loss/Km of segment 3	
dB Loss/Km of segment 4	

Table 2: Summary of OTDR Measurements at $\lambda = 1310\,nm$.

QUESTIONS:

1- Is the *end* of the link reflective or non-reflective? If it is reflective, what can you do to make it non-reflective?

2- Is the third splice you found good or poor? Explain.

3- Are the types of fibers used in this experiment suitable for *a repeaterless* link 50 Km long and operating at $\lambda = 1310\,nm$? Explain briefly.

4- Using the experimental data for $\lambda = 1310\,nm$. What is transmission efficiency of the third splice? (Hint: $\eta = 10^{-0.1dB_{loss}}$).

5- Suppose that the input power to the experimental link at $\lambda = 855\,nm$ is $5mW$. Calculate the power remaining in the fiber *just before the fiber's end.*

6- In some cases, it is possible to immediately know if the link has more one type of fiber (without finding the fiber loss in dB/km). Explain.

EXPERIMENT 9
CHARACTERISTICS OF THE LIGHT-EMMITTING DIODE

OBJECTIVES:

The objective of this experiment is to measure some of the characteristics of the light emitting diode (LED). The LED characteristics that will be measured in this experiment are the LED linearity (for the output optical power versus input current relationship), I-V characteristics, and the LED angular emission profile.

EQUIPMENT REQUIRED

1- Optical power meter: INFOS, Model # M100.
2- Two laboratory jacks.
3- Two digital multimeters.
4- Infra-red LED. (GaAs Infrared Emitter, Siemens: LD 271L).
5- Power supply.
6- $1K\Omega$ resistor.
7- Rotational stage with adapter plate.
8- Cleaved $62.5\mu m$ GI optical fiber (2-5 meters long, Gray Color).

PRELAB ASSIGNMENT

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

INTRODUCTION:

The LED is an important element in fiber optics communication systems. It is used as a light source in multimode optical fibers. It is inexpensive and has a relatively fast response. The LED can be regarded as an ordinary diode, with the exception that it emits light which is generally proportional to the input current. The LED symbol is shown in Figure 1, which is identical to the symbol of the ordinary LED. The diode voltage V_d is defined with + polarity on the p terminal and the diode current I_d is defined to flow through the diode from the p to the n terminal, which is identical to the standard definitions of the voltage and current of the ordinary diode.

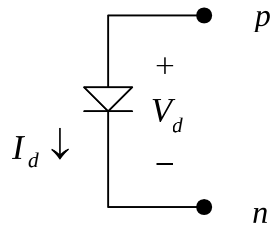

Figure 1: Symbol of the LED, Showing Definition of the Current and Voltage.

The LED must be *forward biased* in order for it to emit light energy. The light power P_o emitted by the LED is generally proportional to current I_d ($P_o \propto I_d$), provided $I_d > 0$. The center wavelength of the LED light emission depends on the bandgap energy of the material used in the fabrication of the LED. The diode used in this experiment emits in the *infrared* region of the spectrum, so you will not be able to see the emitted light without some aid.

The experimental setup used in part A of this experiment is capable only of measuring part of the emitted optical power (see Figure 3). Because we are interested in measuring the diode *linearity* with respect to the diode current, then we need only to detect a fraction of the emitted power, which is obviously proportional to the total power emitted, provide we *fix* the location of the optical power meter relative to the LED. It is thus important in this experiment *not to move* either the power meter or the LED after we start measurements.

The LED emits optical power over a wide range of angles and the output light intensity $I = I(\theta)$ is angle-dependent. Figure 2 shows the basic method used in part B of this experiment to measure $I = I(\theta)$. An optical fiber is first aligned so that its axis is *normal* to the light emitting area of the LED (i.e. $\theta = 0^o$). The fiber is then rotated in such away that its tip remains at a fixed distance d from the center of the light emitting area, while its axis makes angle θ (with respect to the normal). The other end of the fiber is connected to an optical power meter. The variation of the received optical power can then be used to find the angular emission profile of the LED.

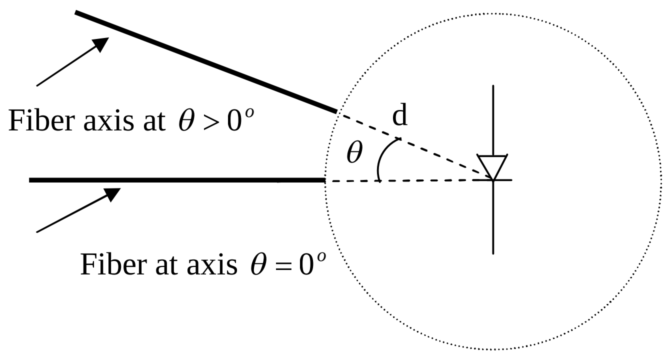

Figure 2: Basic Method for Measuring the Angular Emission Profile of the LED.

The LED used in this experiment has the following specifications:

1- Peak emission wavelength: $950 \pm 20 nm$.
2- Maximum forward current: $100\,mA$.
3- Forward voltage: $1.3V$ (typical).
4- Half angle: $\pm 25^o$.

PROCEDURE:

Part A: LED IV Characteristic and Linearity.

1- Connect the circuit shown in Figure 3. The ammeter should be connected in series with the $1K\Omega$ resistor in order to directly measure the diode current I_d and the voltmeter should be connected across the diode to directly measure the diode voltage V_d.

2- Set the power supply voltage to $V_s = 5V$.

3- Verify that the LED actually emits optical power. [*A mobile phone with camera can be used to view the light emitted by infrared LED's*].

4- Turn on the optical power meter and set it to dBm and $\lambda = 0.85\mu m$.

5- Bring the optical power meter as close as possible to the LED and observe the meter's reading. Try to obtain as much power as you could. [*Do not remove the optical power meter cover*].

6- Set the supply voltage to $V_s = 0V$. Record the values of I_d, V_d and the optical power meter's readings in table 1.

7- Slowly increase V_s until $V_d = 0.1V$. In table 1, record I_d, V_d and the optical power meter reading. [*There is no need to measure and record the value of V_s in this step*].

8- Repeat step 7 for $V_d = 0.2V$, $0.3V$, …., up to $1.0V$. [*Do not record the value of V_s at this point*. *Also, be careful that I_d is initially very small (in the μA range)*].

9- Now, set the supply voltage to $V_s = 2V$. Record the measured values of I_d, V_d, the optical power meter reading and V_s in table 1.

10- Repeat step 9 for $V_s = 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 6.0, ...9.0, 9.5, 10.0\,V$ [*Note the change in the step size of V_s*].

11- Covert the measured optical power in dBm (fourth column of table 1) to mW and record the value in column 5 of the same table. Calculate the normalized power P_N and record the values in column 6 of table 1.

12- Plot P_N versus I_d.

13- On the same graph, plot a *straight line* (*you may need more than one separate straight line to fit with the experimental graph*) that best fits the experimental graph. Comment on the linearity of the output optical power versus diode current and the range of linearity.

14- Plot the LED IV characteristic (I_d versus V_d).

15- Comment on the resulting curve.

16- Estimate the turn-on voltage V_T (*forward voltage*) and compare it with the typical LED specification.

17- Discuss the overall experimental results for this part of the experiment and write some conclusions.

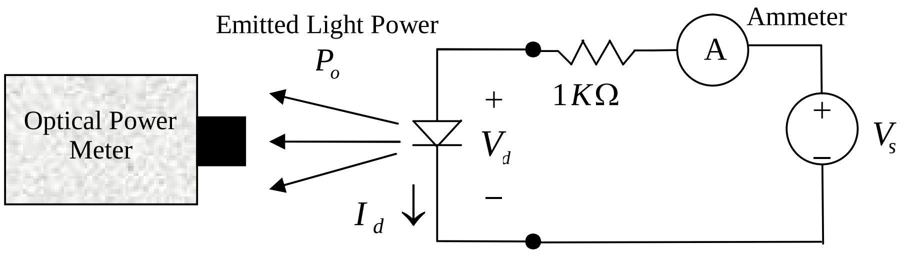

Figure 3: Setup for Measuring Part of the Optical Power Emitted by the LED.

