Finding the Characteristics of a given Laser Beam

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Abstract Measurement of the optical properties of a helium neon laser beam. Polarization of the laser beam was measured to be $\rho = 0.98 \pm 0.02$. Beam diameter was measured with the knife edge method and found to be $1.361 \pm 0.007mm$ which is an error of 75% from the manufacture value of $0.34mm$.Divergence of the laser beam was measured to be $2\Delta\Theta = 1.728 \pm 0.004$ milliradian, which is experimental error of 1.6% compared to the manufacturer's value $2\Delta\Theta = 1.70$ milliradian. Expected divergence was calculated by Fraunhofer diffraction equation is $2\Delta\Theta = 1.134 \pm 0.006$ milliradian, which is experimental error of 33.3%. Beam waist and depth-of-field was found by fitting collected data to regression line. The beam waist was measured to be $0.979 \pm 0.008mm$ and the depth-of-field is $13.9 \pm 0.26mm$.

1 Introduction

In any experiment involving a laser beam it is important to know the properties of the specific beam used in order to obtain accurate data and have a good understanding of the physics involved. This experiment measures the beam polarization, diameter, divergence, and beam waist of a helium - neon laser beam.

(Beam Polarization) The polarization of a laser beam is a measurement of the orientation of the electric field of the laser beam. Due to the Brewster-window inserted into the laser apparatus, the laser beam is expected to be linearly polarized, the electromagnetic fields oscillating in a single direction.

(Beam Diameter) It is possible to find the diameter of a beam without using image processing and without having to measure the complete beam profile. The intensity of many laser beams are Gaussian. By plotting the power of the beam vs the amount of beam covered, the distribution of the intensity can be seen. In the case for a plot that resembles the error function we find

$$P = \frac{P_0}{2} erfc(\frac{a\sqrt{2}}{\omega(z)}) \tag{1}$$

By finding the percentage of the intensity reduced when the beam is covered by one beam radius into the beam axis and one beam radius beyond the beam axis the diameter of the beam can be found.

(Beam Divergence) The beam divergence is how much the diameter of the laser beam increases with distance. Ideally, the divergence of a laser beam is only caused by the Fraunhofer diffraction. The divergence of the beam $\Delta\Theta$ is defined as:

$$\tan \Delta\Theta = \frac{D_f - D_i}{2z} \tag{2}$$

Where D_f is the diameter of the beam after beam has diverged, D_i is the initial diameter of the beam, and z is the distance between the two diameters. If D_f is measured from far away so that $D_f >> D_i$ and $z >> D_f$, beam divergence can be approximated as:

$$\Delta\Theta = \frac{D_f}{2z} \tag{3}$$

Fraunhofer diffraction equation predicts that the divergence of the beam is:

$$\Delta\Theta = \frac{1.22\lambda}{D_0} \tag{4}$$

Where λ is the wavelength of the laser beam and D_0 is the initial diameter of the beam.

(Beam Waist) The beam waist (or characteristic minimum diameter) can be described as the minimum diameter of the beam past a lens with some focal length. The location of the beam waist is known as the depth-of-field L. It is important to know this location as it is where the energy of the beam is most concentrated. These quantities can be found by using the equations

$$d = (\frac{4\lambda}{\pi})(\frac{f}{D_0}) \tag{5}$$

and

$$L = 2(\frac{4\lambda}{\pi})(\frac{f}{D_0})^2 \tag{6}$$

Alternatively, by taking a lens of known focal length and placing it in the path of the beam a plot of beam diameter as a function of lens position can be made which can then be used to find the beam waist by fitting the points to a linear regression line.

2 Experimental Methods

Figure 1: *Photo of the setup. On the left end of the rail, a helium neon laser beam is fired towards to right side. Components such as power meter, polarizer, adjustable knife edge, and lens can be placed on the rail to analyze the laser beam.*

(Polarization) A sheet of linear polarizer is placed in be of the laser beam path, and power of the beam after going through is measured by a power meter. The angle of the linear polarizer can be adjusted and measured. The power of the beam was recorded as the angle of the polarizer was increased by 10 degrees intervals. The degree of polarization ρ is defined as:

$$\rho = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} \tag{7}$$

Where I_{max} is the maximum intensity of the beam and I_{min} is the minimum intensity of the beam.

