Schlieren Diagnostic for the Imaging of Thermal Turbulence

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I Abstract

Turbulence and refractive index gradients arise from heat or gas flow through air and have long been an issue, disrupting the propagation of laser beams as well as their stability and ability to focus on a tight spot. Schlieren, a type of imaging used to visualize gradients in indices of refraction, has been proposed as a possible way to identify turbulence such as that occuring in CLARA amplifiers used at the Laboratory for Laser Energetics. In this experiment, through the setup of a Schlieren system consisting of a pinhole light source, a concave parabolic mirror and a razor blade it was possible to record the flow of heat and gas through air. Using the Schlieren system, a hot plate was analyzed at various temperatures ranging from 40-50 degrees Celsius. Videos were taken at a given temperature and a MATLAB script was devised to average these videos into a composite image. The script then finds the root-mean-square deviation between the averaged image and each individual frame in the video. The resulting matrix when displayed as an image represents turbulence from the hot plate. This process was repeated for nitrogen flow at varying pressures. Upon comparing the hot plate and nitrogen, it was explored whether the effects from turbulence could be reduced through heating nitrogen. Finally, various laser parts were analyzed such as a laser crystal cell and a gas diffuser to see how they may be contributing to gas-related turbulence.

II Introduction

The Laboratory for Laser Energetics (LLE) is home to two of the world's most powerful lasers–the 60 beam OMEGA and four beam OMEGA EP. Analysis of laser systems at the lab has revealed disruptions in the propagation of beams around CLARA amplifiers. Figure 1 shows an image of a laser beam before and after it passes through an amplifier. These images reveal how the laser beam changes from its square shape shown on the left to the more irregular shape on the right. Figure 2 shows an image of the CLARA amplifier, which the beam in Figure 1 is passing through. An image taken with a thermal imager shows this to be an area of high thermal activity relative to room temperature. This leads to the belief that it is turbulence coming from this heat that causes the breakdown in the laser beam's form shown in Figure 1.

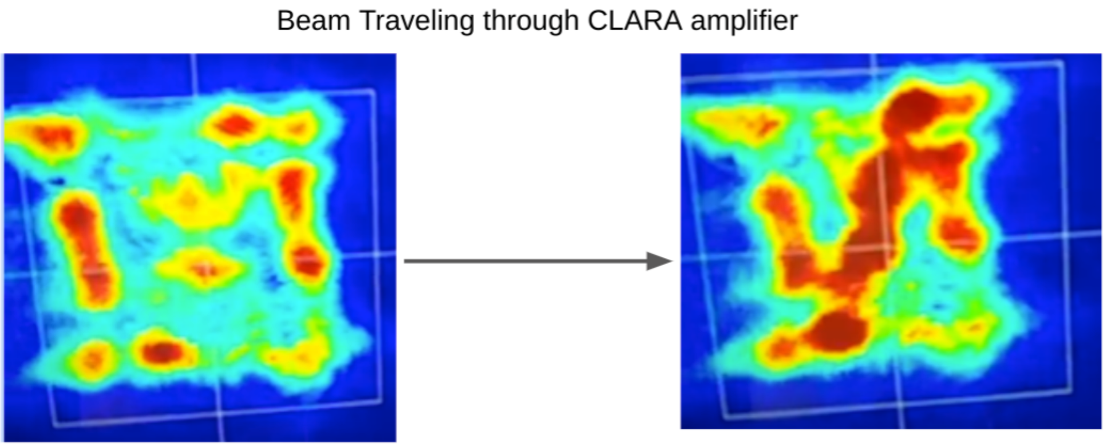


Figure 1: Intensity maps of a square laser beam before and after it passes through a CLARA amplifier. The image on the left shows a square beam with a relatively even distribution of intensities. The beam on the right shows the beam as it exits the amplifier. This image of the beam shows a breakdown in its shape as well as an uneven distribution in the beam's intensity as shown by the change in the red, green and blue spots.

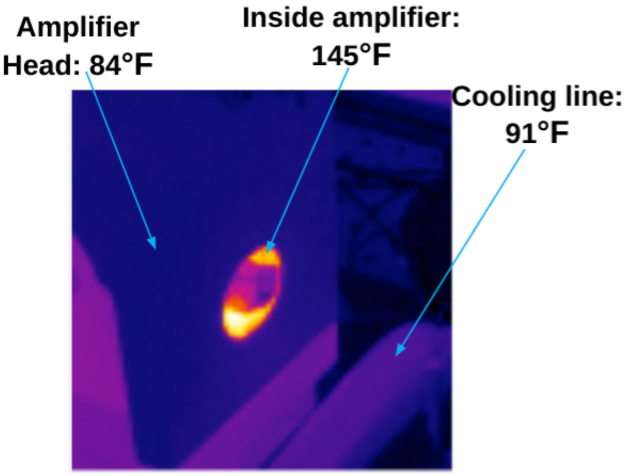


Figure 2: A picture of a CLARA amplifier, which is a rod surrounded by flash lamps with the beam propagating along its axis, that increases the intensity of a laser. This image is taken with a thermal imager, which shows the temperature of the various parts of the amplifier. This helps one understand a potential source of the disruptions seen in Figure 1.