V_s (Volt)	V_d (V)	I_d (mA)	P (dBm)	P (mW)	P_N
0	0				
-	0.1				
-	0.2				
-	0.3				
-	0.4				
-	0.5				
-	0.6				
-	0.7				
-	0.8				
-	0.9				
-	0.95				
-	1.0				
2.0					
2.5					
3.0					
3.5					
4.0					
4.5					
5					
6					
7					
8					
9					
10					

Table 1: Experimental Data for Measuring the LED Linearity and IV Characteristics.

Part B: LED Angular Emission Profile.

1- Use the previous circuit and set the source voltage to $V_s = 25V$ (Figure 3).

2- Refer to the experimental setup shown in Figure 4. Adjust the position of the LED so that the *light emitting surface* is approximately *above* and midway with respect to the center of rotation (COR) of the rotational stage (see Figure 5 for detail).

3- Connect the bare end of the fiber to the fiber holder and connect the other end to the optical power meter.

4- Connect the fiber holder to the rotational stage adapter plate and adjust it, so that there is a gap of approximately $1mm$ separating the fiber's tip is from the LED, as shown in Figure 5.

5- Set the optical power meter to dBm and $\lambda = 0.85\,\mu m$.

6- If necessary readjust the height and orientation of the LED so that it directly faces the fiber's tip (the fiber's *axis* should be approximately normal to and passing through the center of the *light emitting surface* of the LED).
7- Record the power meter reading in dBm in the second column of table 2 (and the row corresponding to $\theta = 0^o$.
8- Rotate the stage clockwise (negative angles) using a step of -4^o and record the meter's readings in table 2.
9- Set the stage back to the position corresponding to step 7 and repeat step 8 by rotating the stage counterclockwise (positive angles) using a step of $+4^o$.
10- Covert the power in dBm to mW, then compute the normalized power P_N. Record the values in table 2.
11- Since P_N is normalized, it is exactly the same as the normalized intensity I_N. Plot I_N versus θ.
12- Comment on the resulting plot including symmetry and the general behavior of I_N with θ.
13- Use the above graph to calculate the half power beam width (HPBW). HPBW is defined as the angular width in degrees at which the power is 50% of the maximum power. [Draw a horizontal line at $P_N = I_N = 0.5$ and use it to find the beam width in degrees]. Compare the result with the typical LED specifications.
14- Discuss the results and write some conclusions.

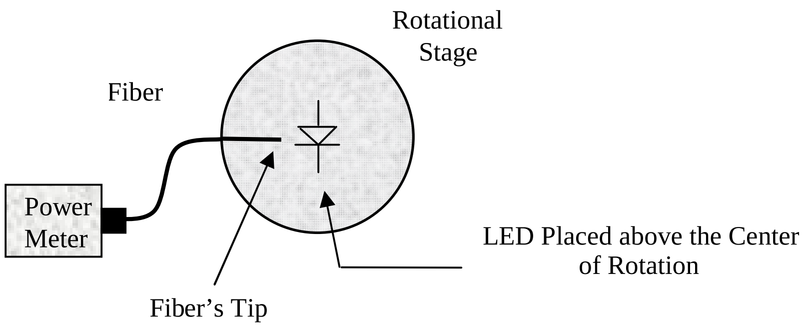

Figure 4: Experimental Setup for Measuring the Angular Emission Profile of the LED.

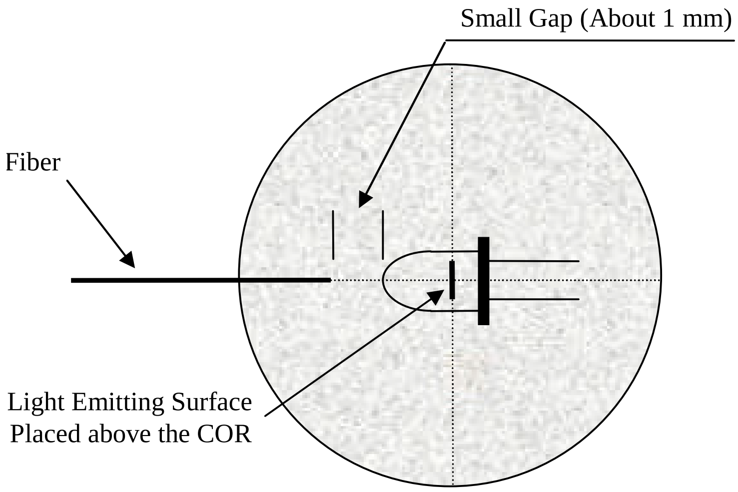

Figure 5: Detailed View of Figure 4.

θ (Degrees)	P (dBm)	P (mW)	$P_N = I_N$
-60			
-56			
-52			
-48			
-44			
-40			
-36			
-32			
-28			
-24			
-20			
-16			
-12			
-8			
-4			
0			
4			
8			
12			
16			
20			
24			
28			
32			
36			
40			
44			
48			
52			
56			
60			

Table 2: Experimental Data for Measuring the LED Angular Emission Profile.

QUESTIONS:

1- Why is it important for the LED to have a linear response? Is the linearity property more important for analog or digital systems?

2- If we keep on increasing I_d, do you think there is a point beyond which the LED response becomes nonlinear? Explain.

3- For part A of the experiment, use a straight line fit to estimate the optical power meter's reading in dBm when $V_s = 20V$.

4- Ordinary semiconductor diodes have a typical forward voltage of about $0.7V$. However, the LED used in this experiment clearly has a higher value of forward voltage (substantially larger than $0.7V$). Briefly explain why this is so.

5- Briefly explain why it is important to know the angular emission profile of the LED.

EXPERIMENT 10
CHARACTERISTICS OF THE PHOTDIODE

OBJECTIVES:

The objective of this experiment is to understand and measure some of the many important characteristics of the photodiode. The photodiode characteristics that will be studied in this experiment are responsivity, I-V characteristics and linearity.

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- Multimeter.
7- Power supply.
8- Decade resistor box.
9- 160 Ω resistor.
10- Medium area silicon photodiode (RS Part Number: 651-995).
11- Polarizer/Analyzer pair.
12- Large carton box with a pinhole.

PRELAB ASSIGNMENT

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

INTRODUCTION:

The photodiode is an essential element in fiber optics communication systems. It is similar to the ordinary semiconductor diode, with one exception: it responds to light. The symbol used for the photodiode is the same as the symbol of the ordinary diode, as seen in Figure 1. The diode voltage V_d is defined with + polarity on the p terminal and the diode current I_d is defined to flow through the diode from the p to the n terminal, which is identical to the standard definitions of the voltage and current of the ordinary diode.

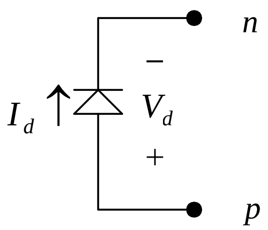

Figure 1: Photodiode Symbol, Showing Definition of the Photodiode Current and Voltage.

The *simplest* way to use a photodiode for the purpose of light detection is to leave its terminals open-circuited, as shown in Figure 2(a). This is an example of the so called *photovolatic* mode of diode operation. In this simple circuit, the photodiode conducts no current (because of the open circuit). When the incident light power P_i is zero, V_d is also zero. However, in this circuit, when $P_i > 0$, a small (at most a fraction of a volt), but measurable voltage V_d appears across the photodiode. This voltage is termed *photovoltage*, because it is caused by the incident light power and it disappears when the incident light power becomes zero. The value of V_d depends on P_i as well as on the incident light wavelength λ. An important example of the application of the photovolatic mode is in solar cells.

