Experimental analysis of properties of Helium-Neon laser light

Lab Report #1

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Abstract

Our experiments focused on measuring and analyzing different properties and characteristics of a Helium-Neon laser. These included the polarization, beam profile, beam divergence, the beam waist created by a lens, and the longitudinal mode spacing. Our measured values were a degree of polarization of $\rho = 0.9955 \pm 6.28 \times 10^{-5}$, an initial beam diameter of 0.8 ± 0.07 mm, a beam divergence of 1.56 ± 0.16 mrads, a minimum beam waist of 1.11 ± 0.10 mm, and a mode spacing of 777 MHz. Some of measurements match or are near the accepted values and the specifications in the manual, except for the beam diameter, for which our measurement was off by a wide margin of error. The specified values for the laser are a minimum polarization of $\rho = 0.998$, a beam diameter of 0.48 ± 0.0144 mm, a beam divergence of 1.7 ± 0.051 mrads, and a longitudinal mode spacing of 1090 MHz [1]. Ultimately the measurements were not consistent with the accepted values for Helium-Neon lasers.

Introduction

The Helium-Neon laser was the first ever gas laser and is still used widely in laboratories and optics demonstrations because of its low cost and high quality beams. A Helium-Neon laser is a gas laser with a mixture of 9:1 Helium to Neon gas in a low pressure tube. By exciting the gas with an electric potential it allows the Neon atoms to be excited to a high energy state and then release light when it decays back down to an ordinary state. The wavelength of light that it releases, 632.8 nm, is specifically correlated to the transition of energy states from 5s to 3p that the outermost electrons in the Neon atom undergo. This released light is then reflected back and forth in a cylindrical mirrored tube, stimulating more excited neon atoms to release light. The tube is designed to only reflect light that is travelling in the axis parallel to its length and one of the mirrored edges of the tube transmits 1% of the light that hits it, forming the laser beam that then leaves the aperture.

Because of how the laser beams are formed in the optical cavity, different designs of laser mechanisms leads to lasers with different properties, even if they share characteristics, such as the monochromatic wavelength of 632.8 nm. One of the important characteristics of lasers is that they have spacial coherence and travel in Gaussian beams. This means that the intensity of the beam can be modeled as

$$I(x,y) = I_0 e^{\frac{-2r^2}{R^2}} \tag{1}$$

where R is the radius at which the intensity falls off to $\frac{1}{e^2}$ of the maximum.

Generally, to measure the different properties of a laser beam we observe how the output power of the laser changes under different circumstances, such as when passed through a polarization filter that only allows light of specific angles to pass through, or by blocking part of the beam to see how much the power is reduced. The power of the beam is just the beam intensity over an area, so the equation for the total power of a laser beam is

$$P_{tot} = 2\pi \int_0^\infty I_0 r e^{\frac{-2r^2}{R^2}} dr \tag{2}$$

or in Cartesian coordinates,

$$P_{tot} = \int_{-\infty}^\infty \int_{-\infty}^\infty I_0 e^{\frac{-2(x^2+y^2)}{R^2}} dxdy \tag{3}$$

by evaluating this integral we see that

$$P_{tot} = \frac{I_0 \pi R^2}{2} \tag{4}$$

where the total intensity inside the radius R is

$$I_{tot} = \frac{P_{tot}}{A} = \frac{I_0}{2} \tag{5}$$

Utilizing these equations and the knowledge of how laser beams are formed and resonate inside the optical cavity we can attempt to accurately assess several different properties of the He-Ne laser by measuring its power output. These properties include the degree of polarization, how much of the light is at one angle, the beam profile and diameter, the beam divergence, how much the beam spreads out as it moves away from the laser aperture, the beam waist, which is how narrow the beam diameter gets focused when the beam passes through a lens, and the mode spacing, which is how wide the spread of the laser's wavelengths is.

Experimental Methods

For all of the experiments our devices were on an optics table and mounted on an optical rail, with the He-Ne laser mounted on one end of the rail and aimed down its length as seen in Figure 1. The optical rail had increments of 1 mm, which we used to determine distance in the direction of the beam axis.