(Beam Diameter) An adjustable knife edge is placed in front of the laser beam path with the power meter behind the laser beam as seen in figure 1. A micrometer controls how far the knife edge extends out into the beam. First knife edge position and power is recorded. The distribution of the power of the laser used in this experiment follows that of the error function. The error function for the power (equation 1) is derived by taking the intensity of a Gaussian beam and integrating over x and y.

$$I(x,y) = \frac{2P_0}{\pi\omega^2} exp(\frac{-2(x^2+y^2}{\omega^2}) \tag{8}$$

$$P = \int_{-\infty}^{\infty}\int_{a}^{\infty} I(x,y)(dx)dy \tag{9}$$

The solution to which is equation (1). When a $= \omega$ the knife is within one beam radius of the beam axis and when a $= -\omega$ the knife is one beam radius beyond the beam axis. These percentages of the total intensity are replicated at 6 different distances between the laser beam origin and knife. A linear fit of the data is created to find the beam diameter at the origin. (Beam divergence) By measuring the beam diameter from 1.595 meter away with the use of the adjustable knife edge, the divergence of the beam can be calculated using equation 3. In addition, equation 4 can be used to calculated the predicted divergence of the beam given its wavelength and beam diameter.

(Beam Waist) A lens is placed in the path of the laser beam. The focal length of the lens needs to be known, in our case the focal length was not known so we used a ceiling light to find at what height above the ground the light is focused and take that as the focal length f. The beam diameter is taken at 8 different lens positions in the z-axis (axis the beam is propagated in) by measuring the knife edge extension into the x-axis at 97.7 per max intensity and 2.3 per max intensity locations. Taking a linear fit of the beam diameter vs lens position plot allows for the minimum diameter and its position on the z-axis to be found.

3 Results and Analysis

A plot of polarizer angle vs power detected (figure 2) shows that the power detected by the power meter follows a sinusoidal pattern. The maximum power detected is $108 \pm 1\mu W$ at 120 degrees and the minimum power detected is $1.22 \pm 0.01\mu W$ at 220 degrees. Therefore, using equation 7, polarization ρ is calculated to be $\rho = 0.98 \pm 0.02$.

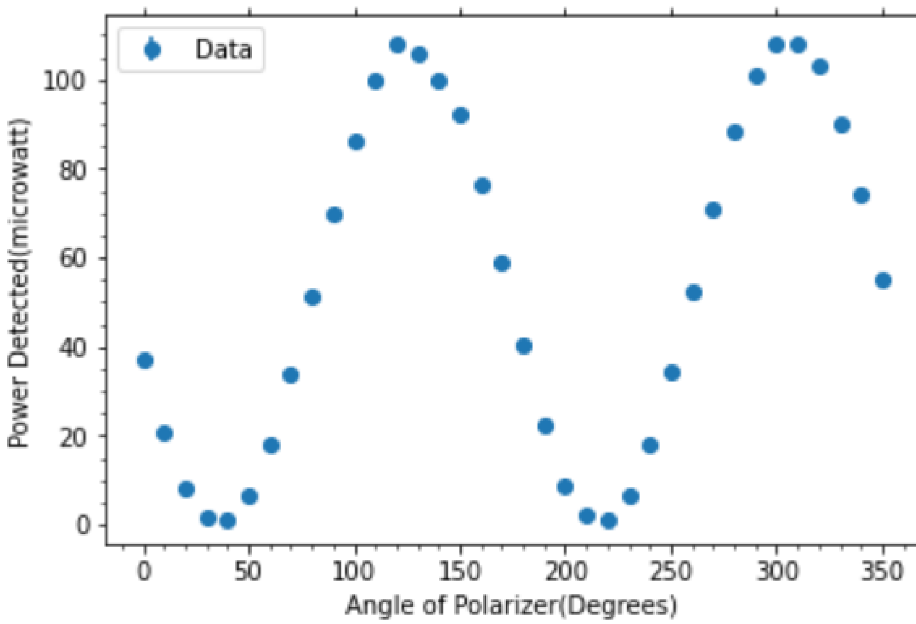

Figure 2: *Plot of power detected by the power meter as the angle of the polarizer was increased from 0 degrees to 350 degrees at 10 degrees intervals.*

Beam Diameter: A plot of knife edge distance vs power is constructed from the data (figure 2).