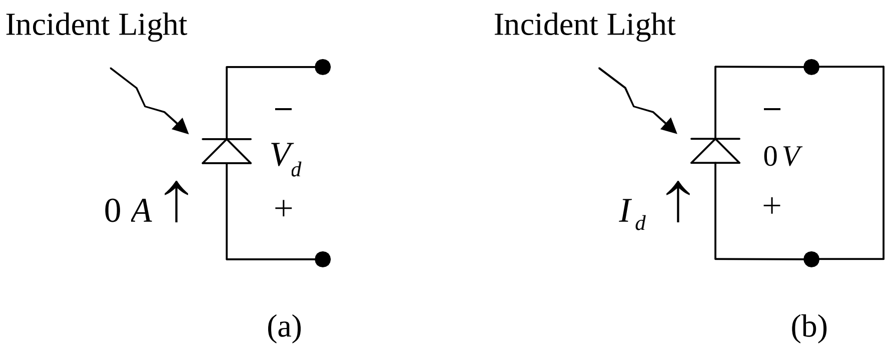

Figure 2: (a) Open Circuited and (b) Short Circuited Photodiode Circuits.

The circuit shown in Figure 2 (b) is an example of the *photoconductive* mode of diode operation. In this circuit, because the photodiode is short circuited, the diode voltage V_d is forced to be zero. The diode *produces* electric current I_d in response to the incident light. The current I_d is called the *photocurrent*, because it caused by the incident light power and it disappears when the incident light power is zero. This photocurrent is *proportional* to the incident light power P_i. In general, the higher the light power is, the higher the photocurrent I_d is. We can then view the photodiode in this circuit as a device that coverts light energy to electric current. The *actual* direction of the photocurrent is opposite to the one shown in Figure 2 (b). Thus, when the photodiode *operates in the photoconductive mode*, I_d is *always* a negative quantity. Let us then define the current $I_p \equiv -I_d$. Because I_p is positive, it is easier to use in our forthcoming discussion and the experimental work to be done.

For fiber optics communication, the photoconductive mode of operation is used to covert communication signals carried by light to signals carried by electric current. Thus, in this laboratory experiment, we will concentrate on the photoconductive mode of photodiode operation. The relationship between the incident power P_i and the induced current I_p is given by:

$$I_p = \bar{R}P_i \tag{1}$$

Where $\bar{R}$ is the photodiode responsivity (see Appendix C). The variation of $\bar{R}$ with λ for the medium area photodiode used in this experiment is shown in Figure 3.

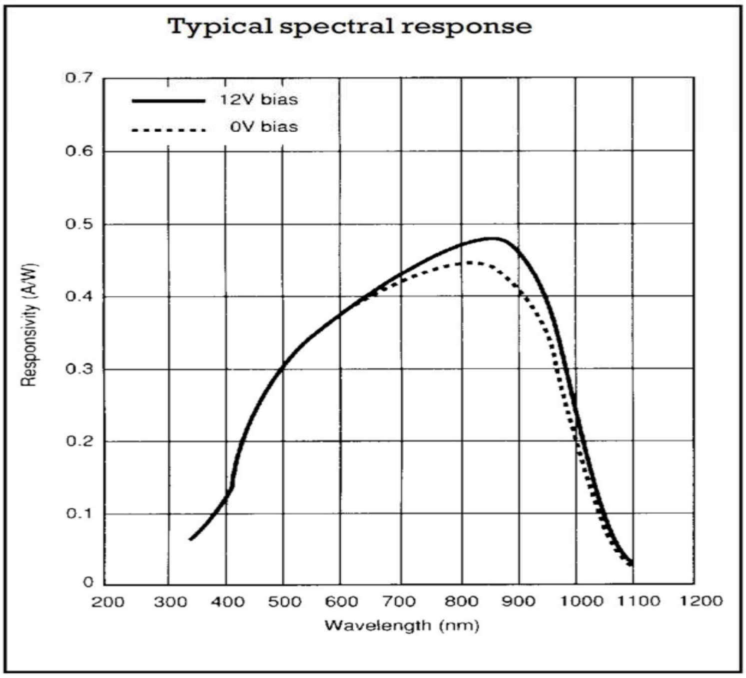

Figure 3: Responsivity Versus Wavelength for the Medium Area Photodiode.

For normal operation, the photodiode is *reversed biased* (i.e. $V_d < 0$). The responsivity $\bar{R}$ of the diode is *largely independent* of the bias voltage, *as long as the diode is reversed biased.* When the diode has zero bias (i.e. $V_d = 0$), $\bar{R}$ decreases slightly below the reversed bias value. This effect can be seen clearly seen in Figure 3, where the 12 V indicated in the figure refers to the value of the reverse bias voltage. However, when the diode is *forward* biased, $\bar{R}$ begin to drop, reaching negligible values when the forward is sufficiently high. It is thus important to keep in mind that the diode *responsivity decreases drastically when the diode is forward biased.* This important feature of the photodiode will be observed in this experiment.

Now, consider the circuit shown in Figure 4, which a simple and practical circuit for light detection. The supply voltage V_s is kept positive. Using Kirchhoff's voltage law and Ohm's law, we have:

$$V_d = V_L - V_s \tag{2}$$

$$V_d = I_p R_L - V_s \tag{3}$$

Let us assume that the incident optical power is fixed at a certain level P_i. When the load resistance R_L equals zero, $V_d = -V_s$. Since $V_s > 0$, then $V_d < 0$ and thus in this case the diode is reversed biased. Since P_i is fixed, we also expect I_p to also be fixed, as long as the diode remains reverse biased. When R_L increases, the voltage

$V_L = I_p R_L$ also increases. Thus we can continue to increase V_L by simply increasing R_L *as long as the photodiode remains reversed biased*. However, at some point, $I_p R_L$ will exceed V_s causing the diode to be forward biased and becoming less and less responsive to the incident power (i.e. $\bar{R}$ starts to decrease, causing I_p to decrease). In short, the *maximum* obtainable value of the load voltage $V_L = I_p R_L$ is slightly larger than the value of V_s. Thus, for this circuit, the following relationship applies:

$$(V_L)_{\max} \approx V_s \tag{4}$$

This important relationship will be verified in this experiment.

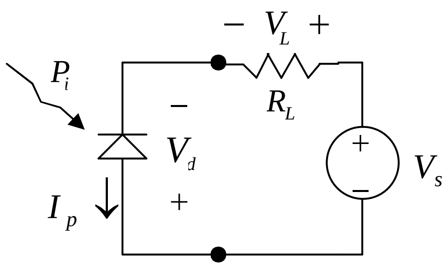

Figure 4: Practical Simple Circuit for Light Detection.

PROCEDURE:

Part A: **Using the Photodiode in Light Power Measurement and Diode Responsivity.**

1- Connect the circuit shown in Figure 5.
2- Turn the HeNe laser on and keep it approximately 1m from the photodiode.
3- Align the laser so that the center of the laser beam is approximately normal and in the middle of the light sensitive of the photodiode. Notice that laser beam is completely within the light sensitive area of the diode, so that *all* the laser power is sensed by the diode.
4- Use an object to block the laser beam and read the ammeter reading. Record the value in table 1.
5- Remove the object and read the ammeter reading. Verify that the induced current *actually* flows through the diode from the n terminal to the p terminal, not the other way around. Record the results in table 1.
6- Use Figure 3, equation (1) and the ammeter reading of step (5) to estimate the output power of the HeNe laser. Record the value in table 2.
7- Compare your result with the HeNe Laser specifications. Discuss the results and draw some conclusions.

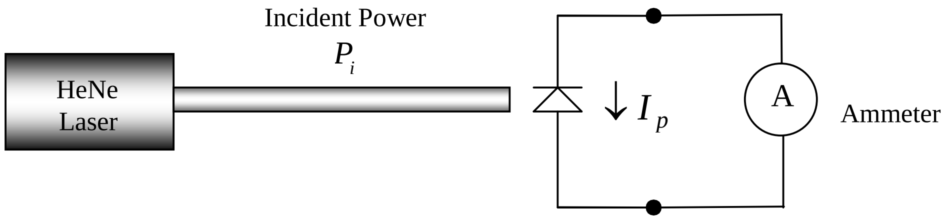

Figure 5: Setup Used for Measuring the Power Emitted by a HeNe Laser Source.