The optical tools and devices that we used in our experiments included a laser power meter, which measures the power, in microwatts, received into the meter's aperture. The power meter had a maximum rated uncertainty of 1% of the measured power, meaning $\delta P = \frac{|P|}{100}$. The next tool was a polarizer sheet mounted on a rotating dial with a precision of 2°. This allowed us to vary the angle at which the beam went through the polarized material. For our experiment we recorded the power output at angles from 0° to 180° in 10° increments, searching for the minimum and maximum values of intensity in order to calculate how much of the laser beam was polarized in a single direction. The third tool we used was a razor edge mounted on a micrometer. The micrometer could move perpendicularly to the beam axis, meaning we could use the razor edge to block part or all of the laser beam, which can be seen in Figure 2.

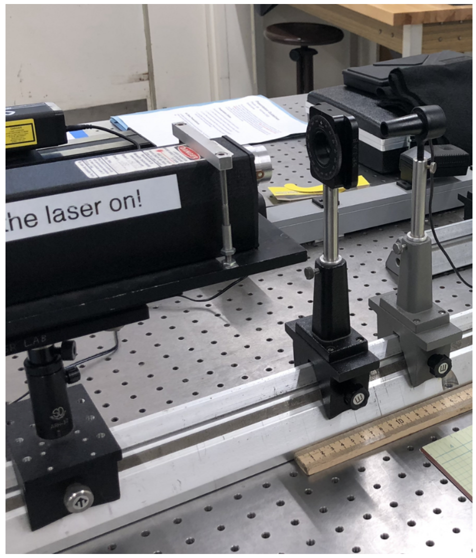

Figure 1: Picture of setup for beam polarization experiment. Shows the optical table and rail that the devices are mounted on. The devices seen in the picture, from left to right, are the Helium-Neon laser, the polarizer sheet, and the power meter.

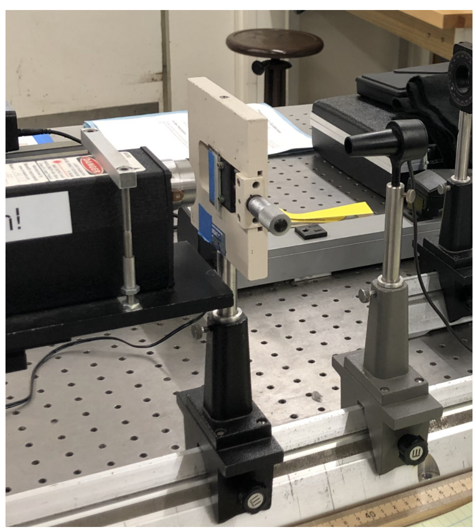

Figure 2: Picture of setup for beam profile experiment. The razor edge can be seen in between the laser and power meter blocking part of the laser beam. This same setup is used for measuring the beam diameter

By comparing the power output when different amounts of the beam are blocked we can then create an accurate depiction of the power output of the beam over its cross section, also referred to as the beam profile. For our experiment we recorded the power output as a function of the position of the razor edge position perpendicular to the beam axis, and then fit this data to Equation 1, to create a model for the beam intensity profile. This leads directly into how we can calculate beam diameter using the razor edge obstruction and Equations 3 and 4. To measure beam diameter first calculate the percentage of the total power when the razor edge is one radius away from the beam axis

$$P_1 = I_0 \int_{-\infty}^{\infty} e^{\frac{-2y^2}{R^2}} dy \int_{-R}^{\infty} e^{\frac{-2x^2}{R^2}} dx$$

From this we find $\frac{P_1}{P_{tot}} = 97.73\%$. Next find the percentage of total power when the razor edge is one radius beyond the beam axis

$$P_2 = I_0 \int_{-\infty}^{\infty} e^{\frac{-2y^2}{R^2}} dy \int_{R}^{\infty} e^{\frac{-2x^2}{R^2}} dx$$

