

Analysis of Gaussian Beam Distribution Qualities of a Helium-Neon Laser

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Abstract

The properties of laser light naturally change as it propagates over any path. Our work intends to verify that the propagation happens in accordance with what is expected for a Gaussian beam, and to make precise measurements of the location, size, and curvature of the beam waist to show that there is indeed a location of smallest spot diameter over the course of the beam. We found that there is indeed a minimum spot radius of the beam, located approximately 14cm away from the aperture of the laser.

Introduction

Many common types of lasers emit electromagnetic radiation in a profile that is well-approximated by a Gaussian function. If the assumption of Gaussian-qualities holds over the trajectory of the beam, the intensity and physical size of the emitted beam is expected to vary over the path of propagation according to factors determined by the construction of the laser and environmental components. Most notably, the beam is expected to pass through an absolute minimum of size and intensity as opposed to expanding uniformly over the entire path. This minimum is a result of the internal optics that collimate the laser light, leading to a focal point, of sorts, where the beam waist is.

Theory

According to Gaussian beam theory, the intensity of the beam should vary according to:

$$I(x) = Ae^{\frac{-2r^2}{w^2}}$$

Where A is the maximum intensity of the laser at the given distance, r is the radius of the beam from the axis, and w is a normalized radius, located at the distance from the axis that the intensity of the beam has dropped to $\frac{1}{e^2}$ of its original value.

If we plot the values of intensity over all measurements of the laser we collect, we would then be able to make an estimate of the derivative of the function comprised of those data points and obtain an estimate for the minimum intensity, or beam waist.

While the beam waist is defined in terms of intensity, the Gaussian beam profile implies that the waist will also be manifested as a physically smaller spot radius. If this is true, differential calculus predicts that the beam equation at the

waist will have a first derivative equal to zero and a second derivative equal to some maximum curvature.

Methods

To verify that the helium-neon laser propagates with Gaussian distribution and that a waist exists, we used a ThorLabs HNL020L 632.8nm Helium-Neon laser and measured its propagation with a Coherent Lasercam-HR camera after filtering the light with a red filter and an appropriate number of neutral density filters based on the propagation distance. The experiment was performed on an optics table with pneumatic vibration damping in an attempt to minimize environmental effects on measurement of the beam's propagation.

The sensor was placed at varying distances from the laser, ranging from 10cm to 201cm. The specific distances were chosen to give the best representation of beam propagation. Measurements were taken more often at positions closer to the sensor in order to enhance efforts to determine the existence of the beam's waist. For measurements taken further away from the laser and at less evenly spaced intervals, accompanying measurements were taken at ± 1 cm from the central location to provide enough data to calculate the first and second derivatives at that location. Neutral density filters were placed on the sensor to temper the beam's intensity upon meeting the sensor.

One of the problems in determining the beam size is deciding exactly what constitutes the edge of the beam as there is always noise on the sensor and the data points of the beam become increasingly scattered at greater distance. There are numerous "accepted" definitions of the beam radius, like $\frac{1}{2}$ and $\frac{1}{e^2}$ of its greatest value. Given the relative imprecision of our measurement techniques, we instead opted to look at a range of beam diameters, starting at $\frac{1}{10}$ of the max up to $\frac{9}{10}$ of the max.

Using MATLAB, we wrote a program to batch process the image files using the following algorithm:

1. Compile image data into array
2. Calculate maximum intensity value of each image
3. Scale the maximum values to account for varying levels of neutral density filters
4. Reduce the maximum value by a coefficient as described above

5. Find the x-y coordinates of a contour of that image at the reduced maximum level
6. Find the distance between the minimum and maximum x- and y-coordinates of the contour and average them as a measurement of the spot diameter
7. Compute the first derivative by $\frac{f(x+h)-f(x-h)}{2h}$
8. Compute the second derivative by $\frac{f(x+h)-2f(x)+f(x-h)}{h}$

Results

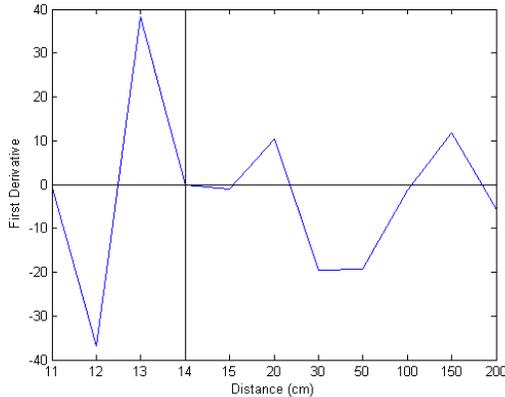


Figure 1: First derivative data averaged over all diameters. Note the near-zero value at 14cm.

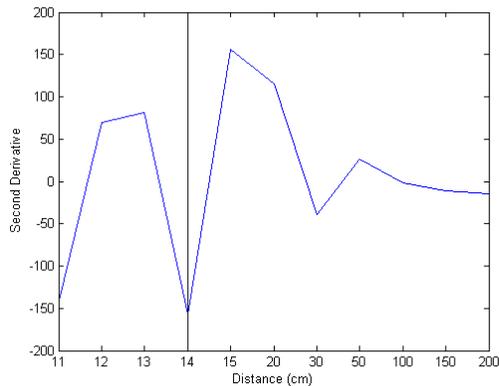


Figure 2: Second derivative data averaged over all diameters. Note the absolute minimum value at 14cm.

As is evident from these two figures, our measurement of the beam at 14cm from the aperture exhibits precisely the two criteria we predicted the beam waist would exhibit. We know the valley on the Figure 2 is indeed a universal extreme as this particular point was exhibited by graphs over all beam diameter definitions, while any other peaks were unique to one graph or another. Similarly for Figure 1, graphs of all definitions show the value at 14 cm to be zero, despite some having zero-valued derivatives at other locations.

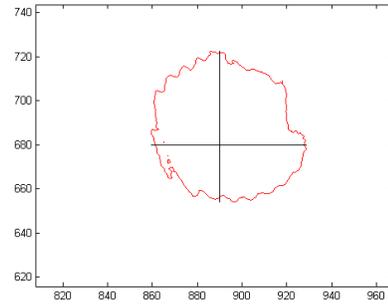


Figure 3: Sample contour of measurement at 14cm at 0.5*max level. The crossing lines connect the max and min x and y coordinates.

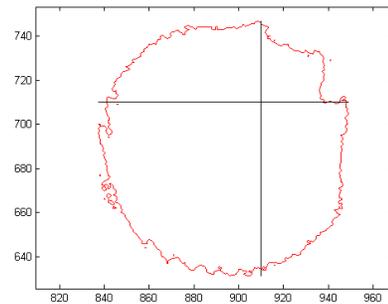


Figure 4: Sample contour of measurement at 14cm at $\frac{1}{e^2}$ *max level. The crossing lines connect the max and min x and y coordinates.

Conclusions

Based on our data, there is a readily apparent minimum size of the beam located around the 14 cm mark. The existence of this minimum is corroborated by both the numerically calculated first and second derivatives of the beam size over numerous definitions of beam diameter and a two dimensional averaged diameter measurement. Since our measurements were only taken at integer distances from the laser's aperture, there is a high likelihood that the exact location of the waist differs from our measurement, though it differs by no more than 1cm in either direction and is most likely within 0.5 cm of the 14cm mark.

References

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3. Klein, Deb. Learning How Laser Beams Propagate. <http://laser.physics.sunysb.edu/~wise/wise187/2005/reports/deb/report.html>