Condition	I_p (mA)	Actual Direction of I_p
Laser Blocked		From n to p
Laser Unblocked		From p to n

Table 1: Photocurrent Current Measurement for Part A of the Experiment.

$\bar{R}(\lambda = 0.633\mu m)$ in (A/W)	I_p (mA)	HeNe Laser Power (mW) (Experimental)	HeNe Laser Power (mW) (Manufacturer's Specification)

Table 2: Photodiode Responsivity and Estimated Power of the HeNe Laser.

Part B: Practical Circuit for Light Detection and Photodiode IV Characteristics.

1- Connect the circuit shown in Figure 6 and repeat steps 1) and 2) of part A.
2- Set V_s to 0 Volts [Disconnect the leads from the power and connect them together to produce a short circuit, which is equivalent to $V_s = 0V$. *Turning the power supply off or setting the power supply voltage to zero does not work well in this case*].
3- Set the decade resistance R to $0\,\Omega$ and then measure V_L and record its value in table 3.
4- Repeat step 3 for $R = 100\,\Omega$, $200\,\Omega$, until the third column of table 3 is filled. *To simulate $R = \infty$, remove the lead that connects the decade box to the* $160\,\Omega$ *resistor*.
5- Calculate the photodiode current and voltage and record them in table 3.
6- Connect the circuit to the power supply and set V_s to 5 Volts [You should use a digital volt meter to measure V_s to set it precisely to 5V. [*Do not rely on the power supply meter for this measurement*]. Record the *precise* value of V_s in the top row of table 4.
7- Set the decade resistance R to $0\,\Omega$, then measure V_L and record its value in table 4.
8- Repeat step 8 for $R = 100\,\Omega$, $200\,\Omega$, until the third column of table 4 is filled.
9- Calculate the photodiode current and voltage and record them in table 4.

10- Repeats steps 6 through 9, for $V_s = 15V$ (precise) and record the results in table 5.

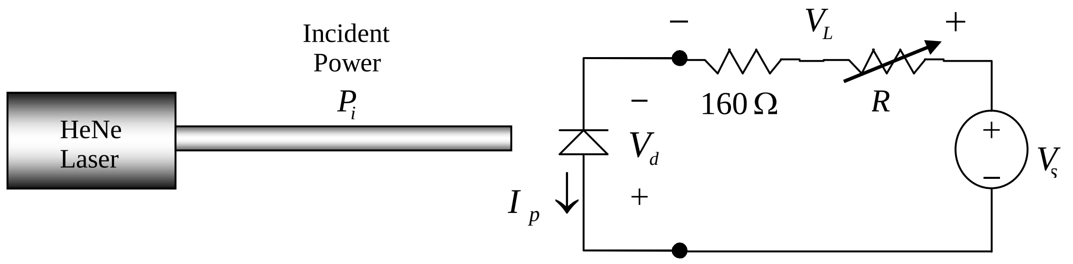

Figure 6: Circuit Diagram for Part B.

$R(\Omega)$	$R_L = R + 160\,(\Omega)$	V_L (V)	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			
600	760			
700	860			
800	960			
900	1060			
1000	1160			
10000	10160			
∞	∞			

Table 3: Measured Load Voltage Versus Load Resistance for $V_s = 0V$.

V_s (Measured) = Volts				
$R(\Omega)$	$R_L = R + 160\,(\Omega)$	V_L (V)	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			

600	760			
700	860			
800	960			
900	1060			
1000	1160			
1100	1260			
1200	1360			
1300	1460			
1400	1560			
1500	1660			
1600	1760			
1700	1860			
1800	1960			
1900	2060			
2000	2160			
10000	10160			
∞	∞			

Table 4: Measured Load Voltage Versus Load Resistance for $V_s = 5V$.

V_s (Measured) = Volts				
$R\,(\Omega)$	$R_L = R + 160\,(\Omega)$	$V_L\,(\mathrm{V})$	I_p (mA)	V_d (V)
0	160			
100	260			
200	360			
300	460			
400	560			
500	660			
600	760			
700	860			
800	960			
900	1060			
1000	1160			
1100	1260			
1200	1360			
1300	1460			
1400	1560			

1500	1660			
1600	1760			
1700	1860			
1800	1960			
1900	2060			
2000	2160			
2100	2260			
2200	2360			
2300	2460			
2400	2560			
2500	2660			
2600	2760			
2700	2860			
2800	2960			
2900	3060			
3000	3160			
3100	3260			
3200	3360			
3300	3460			
3400	3560			
3500	3660			
3600	3760			
3700	3860			
3800	3960			
3900	4060			
4000	4160			
5000	5160			
10000	10160			
∞	∞			

Table 5: Measured Load Voltage Versus Load Resistance for $V_s = 15V$.

Part C: Photodiode Linearity.

[<u>IMPRTANT</u>: FOR THIS PART OF THE EXPERIMENT, THE LASER MUST BE TURNED ON FOR AT LEAST ONE HOUR BRFORE RELIABLE MEASUREMENTS CAN BE TAKEN].

1- Refer to the experimental setup shown in Figure 7.
2- Set the following circuit setting: $R = 1K\Omega$ $(R_L = 1160\Omega)$ and $V_s = 5V$.

3- Insure that the beam is reasonable centered within the light sensitive area of the diode.
4- Insert a polarizer/analyzer pair between the laser and the photodiode.
5- Set the *analyzer* angle θ_p to 90^o.
6- Rotate the *polarizer* until V_L is minimized. The light incident on the photodiode should be too weak to see with the naked eye.
7- Set the *analyzer* angle θ_p to 10^o. Now, the light beam is visible again.
8- Cover the circuit with the carton box in such away that the laser beam passes through the center of the pinhole. [*Take care not to disturb the circuit while placing the box*].
9- Now, measure V_L and record its value in table 6.
10- Repeat step 9 for $\theta_p = 20^o$ and all remaining values of θ_p shown in table 6. [*Note that the step size for θ_p is not fixed*].
11- Remove the circuit and replace it with the optical power meter. Set the meter to dBm and $\lambda = 0.85\,\mu m$.
12- Adjust the position of the optical power meter for maximum power reading. [*DO not remove the cover of the power meter*]. There is no need to use the carton box in this case.
13- Set the analyzer angle θ_p to 10^o and record the power meter reading in table 6.
14- Repeat step 13 for $\theta_p = 20^o$ and all the remaining values of θ_p shown in table 6.
15- Calculate the current I_p and record its value in table 6.
16- Convert the power meter readings to mW and record the values in the fifth column of table 6.
17- Plot I_p versus the optical power in mW.
18- On the *same graph*, draw a straight line that best fits the experimental graph, and then comment on the linearity of the photodiode.
19- Why did we use a polarizer/analyzer pair? What function do they serve in this part of the experiment? Why did we use a box cover in the first part? Discuss the experimental results and write some conclusions.

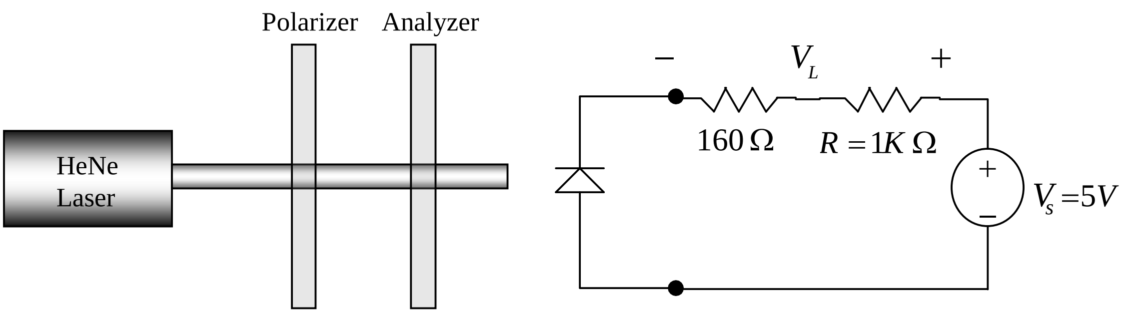

Figure 7: Setup Used for Photodiode Linearity Measurements.