From this we find $\frac{P_2}{P_{tot}} = 2.27\%$. These percentages form a basis with which we can compare to the measured total laser power and determine the razor edge positions of the two sides of the beam diameter. The procedure is as follows: first measure the total power of the laser when unobstructed with the power meter. Next move the razor edge across the beam until the measured power is 97.73% of the measured total power, and record the position of the knife edge, x_1. Then continue moving the razor edge across the beam until the measured power is 2.27% of the measured total power, and record the position of the knife edge, x_2. The beam diameter, D_0, is then the difference between the two razor edge positions

$$D_0 = x_1 - x_2$$

This method of determining the beam diameter is also part the procedure for measuring the beam divergence, which is just how much the diameter increases at distances far from the laser aperture. To find the beam divergence, we recorded the beam diameter at a distance of 1.5 cm away from the laser aperture and again at a distance of 1.5 m away from the laser aperture. By comparing the difference in diameter and distance between these measurements we can determine the beam divergence.

The next experiment was the measurement of the beam waist, which is the minimum diameter of a laser beam passed through a lens. For this experiment we used a lens, with focal length of 0.1 m, placed 0.1 m away from the laser aperture along the beam axis. We then measured the diameter of the beam at different positions by moving the razor edge in 5 cm increments along the beam axis. We had our power meter at a distance of 0.8 m from the lens for the entirety of this experiment.

The last experiment was the measurement of the mode spacing using the Fabry-Perot interferometer. The Fabry-Perot interferometer works by funneling light into an optical cavity, however, due to its design only frequencies of light that resonate with the cavity can pass through and be measured by a photo-multiplier tube, converted to a voltage, and displayed on an adjacent oscilloscope. The optical cavity is also capable of changing length, which also changes the frequencies of light that resonate in it. This allows the Fabry-Perot interferometer to display the intensity of laser light as a function of frequency. Prior to our experiment we calibrated and initialized our setup using the following procedure. First turn the RISE-TIME knob counterclockwise until it reaches the mechanical end. Continue rotating the knob until the line on the knob coincides with the panel marking on the right side of the range. Next we slowly rotated the knob clockwise until it reaches the mechanical end and the line coincides with the left side marking. Repeat this process for the offset and amplitude knobs.

To measure the mode spacing we direct the laser into the optical cavity, and set the interferometer to sweep through different lengths. The oscilloscope outputs the laser intensity and length of cavity as voltages. By aligning the different clusters along the divisions of the oscilloscope we can convert the horizontal divisions to the Free Spectral Range frequency of the interferometer, which for our instrument was 7.5 GHz. Then by using the cursor and scope caps from the oscilloscope we found the difference in frequencies that each mode resonates at.

Raw Data

Polarization

The data collected for our measurements of the beam polarization can be seen below in Table 1 and is visualized in the plot in Figure 3. Error in this experiment comes from the dial holding the polarizer sheet which had precision of 2° and the uncertainty of the power meter, which is rated to 1% of the measured power. Our minimum and maximum measured intensity, respectively, were 1 ± 0.01 μW and 448 ± 4.48 μW

Polarizer Angle (°)	Power (μW)	δP (μW)
0	159	1.59
10	87	0.87
20	35	0.35
30	6	0.06
40	3	0.03
50	28	0.28
60	76	0.76
70	142	1.42
80	219	2.19
90	296	2.96
100	366	3.66
110	417	4.17
120	444	4.44
130	446	4.46
140	420	4.20
150	375	3.75
160	307	3.07
170	236	2.36
180	159	1.59

Table 1: Power output at different angles of the polarizer sheet. From the data it can be seen the maximum power is at 130° and the minimum is at 40°, which are 90° apart. The uncertainty in the angle is $\delta\theta = \pm 1°$ and the uncertainty in power is $\frac{\delta P}{|P|} = 1\%$

