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):

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

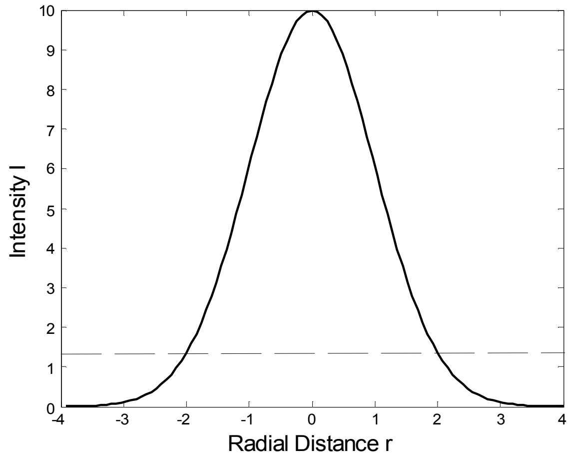

Figure 1: Gaussian Intensity Distribution in the Radial Direction.

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

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

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

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:

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

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:

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

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.

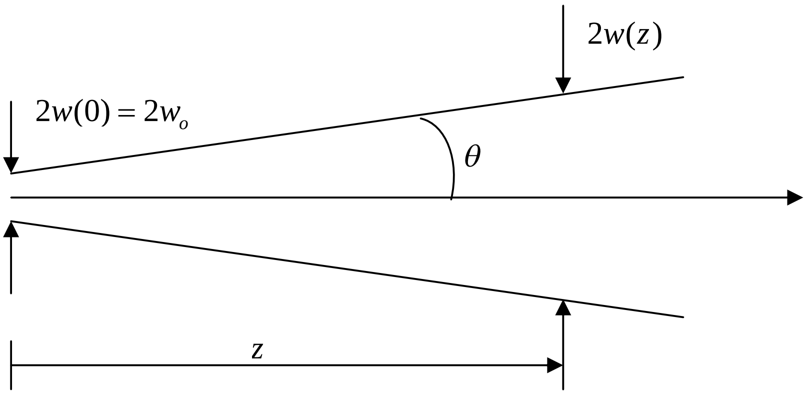

Figure 2: Illustration of Gaussian Beam Expansion, Showing the Initial Spot Size $w(0)$ and the Definition of the Distance z.

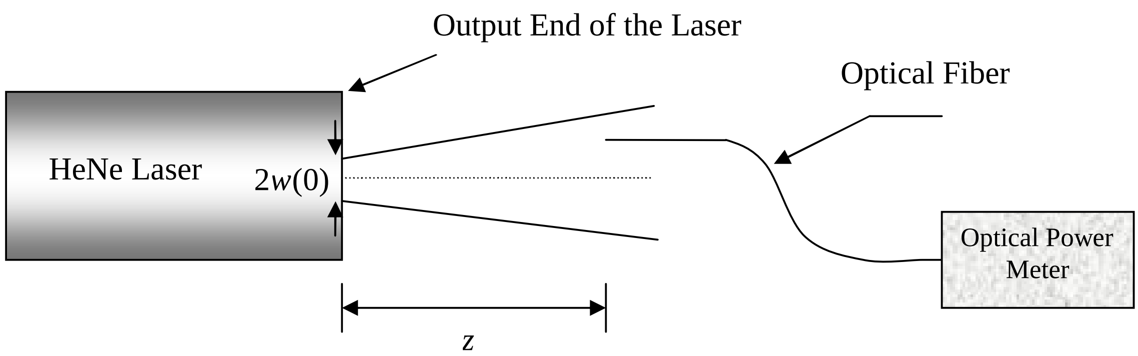

Figure 3: An Optical Fiber Used for Scanning the Laser Intensity Profile at a Fixed Distance z from the Laser Output End.

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*].

REPORT REQUIREMENTS:

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 $r = 2w$.