θ_p (Degree)	V_L (V)	PdBm	I_p (mA)	P (mW)
10				
20				
30				
35				
40				
45				
50				
55				
60				
65				
70				
80				
82				
84				
86				
88				
90				

Table 6: Experimental Data for Part C.

REPORT REQUIREMENTS:

Part A: The requirements for part A were already stated in the procedure.

Part B:

1- *On the same graph*, plot V_L versus R_L for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

2- Comment on the maximum voltage obtainable in each case. Compare the results with the theoretical prediction of equation (4).

3- *On the same graph, plot* I_p *versus* R_L for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

4- Comment on the behavior of I_p. Is it always constant? If not when is it constant and when is it not constant?

5- *On the same graph, plot* the photodiode IV characteristics (i.e. V_s versus I_d, *not* V_s *versus* I_p) for the cases $V_s = 0V$, $V_s = 5V$ and $V_s = 15V$.

6- Comment on the resulting graphs. In what way are they different and in what way are they similar?

7- In order to enrich your report, ask yourself the following questions which will help you in developing comments and conclusions appropriate for this part of the experiment.

- Does the photocurrent (increase or decrease) (rapidly or slowly) with the forward bias?
- Do you see approximately straight lines in the IV characteristics?
- Can we model the photodiode as an optical power-dependent current source? If yes, what conditions must be satisfied for the validity of this model?
- Do you expect the IV characteristics of the photodiode to change when the incident optical power changes? Explain.
- Do you expect the IV characteristics of the photodiode to change when the incident light wavelength changes? Explain.
- When $V_s = 0V$, do we obtain a complete or partial IV characteristic? Explain.

PART C: The requirements for part C were already stated in the procedure.

QUESTIONS:

1- Suppose the incident power is extremely low, but measurable, what changes and precautions should be done in part B of this experiment to make it successful?

2- The circuit shown in Figure 4 is much more practical for fiber optics communication than the one shown in Figure 2 (b). Explain why, giving as many reasons as you can think of. [Hint 1: current is harder to deal with than voltage. Hint 2: Different circuits require different voltage levels].

3- When does the circuit used in part B operate in pure photovolatic mode?

4- Using the experimental results, estimate the maximum obtainable voltage V_d when the photodiode operates in the photovolatic mode.

5- Imagine that you were asked to design a photodetector circuit for use in an optical fiber communication system operating at $\lambda = 1.55\ \mu m$. Is the photodiode used in this experiment a suitable choice? Justify your answer.

6- In part B of the experiment with $V_s = 15\text{V}$, estimate the range of load resistance R_L in which we can model the photodiode (approximately) as an ideal current source?

7- In part B of the experiment with $V_s = 15\text{V}$ and $R = 200\,\Omega$, use the experimental data to predict the load voltage V_L when the incident power is reduced by a factor of 2.

8- Answer question (6), assuming the incident power is reduced by a factor of 1000.

9- In part B of the experiment, with $V_s = 5\text{V}$ and $V_s = 15\text{V}$, the photocurrent I_p remains almost independent of R_L in a certain range of R_L. However, with $V_s = 0\text{V}$, I_p does not remain constant as R_L changes, even for low values of R_L. Briefly explain why this is so. [Hint: Find out what the bias of the photodiode is when $V_s = 0\,\mathrm{V}$. Is it forward or reverse biased?].

10- Assuming we can model the photodiode as an *optical power-dependent* current source, develop an appropriate approximate mathematical model for this source [i.e. $I_p = \mathrm{constant} \times P_i$, find the approximate value of the constant at $\lambda = 0.633\,\mu m$]. Use the experimental data and the known responsivity of the diode for this purpose.

APPENDIX A
GUIDELINES FOR PREPARING LABORATORY REPORTS

In the following, general guidelines are given to help the EE 420 laboratory student write well-prepared laboratory reports. A good laboratory report must have the following items:

1- A front page: this page should contain:

- The experiment title and number.
- The student name and ID number.
- The laboratory name and section number.
- Date.
- The name of the laboratory instructor.

Use of fancy fonts and color is strongly discouraged throughout the report.

2- Objectives of the experiment. Do not copy the objectives from the experimental manual, use your *own wording*.

3- A list of equipment used with details, if available.

4- A short introduction. Again, use your own wording to write a short introduction to explain to the reader what he is expected to see in the report. Many students take extreme short cuts when preparing their laboratory reports, by omitting essential items such as a proper introduction.

5- Results and Discussion: This section is the main body of the experimental report. It should contain the figure, tables, explanations, discussion, etc.

6- Diagrams of any experimental setups.

7- Equations if any. Always number the equations and type the equations using an equation editor.

8- Figures and tables if any. Always number the figures and tables. Do not leave a figure or a table without a number. Also, immediately following the *figure number* or *table number*, describe the contents of the figure or table.

Always refer to the figure or table in the body of the report and explain what the figure or table contains.

Always label the vertical and horizontal axes of the figures.

If more than one curve is drawn in the same figure, make sure that these curves are properly labeled.

9- *Always* calculate and *report* the percent error between the experimental data and theory, even if you were not explicitly asked to do so in the experimental manual. Report this error in a table or in the form of graph or both.

Always comment on the percent error. Whether it is low, moderate or high and try to explain any possible reasons when the error is not low.

10- Pay attention to the units used and report them.

11- Summary. Include a summary immediately before the conclusion.

12- Conclusion. Take care not to confuse summary and conclusions and write as many conclusions as you can think of. It is best if you itemize the conclusions.

13- Answers to questions if any. Write the answers to the questions at the very end of the laboratory report, after the conclusion, using a separate page entitled "ANSWERS TO QUESTIONS". Type the questions as well as the answers.

14- Proper language. Take extra care to write the report in proper language using your own words. Poor English gives a poor impression and may cause the laboratory instructor not to understand the full meaning of the idea that you want to convey. This may also result in lowering the grade of your report.

A sample report is shown next. Examine this report and check if the above-mentioned items have been properly implemented. The sample is based on a *hypothetical* experiment. The sample report contains comments in *italic* font to highlight the important points that you should pay attention to when you prepare your report.

KING FAHD UNIVERSITY OF PETROLEUM AND MINERALS

ELECTRICAL ENGINEERING DEAPRTMENT

EE 420

Fiber Optics Communication

Laboratory Report

Experiment #1

Title: Heat Expansion of a Steel Rod

Name: ………………

ID Number: ………….

Section #55

Date of Experiment: ……………………

Submission Date: ………………………

Submitted to: …………………………..

OBJECTIVES:

The main objectives of this experiment are to:

1- Experimentally investigate how the length of a steel rod changes with temperature.
2- Compare theoretical and experimental results.
3- Experimentally measure the thermal expansion coefficient of steel and to compare it wit the established value.

[Notice that the objectives were itemized for clarity].

EQUIPMENT:

1- A steel rod, approximately 1m long.
2- A ruler.
3- Coupler.
4- Temperature meter (HP-Model Number 2222).
5- Heat source (Westinghouse, Model Number 1111).

[*Notice that the equipment model number has been added. Add the model number whenever it is available*].

INTRODUCTION:

It is well-known that when the temperature of a rod is increased, the rod expands. The change in the length of a rod of length L (meter) dependence on the temperature T (C^o), according to the following relationship:

$$\Delta L = \gamma L \Delta T \qquad (1)$$

This means that:

$$L(T_2) = L(T_1) + \gamma (T_2 - T_1) L(T_1) \qquad (2)$$

[*Notice that:*
- *The equations were written using an equation editor.*
- *The equations were numbered.*
- *The equation numbers were* <u>*aligned*</u>].