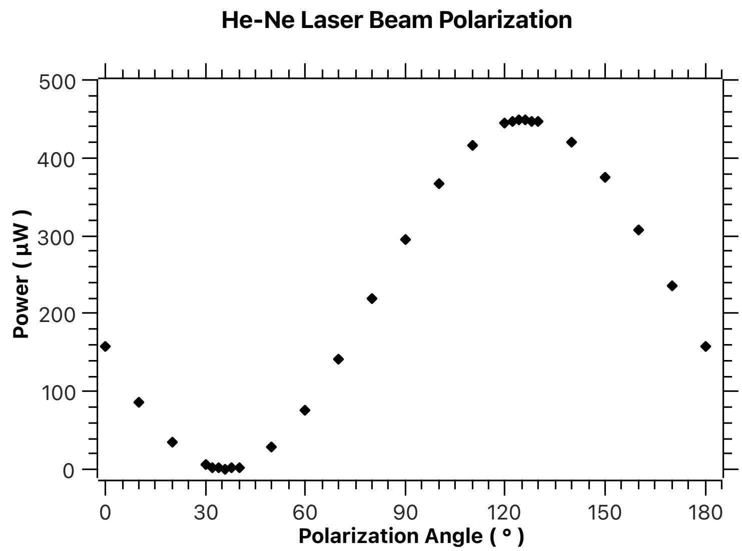

Figure 3: Plot of data for laser polarization. Clearly shows minimum power when the polarizer sheet is at 35° and maximum at 125°. Also displays period of 180° as polarized light can pass through either angle. Uncertainties in data points are comparable to symbol size.

Beam Profile

The data collected for this experiment can be seen below in Table 2 and visualized in the plot in Figure 4. The error in this experiment came mainly from the precision of our equipment. The micrometer holding the razor edge has a precision of 10 μm and the uncertainty of the power meter is rated to 1% of the measured power.

Edge Position (m)	Power (μW)	δP (μW)
0	0.54	0.0054
0.001	0.54	0.0054
0.002	0.54	0.0054
0.003	0.54	0.0054
0.004	0.54	0.0054
0.005	0.54	0.0054
0.006	0.54	0.0054
0.007	0.54	0.0054
0.008	0.54	0.0054
0.009	0.58	0.0058
0.00925	1.56	0.0156
0.0095	13.1	0.131
0.00975	206	2.06
0.01	571	5.71
0.01025	726	7.26
0.0105	738	7.38
0.01075	740	7.40
0.011	741	7.41
0.012	741	7.41
0.013	741	7.41
0.014	741	7.41

Table 2: Power output of He-Ne laser as the razor edge moves across the beam profile. From the data it can be seen that the power first begins changing at 0.009 m and plateaus around 0.0105 m. The uncertainty in edge position is $\delta x = \pm 5 \times 10^{-6}$ m and the uncertainty in power is $\frac{\delta P}{|P|} = 1\%$

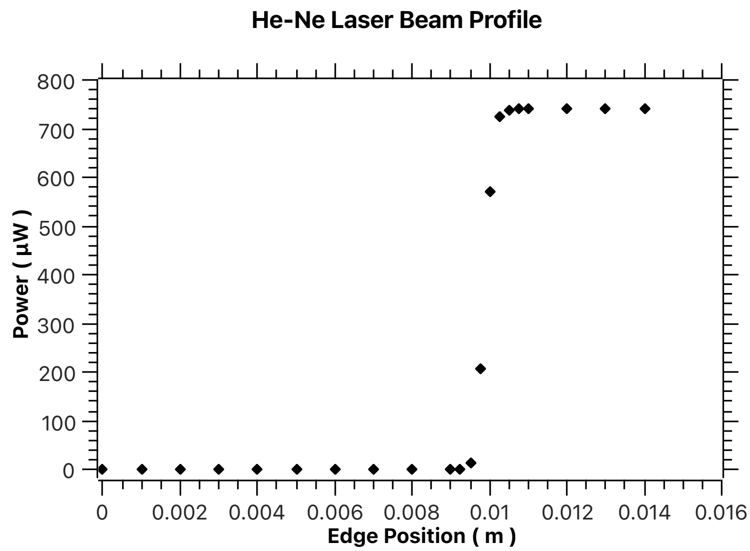

Figure 4: Plot of He-Ne laser beam profile taken by measuring the power output while an edge blocks part of the beam. The sharp increase and plateau displays how narrow the beam is. Uncertainties in data points are comparable to symbol size.