This plot (figure 2) resembles that of an error function which suggest the intensity is Gaussian. That allows us to use equation 1 . In the equation above P_0 is the full initial power of the beam, $\omega(z)$ is the radius of the beam, and a is the distance the knife edge is into the beam. Due to divergence the radius of the beam varies with the distance from the beam origin z. The initial beam power measured by the power meter is $180\mu W$. When the knife is one beam radius within the beam $a = -\omega$ and when the knife is one beam radius beyond the center of the beam axis $a = \omega$. This correlates to 0.977 and 0.023 of the original beam power respectively. These fractions of the beam power are reproduced at several distances to create a linear fit of distance in the z-axis vs beam diameter.

Using figure 3 we can see the y-intercept, and therefore the beam diameter at the origin D_0, is $1.361 \pm 0.007mm$.

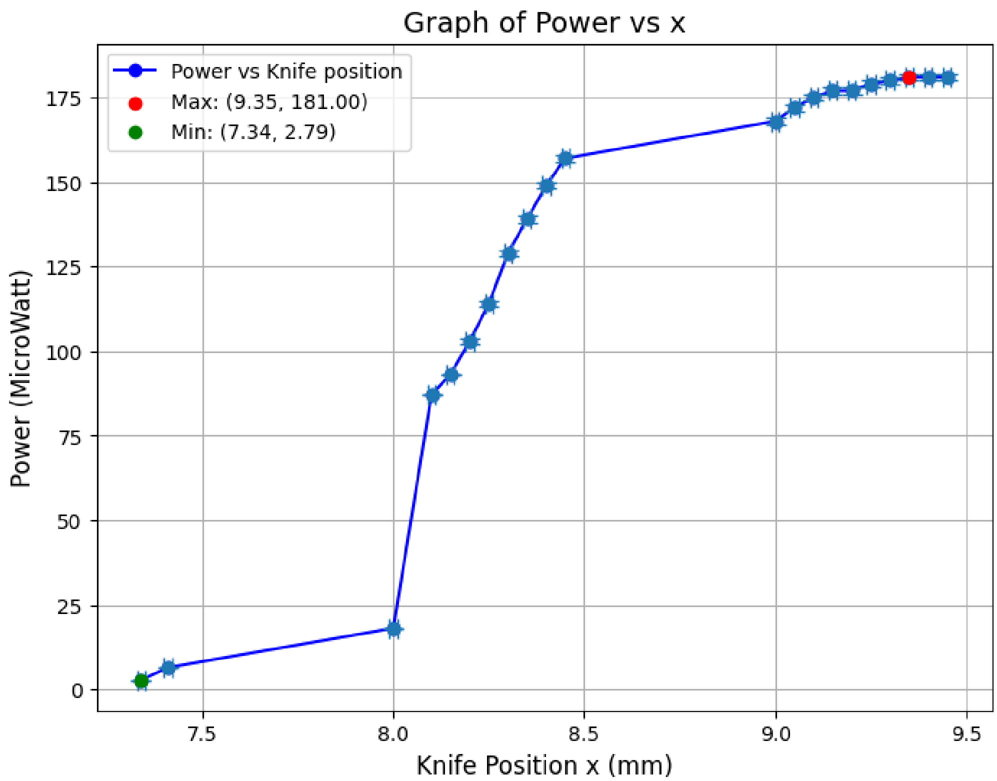

Figure 3: A plot of knife position x vs the power detected by the power meter. This plot is used to find the distribution of power for the laser beam used in our experiment. The uncertainty of the knife position and power are from the minimum resolution of the micrometer and power meter respectively.