Where ΔL and ΔT are the change in the length and temperature of the rod, respectively. The parameter $\gamma\,[1/C^o]$ is called the thermal expansion coefficient. The value of γ depends on the material used. The parameters T_1 and T_2 are the initial and final temperatures, respectively. The experimental data given in this report has been obtained using steel and copper rods. The established expansion coefficients of steel is given by $\gamma = 10^{-3}[1/C^o]$. [*This is not the actual value of γ for steel and remember that this is only a hypothetical experiment*]. This value will be used to assess the accuracy of our experimental results.

EXPERIMENTAL SETUP:

Figure 1 shows the experimental setup used in this experiment. The coupler is used to connect the steel rod to the heat source.

[*Notice that Figure 1 has been* <u>*referred to*</u> *in the text,* <u>*before*</u> *the figure is actually shown*].

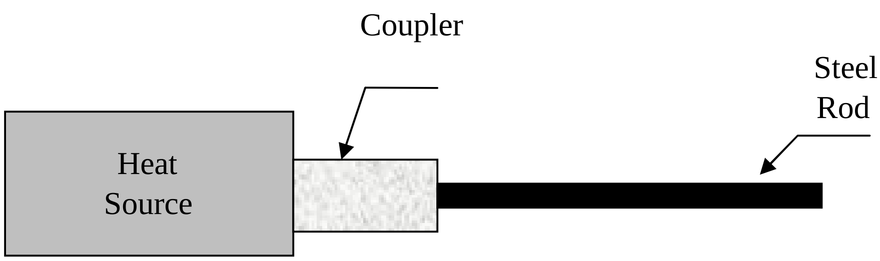

Figure 1: Experimental Setup Showing the Heat Source, Coupler and Steel Rod.

[*Notice the Figure has been given a number followed by a description*].

RESULTS AND DISCUSSION:

Tables 1 summarizes the experimentally obtained data for the steel. The data was taken using an initial steel temperature of $30\,C^o$.

[*Notice that the table has been referred to in the text, before the table is shown*].

Temperature $T\,(C^o)$	Length L (m), Experimental	Length L (m), Theoretical	Relative Error (%)
30	0.995	0.995	0
80	1.055	1.045	0.96
130	1.12	1.095	2.23
180	1.17	1.144	2.27
230	1.21	1.194	1.34
280	1.22	1.244	-1.93
330	1.45	1.294	12.1
380	1.39	1.343	3.50
430	1.50	1.393	7.68

Table 1: Experimental and Theoretical Data for the Steel Rod Length Dependence on Temperature.

[*Notice that:*
- *the table has been given a number followed by a description of contents.*
- *Also a column is added to show the percent error. Add this column, even if your were not asked to do so.*
- *The units are clearly indicated*].

Figure 2 shows the experimental and theoretical results based on the data presented in table 1. This figure shows that the experimental and theoretical calculations are generally in good agreement. The results shown in Figure 2 indicate that the length of the steel rod increases with temperature and follows roughly a linear variation, as predicted by theory.

[*Notice:*

- *The source of the data used to draw Figure2 is identified.*
- *Since the experimental curve is not a straight line, but it resembles a straight line, the word roughly has been added above.*
- *The results shown in Figure 2 have been discussed and were not left to the reader to make his own interpretation*].

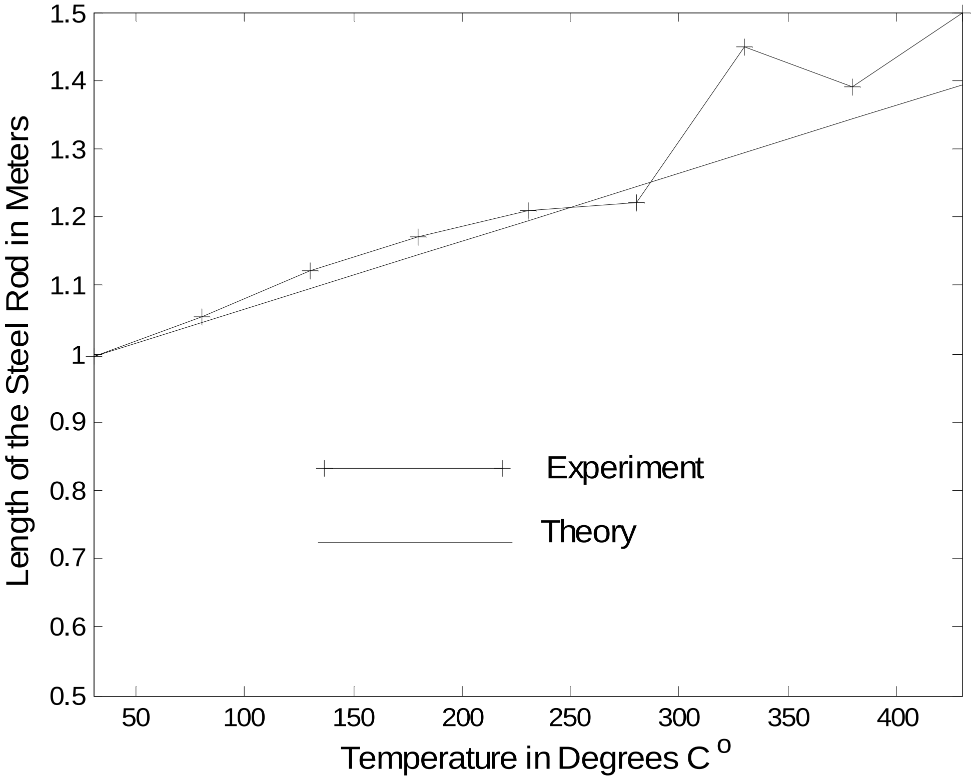

Figure 2: Experimental and Theoretical Variation of the Steel Rod Length as a Function of Temperature.

[*Notice that:*

- *Both axes of the figure are labeled and units were included.*
- *The two curves are clearly labeled to prevent confusion.*
- *The next available Figure number is assigned to this figure*].

Figure 3 shows the relative error in percent as a function of temperature, based on data from table 1. The relative error is generally low (below 5% for most reading). However, a relatively large disagreement between the experimental and theoretical results occur at $T = 330\,C^o$. The percent error reaches a maximum of approximately 12% at $T = 330\,C^o$. A possible source of this relatively large error may be due to the measurement of the steel rod length or due to inaccuracy of the temperature meter.

[*Notice that:*
- *Data source was identified.*
- *The error was discussed.*
- *Possible sources of error were identified*].

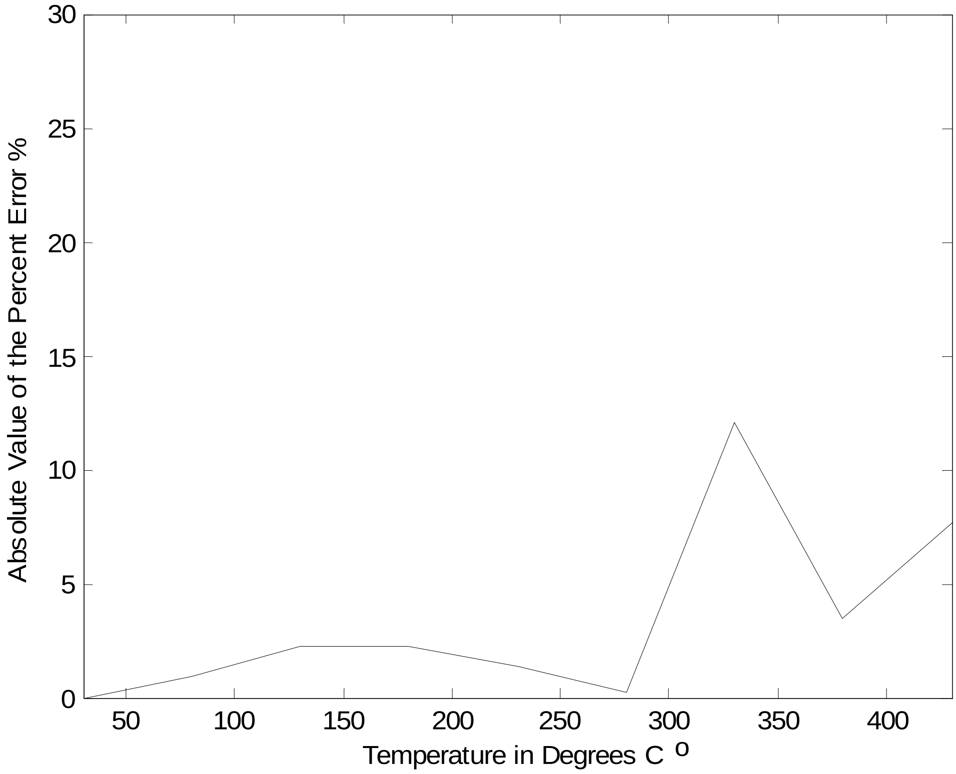

Figure 3: Absolute Value of the Percent Error (for the Experimental and Theoretical Lengths of the Steel Rod) as a Function of Temperature.