Beam Divergence

Our measurements for the Beam divergence can be seen below in Table 3. The error in this experiment came mainly from the precision of our equipment. The optical rail with which we measured the distance from the lens had an uncertainty of $\delta x = \pm 5$ mm and the micrometer holding the razor edge has a precision of 10 μm, so therefore the measured diameter has an uncertainty of $\delta D = \pm 0.07$ mm.

Distance from lens (m)	x_1 (mm)	x_2 (mm)	Beam diameter (mm)
1.5	10.45	8.50	1.95
0.0015	10.94	10.14	0.80

Table 3: Diameter of He-Ne laser beam at two different distances from the laser aperture. The edges of the beam were found using the method discussed in the Experimental Methods section. x_1 is at $0.9773P_{tot}$ and x_2 is at $0.0227P_{tot}$, where P_{tot} is measured at the same distance without any obstruction from the razor edge.

Beam Waist

The data collected for this experiment can be seen below in Table 4. In our measurements we saw a minimum beam waist value of 1.11 $\pm$0.1 mm. The error in this experiment came mainly from the precision of our equipment. The optical rail with which we measured the distance from the lens had an uncertainty of $\delta x = \pm 5$ mm and the micrometer holding the razor edge has a precision of 10 μm, so the uncertainty in the diameter is $\delta D = \pm 0.1$ mm. Also since we could not find a manufacturers measurement for the focal length of our lens, we attempted to measure it ourselves and determined the focal length, f, had a value of f $= 10 \pm 0.5$ cm.

Distance from lens (m)	Diameter (mm)
0.05	1.68
0.1	1.62
0.15	1.49
0.2	1.11
0.25	1.67
0.3	1.47
0.35	1.67
0.4	1.95
0.45	2.26
0.5	2.63
0.55	3.04
0.6	3.43

Table 4: Diameter of the laser beam as distance from the lens increases. The measurements show a minimum of the beam waist at 0.2 m, where the beam has a diameter of 1.11 mm. The uncertainty for the distance is $\delta x = \pm 5 \times 10^{-3}$ m and the uncertainty in the diameter is $\delta D = \pm 0.1$mm.

Mode Spacing

The data we collected during our mode spacing experiment can be seen in the scope captures below in Figures 5 and 6. The clusters in Figure 5 are approximately 1 division apart so the FSR/div. is 1. Figure 6 is a scaled up picture of one of the clusters and the division is $\frac{1}{10}$ the size so the FSR/div. is $\frac{1}{10}$ or 750 MHz/div..

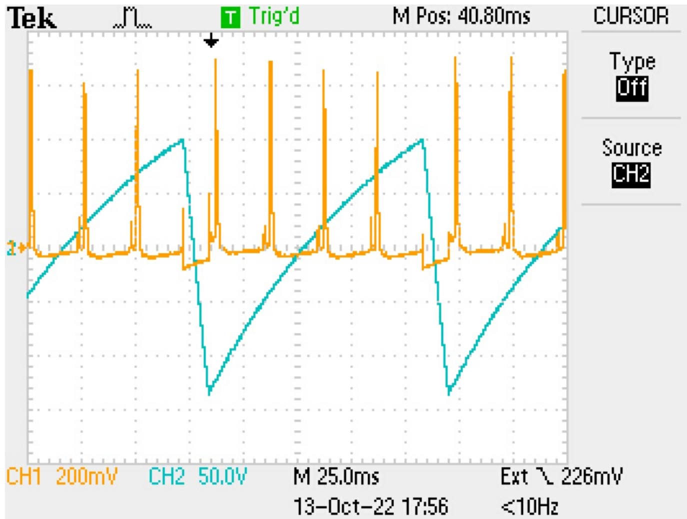

Figure 5: Screen capture from the Fabry-Perot Interferometer oscilloscope showing 4 longitudinal modes over the ramp cycle.