At distance 1.595 ± 0.0025m, diameter of the laser beam was measured to be 2.755 ± 0.005mm. Using equation 3, divergence of the beam is calculated to be $\Delta\Theta = 0.864 \pm 0.002$ milliradian. Compared to manufacturer's value $2\Delta\Theta = 1.70$ milliradian, $2\Delta\Theta = 1.728 \pm 0.004$ milliradian, which is experimental error of 1.6%. The initial diameter of the beam is $D_0 = 1.361 \pm 0.001$mm and the wavelength of the beam is $\lambda = 632.8$nm. Using Fraunhofer diffraction equation(equation 4), divergence of the beam is calculated to be $\Delta\Theta = 0.567 \pm 0.003$ milliradian. $2\Delta\Theta = 1.134 \pm 0.006$ milliradian, which is an experimental error of 33.3%.

Method of Measurement	$2\Delta\Theta$ (Milliradian)	Uncertainty
Directly Measured	1.728	0.004
Fraunhofer Diffraction	1.134	0.006
Manufacturer's Value	1.70	N/A

Table 1: Measurement of Beam Divergence Using direct measurement of beam diameter, calculation using Fraunhofer Diffraction equation, and Manufacturer's value.

(Beam Waist)

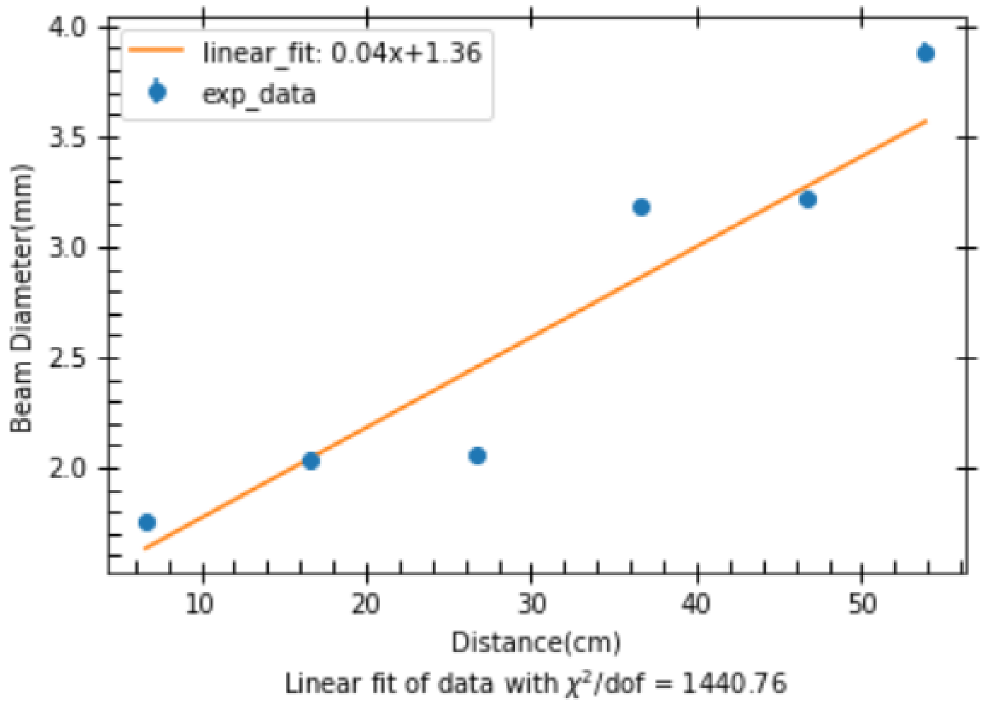

Figure 4: Linear fit of distance in z-axis vs beam diameter. The y-intercept gives the diameter of the beam at the origin.

A plot is constructed of distance from the beam waist and knife. Using the equation below:

$$D(z) = d\sqrt{1 + (\frac{z}{L}))^2} \tag{10}$$

where L is the distance to the beam waist and d is the beam waist itself, a linear fit can be constructed (Figure 4) by squaring both sides of the equation. The square root of the intercept is the beam waist $d = 0.979 \pm 0.008mm$ and the distance to the beam waist $L = 13.9 \pm 0.26mm$, this can be found by dividing the beam waist over the slope $(0.0703 \pm 0.00003mm)$.

4 Discussion

Polarization of the laser beam was measured to be $\rho = 0.98 \pm 0.02$, which is within 2% of perfect polarization of 1, which is the expected result due to the Brewster-window inside the laser linearly polarizing the laser beam.