[*Notice that the* <u>absolute value</u> *of the percent error was plotted, not the relative error documented in table 1. The label of the vertical axis in Figure 3 clearly indicates this*].

In order to experimentally determine the expansion coefficient γ of steel from the experimental data, a straight line fit was first performed. Using the slope of the resulting straight line in conjunction with equation (2), we have calculated γ for steel. The resulting experimental value of γ is approximately $1.06\times10^{-3}\ [1/C^{o}]$, which is in good agreement with the established value of $1.00\times10^{-3}\ [1/C^{o}]$.

[*Notice:*
- *The method used to calculate γ was described.*
- *A comment on the degree of agreement was made*].

SUMMARY:

In this experiment, we have measured the length of a steel rod as a function of temperature. The experimental and theoretical results are in good agreement for most measurements. The thermal expansion coefficient of steel has been also calculated using experimental data.

[*Notice that the summary* *generally and briefly* *mentions what has been done in the experiment with little detail, if any, of the specific results obtained*].

CONCLUSION:

From the results of this experiment, we can conclude the following:

1- The length of a steel rod increases with temperature.
2- The relation between the steel rod length and temperature is roughly linear.
3- The experimentally determined thermal expansion of steel $\gamma \approx 1.06\times10^{-3}\ [1/C^{o}]$ is in good agreement with the established value of $\gamma = 1.00\times10^{-3}\ [1/C^{o}]$.
4- The relative error is found to be below 5% for most readings. However at $T = 330\,C^{o}$ the relative error reaches its maximum value of about 12%.
5- The sources of error in this experiment could be due to measurement of the length of the steel rod and the poor accuracy of the temperature meter used.

[*Notice that:*

- *The conclusion briefly mentions the specific results and the most important outcomes obtained after performing the experiment.*
- *The conclusions are itemized.*
- *A number of conclusions were written, not just one or two conclusions.*
- *Possible sources of error are indicated*].

ANSWERS TO QUETIONS

Q1: Does the length of the steel rod increases or decreases with temperature?

Answer: It increases with temperature.

Q2: Estimate the length of the steel rod used in the experiment when its temperature is raised to $600\,C^{\circ}$?

Answer: 1.6 m.

[*Notice:*
- *The answers to the questions were written at the end of the report.*
- *The answers were written on a separate page.*
- *Both the questions and their corresponding answers were written.*]

[*Notice also that fancy fonts were not used in the sample report*].

APPENDIX B
UNITS OF OPTICAL POWER

Optical power can be expressed either in linear units [such as watt (W), milliwatt (mW) or microwatt (μW)] or in dB units [such as dB, dB-milli (dBm) or dB-micro (dBμ)]. The unit dBm is dB with respect to milliwatt. The unit dBμ is dB with respect to microwatt. The various units of optical power will be explained in this appendix. The majority of optical power meters give the user an option for displaying the optical power using one of these units.

An optical power P expressed in Watts, can also be expressed in dB using the following expression:

$P_{dB} = 10\log P$ [P is in Watts] (1)

An optical power P expressed in mW or μW, may be expressed in dBm or dBμ, respectively, using:

$P_{dBm} = 10\log P$ [P is in mW] (2)

$P_{dB\mu} = 10\log P$ [P is in μW] (3)

Example 1:

Express 4 mW in: a) Watts and μW b) dB c) dBm d) dBμ

Solution:

a) 4 mW = $0.004\,W$ = $4000\ \mu W$

b) $P_{\text{dB}} = 10\log 0.004 = -23.979\text{ dB}$

c) $P_{dBm} = 10\log 4 = 6.021\text{ dBm}$

d) $P_{dB\mu} = 10\log 4000 = 36.021\text{ dB}\mu$

Notice that the difference between P_{dB} and P_{dBm} is 30 dB. Also the difference between P_{dBm} and $P_{dB\mu}$ is 30 dB. The reason is that 30 dB corresponds to a *factor* of 1000 in linear units.

Example 2:

Express 13 dBm in: a) mW b) W and μW c) dB and dBμ

Solution:

a) $P = 10^{13/10} = 10^{1.3} = 19.95\ mW$

b) $P = 19.953\, mW = 0.019953\, W = 19953 \mu W$
c) 13 dBm = 13 - 30 = -27dB   &   13 dBm = 13+30 = 43 dBμ

In many EE 420 laboratory experiments, we will be required to calculate optical power loss. Consider for instance the situation illustrated in Figure 1, where a given optical beam is incident on a *lossy* optical element. The input optical power is P_i and the output optical power is P_o. Since the optical element is lossy, it follows that $P_o < P_i$.

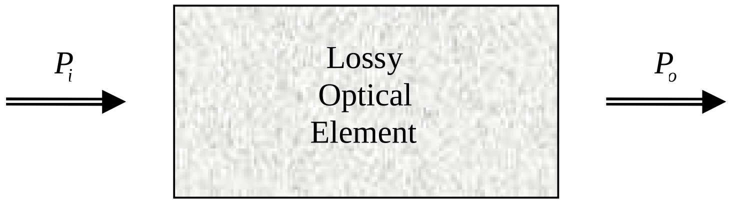

Figure 1: Input and Output Optical Powers through a Lossy Optical Element.

For a *linear* element, it is well-known that the output optical power is proportional to the input optical power, i.e. $P_i / P_o = \eta$, where η is some constant. This constant is larger than unity, simply because $P_i > P_o$. The parameter η can be used to represent the loss of the element. When η increases, the loss of the optical element also increases. For instance, when $\eta = 3$, then $P_o = P_i / 3$ and therefore, only one third of the incident optical power is available at the output end of the element.

The element loss can also be expressed using the dB measure, using the expression:

$$\text{dB}_{Loss} = 10 \log \eta = 10 \log \frac{P_i}{P_o} \tag{4}$$

Where P_i and P_o are expressed in the *same linear* units. For instance, if P_i is expressed in mW, then P_o must also be expressed in mW.

The loss in dB can also be expressed as the difference between the power levels in dB, as shown next. Using equation (4), and assuming that P_i and P_o are expressed in Watt, we have:

$$\text{dB}_{Loss} = 10 \log \frac{P_i}{P_o} = 10 \log P_i - 10 \log P_o = P_{idB} - P_{odB} \tag{5}$$

In a similar fashion, it is easy to show that:

$$\text{dB}_{Loss} = P_{idBm} - P_{odBm} \tag{6}$$

$$\mathrm{dB}_{Loss} = P_{idB\mu} - P_{odB\mu} \qquad (7)$$

Notice that in expressions (5), (6) and (7), *both* the input and output power levels are expressed in the *same* dB units, such as dB, dBm or dBμ. In addition, the dB_{Loss} is always expressed in dB, *even if* the power levels are expressed in dBm or dBμ. It is *meaningless* to express the power loss in dBm or dBμ. For instance, the difference between 10dBμ and 3dBμ is given by:

$10\mathrm{dB}\mu - 3\mathrm{dB}\mu = 7\mathrm{dB}$ (i.e. $10\mathrm{dB}\mu - 3\mathrm{dB}\mu \neq 7\mathrm{dB}\mu$)

<u>Example 3:</u>

With reference to Figure 3 above, assume that $P_i = 10\ mW$ and $P_o = 0.5mW$. Calculate:

a) $\eta = \frac{P_i}{P_o}$ b) the element loss in dB using two different methods.