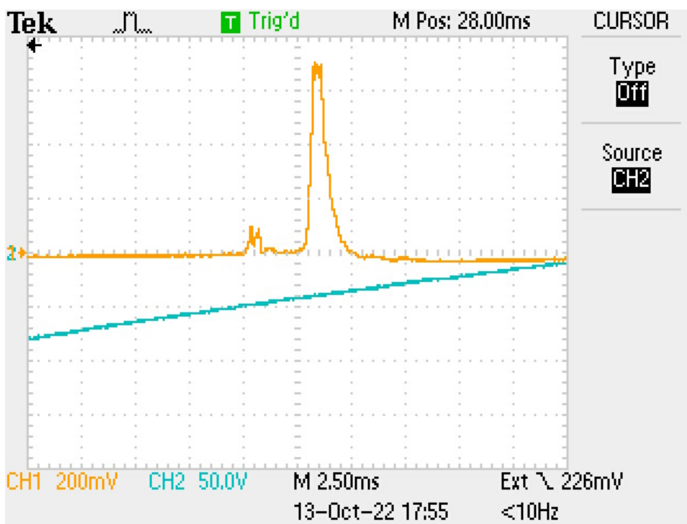

Figure 6: Screen capture from the Fabry-Perot Interferometer oscilloscope showing a closeup of the mode spacing.

Results

Degree of Polarization

To calculate the degree of polarization for our laser from our intensity data we used the formula

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

with the formula for error propagation being

$$\delta \mathrm{P} = \sqrt{\left(\frac{\partial \mathrm{P}}{\partial \mathrm{I_{max}}} \delta \mathrm{I_{max}}\right)^2 + \left(\frac{\partial \mathrm{P}}{\partial \mathrm{I_{min}}} \delta \mathrm{I_{min}}\right)^2}$$

Calculating from our collected data we found a degree of polarization

$$\rho = 0.9955 \pm 6.28 \times 10^{-5}$$

Beam Profile

From the measurements taken in our beam profile, we fit the data to our Gaussian model of beam intensity in Equation 1 to find

$$\mathrm{R} = 0.75 \pm 0.18 \mathrm{mm}$$

and

$$I_0 = 8.38 \times 10^8 \pm 8.38 \times 10^6 \ \frac{\mu \mathrm{W}}{\mathrm{m}^2}$$

Beam Divergence

To calculate the beam divergence from our collected data we used the formula

$$2\Delta\theta = 2 \arctan \frac{r_{beam\ 1} - r_{beam\ 2}}{x_1 - x_2} \approx 2 \left(\frac{r_{beam\ 1} - r_{beam\ 2}}{x_1 - x_2}\right)$$

where x_1 and x_2 are the two distances from the laser aperture and $r_{beam\ 1}$ and $r_{beam\ 2}$ are the radii at those two respective distances. The error propagation is then given by

$$\delta \mathrm{Div} = \sqrt{\left(\frac{\partial \mathrm{Div}}{\partial r_1} \delta r_1\right)^2 + \left(\frac{\partial \mathrm{Div}}{\partial r_2} \delta r_2\right)^2 + \left(\frac{\partial \mathrm{Div}}{\partial x_1} \delta x_1\right)^2 + \left(\frac{\partial \mathrm{Div}}{\partial x_2} \delta x_2\right)^2}$$

From these equations we calculated that the beam had a divergence 1.56 ± 0.16 mrads.