The beam diameter was measured to be $1.361 \pm 0.007mm$ which is an error of 75% from the manufacture value of $0.34mm$. The large discrepancy could be due to a number of factors. The knife edge used in this experiment was fairly dull which could cause the beam to scatter which would increase the measured length.

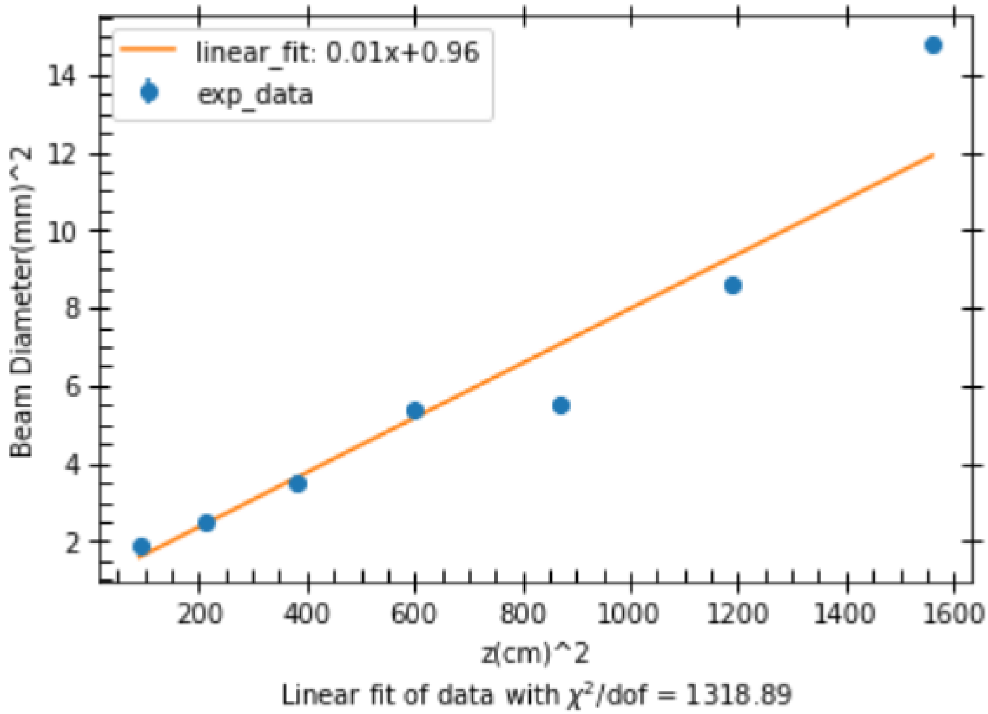

Figure 5: A plot of position from beam origin squared vs beam diameter squared. The y-intercept is $0.958 \pm 0.015mm$ and the slope is 0.0703 ± 0.0003 .

Another source of error comes from the power meter reading. The power readings were all shifted by the background light and small air currents such as a gust from a hand wave altered the reading. If the power readings were off the knife edge points we used would also be off as a result. More accurate data could be obtained by taking this measurement in a dark room and using a sharper edge.

Divergence of the laser beam was measured to be $2\Delta\Theta = 1.728 \pm 0.004$ milliradian, which is error of 1.6% of the expected value given by the manufacturere $2\Delta\Theta = 1.70$ milliradian. However, when the expected divergence was calculated by Fraunhofer diffraction equation(equation 4), $2\Delta\Theta = 1.134 \pm 0.006$ milliradian, which is 33.3% less than the expected value. This shows that Fraunhofer diffraction was not the only contribution to the laser beam's divergence, meaning that there were other factors diverging the beam further.

The beam waist was measured to be $0.979 \pm 0.008mm$ and the distance to the beam waist is $13.9 \pm 0.26mm$. Using equations 5 and 6 the calculated values for the beam waist is $1.361 \pm 0.007mm$ and the distance to the beam waist is $9.59 \pm 1.14mm$. This corresponds to a 28.1% and 31.0% error respectively. These errors are most likely due to the beam diameter measurement. That measurement was used in D_0 and as stated above it is off from the manufacturer value.