Solution:

a) $\eta = \frac{P_i}{P_o} = \frac{10}{0.5} = 20$

b) <u>Method 1</u>: $\mathrm{dB_{Loss}} = 10\log 20 = 13.01\,\mathrm{dB}$

<u>Method 2</u>: $P_{idBm} = 10\log 10 = 10\ \mathrm{dBm}$

$P_{0dBm} = 10\log 0.5 = -3.01\,\mathrm{dBm}$

$\mathrm{dB_{Loss}}$ =10 dBm - (- 3.01 dBm) = 13.01 dB (the same answer as above).

APPENDIX C
OPERATION OF OPTICAL POWER METERS

An optical power meter is a relatively simple device. It utilizes a photodiode as the light sensing element. This photodiode generates an electric current I (see Figure 1), which is *proportional* to the incident optical power P (i.e. $I \propto P$). The electric circuit within the optical power meter senses the electric current generated by the photodiode, processes it and then displays the corresponding optical power.

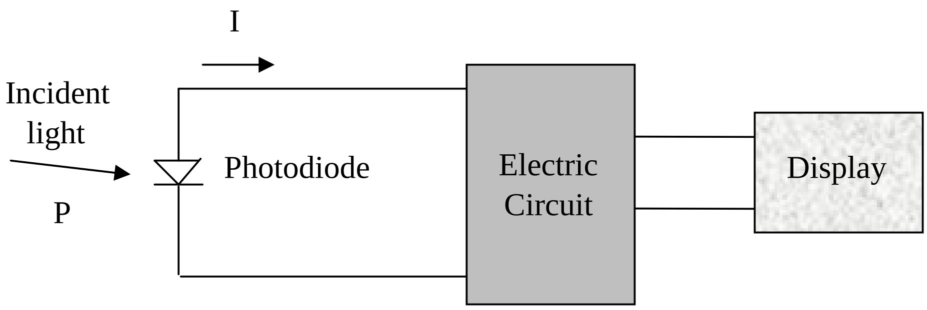

Figure 1: Basic Structure of an Optical Power Meter.

The parameter that relates the generated current to the incident optical power is called the responsivity, R, so that $I = RP$. The responsivity R of the photodiode is a function of the wavelength of the incident light, i.e. $R = R(\lambda)$. A typical photodiode responsivity curve is shown in Figure 2.

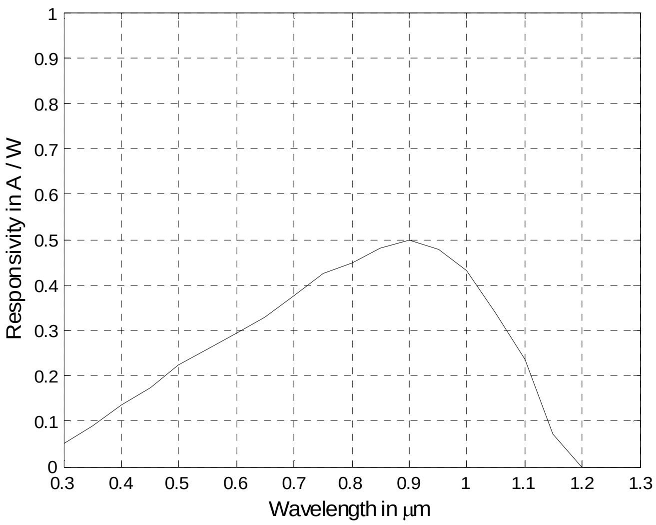

Figure 2: Typical Photodiode Responsivity Graph.

As seen in Figure 2, the maximum responsivity occurs at $\lambda = 0.9\ \mu m$. Notice also that above $\lambda = 1.2\ \mu m$, the photodiode does not detect any optical power. The wavelength $\lambda = 1.2\ \mu m$ is called the *cutoff wavelength*. Different types of photodiodes have different responsivity curves and thus also have different peak responsivity and cutoff wavelengths.

Because the responsivity of the photodiode is a strong function of wavelength, the internal circuit of the optical power meter, which can only sense the current generated by the photodiode, is usually designed to account for the dependence of R on λ. Otherwise, the meter will not be capable of displaying the correct optical power. Optical power meters usually have a wavelength setting. The user needs to select the correct wavelength of the light in order for the optical power meter to display the optical power correctly.

A *calibrated* optical power meter displays the correct value of the incident optical power *at a given wavelength*.

A *non-calibrated* optical power meter does not display the correct optical power. However, a non-calibrated optical power meter remains useful in optical power measurements, because it can be used to measure *relative* optical power. For instance, a non-calibrated optical power meter can be used to measure the loss of an optical element (see Appendix B). Let us assume that at a particular wavelength a non-calibrated optical power meter has a relative error κ. Instead of displaying the correct input and output power levels P_i and P_o, respectively, it will then display κP_i and κP_o, respectively. The ratio of the input to output powers in this case is given by:

$$\eta = \frac{\kappa P_i}{\kappa P_o} = \frac{P_i}{P_o} \qquad (1)$$

According to equation (1), a non-calibrated optical meter gives the correct ratio η. Another way to think of this idea is by finding the element loss in dB. Using equation (1), we have:

$$\begin{aligned} \mathrm{dB}_{Loss} &= 10\log\eta = 10\log\frac{\kappa P_i}{\kappa P_o} = (10\log\kappa P_i) - (10\log\kappa P_o) \\ &= (10\log\kappa + 10\log P_i) - (10\log\kappa + 10\log P_o) \\ &= (10\log\kappa - 10\log\kappa) + (10\log P_i - 10\log P_o) \\ &= 10\log P_i - 10\log P_o \qquad (2) \end{aligned}$$

Equation (2) shows that when taking the difference in the power levels in dB, the error in dB, given by $10\log\kappa$, simply cancels out. Equation (2) clearly shows that the dB error $10\log\kappa$ is the same for both the input and output power measurements. It should be obvious now that the dB error $10\log\kappa$ must be the same for all power measurements performed by the *same meter* at a *particular* wavelength.

LABORATORY SAFETY

INTRODUCTION:

In practice, optical fibers utilize invisible light (in the infrared region of the electromagnetic spectrum). There are several reasons for the use infrared light in fiber optics communication. Those reasons will be explained in the lecture. In addition, many fibers optics systems utilize laser light instead of ordinary light. The laser diode (LD) emits a coherent beam of light which can be harmful to the eye, whether the light is visible or invisible. The light emitting diode (LED) emits ordinary light, which is not harmful to the eye.

SAFETY CONSIDERATIONS:

Students attending the fiber optics communication laboratory are advised to adhere to the following safety precautions:

1- Never directly look at laser light, whether visible or invisible, not even for a short time. Damage to the eye can occur before you realize it.

2- Never directly look at the output end of an optical fiber, if the fiber carries laser light.

3- Watch also for any laser light that is reflected by smooth highly reflecting surfaces and avoid looking at it directly.

4- Some fiber optics communication experiments utilize a device called the Optical Time Domain Reflectometer (OTDR). This device emits invisible laser light from its output terminal. Never look directly at the output terminal of an OTDR when the device is turned on.

5- In this experiment, a HeNe laser source will be used in some experiments. There are special protective goggles designed to block this laser light in order to protect the eye against accidental exposure. The students are encouraged to use those goggles. However, it must be kept in mind that these goggles are only useful at the HeNe wavelength.

You can view infrared light using an infrared viewer. If an infrared viewer is not available in the laboratory, you can use a mobile phone that has a camera to view infrared light.