Beam Waist

Our analyzed data for our measurements of the beam waist can be seen in the plot below in Figure 7. According to the beam waist formula

$$d = \left(\frac{4\lambda}{\pi}\right)\left(\frac{f}{D_0}\right)$$

The minimum beam waist for our lens' focal length and measured initial diameter should be $d = 1.01 \times 10^{-4}$ However our measured value for the minimum beam waist of 1.11 ± 0.1 mm is almost a full order of magnitude larger than this expected value. This large source of error may have been due to the fact that our power meter was in the same place for all of our trials, even as the razor edge was being moved up and down the beam axis. This may have caused some kind of diffraction or divergence of the beam when being obscured by the razor edge which could have skewed our reading on the power meter, which was vital in our procedure to measure the beam diameter.

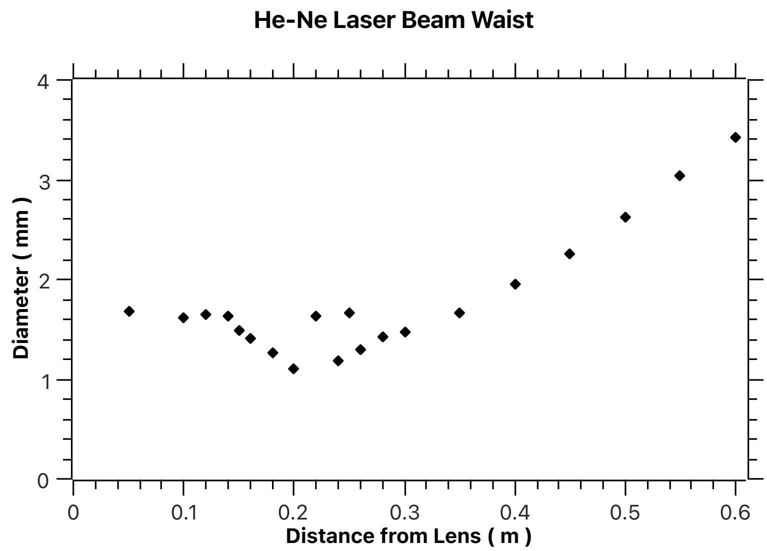

Figure 7: Beam diameter at different distances from a 10 cm focal length lens. Beam waist is visible at 0.2 m. However there was a large spike in measured diameter in what should have been the narrowest part of the beam waist, seen in the two outlying points above the others at 0.22 m and 0.25 m. Uncertainties in data points are comparable to symbol size.

Mode Spacing

As seen in Figure 6 the distance between the modes is approximately 1 division. More specifically by using the .csv data from this scope capture we found the the seperation between the maximums was 2.59 ms. This is converted into the mode spacing in frequency with

$$2.59 \text{ ms} \times \frac{1 \text{ div.}}{2.50 \text{ ms}} \times \frac{0.1 \text{ FSR}}{1 \text{ div.}} \times 7.5 \times 10^9 \text{ Hz} = 777 \text{ MHz}$$

Discussion

The results that we measured for the lasers properties of polarization, beam diameter, beam divergence, beam waist, and mode spacing were, for the most part, far from the accepted values for the type of laser that we were using, even when considering the uncertainties on the measured values. In some areas our experiments agreed with the accepted values such as the degree of polarization, and showed that the laser beam had a 99% level of polarization at the angle of 125°. Also in this category is the beam divergence, which coincided with the expected value of 1.7 $\pm$0.051 mrads, but had a much wider range of uncertainty. Other measurements such as the beam waist, beam diameter at the laser out port, and mode spacing were off from the expected values by a wide margin. These experiments may have had some source of systemic error that we overlooked while undertaking our experiment. For example in the beam waist and mode spacing our detectors were very far from the laser aperture and well past the coherence length of our laser, which could have adversely effected our measurements. If we were to repeat our experiments it could be beneficial to try and keep the sensors as close to the laser out port as possible for our measurements and see if that would make any noticeable difference.

References

[1] "Hnls008l self-contained hene laser, 632.8 nm, 0.8 mw, polarized, 120 vac power supply." [Online]. Available: https://www.thorlabs.com/thorproduct.cfm?partnumber=HNLS008L#ad-image-0