In fluid mechanics there are two predominant types of flow, laminar and turbulent. Laminar flow is characterized by a streamlined flow, lacking irregularities, in which fluid layers move parallel to each other. Laminar flow is also typical of fluids moving at a slower velocity. Turbulent flow in contrast is disorderly and occurs when fluid layers cross each other, moving at high velocities [1]. Any deflections caused by a refractive index gradient–coming from either laminar or turbulent flow–can disrupt the travel of lasers. However, those caused by turbulent flow are the most problematic.

Schlieren is a method of imaging originating from the German word *Schliere*, meaning streak. Historically, Schlieren has been used to visualize the flow of fluids which form a refractive index gradient, finding application in aerospace engineering and glass making [2]. Modern computers and programming languages such as MATLAB, however, allow for novel forms of analyzing and quantifying a Schlieren image. With this in mind, the goal of this project is to visualize nonuniformities in the index of refraction, including those coming from turbulent flow, through building a Schlieren system and writing a MATLAB script. In doing this work, LLE has gained insight into disturbances which affect laser systems as well as information which will allow for possible solutions to these problems.

III Experimental Setup

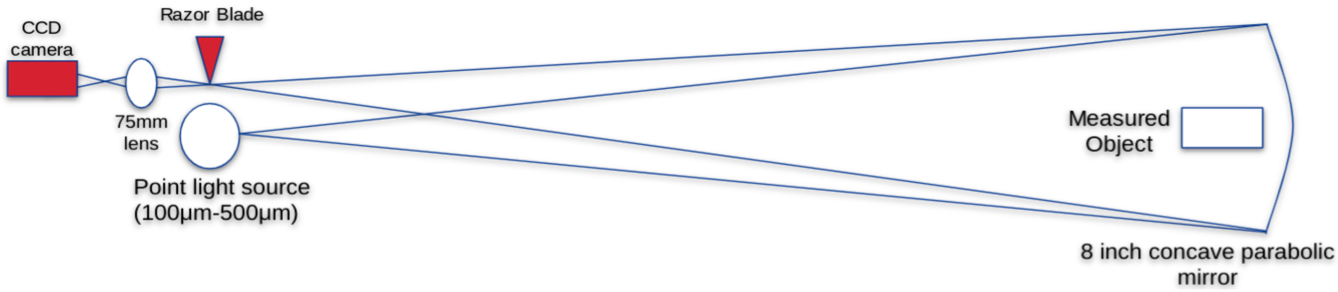


Figure 3: Experimental setup. A light source of diameter 100-500 microns expands and is reflected off a concave parabolic mirror, causing it to refocus near the original point. A razor blade is inserted at the new focus, cutting off exactly half of the refocused light. The remaining light passes through and is imaged by a 75 mm lens onto a CCD camera which displays the Schlieren image of the measured object onto a computer. The point light source is placed 2 focal distances away (400 cm) from the mirror at half the mirror's height (10 cm)

The optical basis behind Schlieren comes from Snell's law, which indicates that as a wave, in our case light, passes between two optical media it refracts or bends relative to the interface normal based on the change in index of refraction. Snell's law can be stated as the equation: $N_1 Sin\theta_1 = N_2 Sin\theta_2$ where N_1 is the index of refraction of the first medium, N_2 is that of the second medium, θ_1 is the angle of incidence relative to the interface normal, and θ_2 is the angle of refraction. Changes in temperature lead to small changes in index of refraction, somewhere on the order of one thousandth of a percent for each degree. In Figure 3 as light passes through the point labeled "measured object," it refracts relative to the amount of heat–or type and amount of gas–it passes through. The light having been refracted, the new focus will be moved by an infinitesimally small amount, invisible to the human eye. The position of the razor blade can then block a portion of this refracted light, preventing it from reaching the camera. The opposite is also true in that refracted light can shift part of the focus sideways, off the razor blade, allowing more light to reach the camera. These slight changes in the position of the focus create dark and light regions respectively where there are nonuniformities in refractive index [2]. A Schlieren image of a hot plate, placed in the area labeled "measured object," is seen in Figure 4 showing the dark and light spots created by the flow of heat through air.

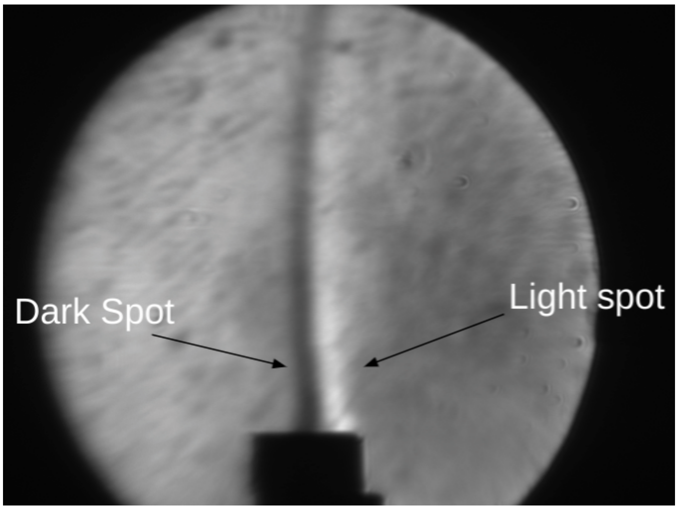


Figure 4: Schlieren image of a hot plate, illustrating dark and light regions caused by the refraction of light as it passes through the warm air. The hot plate is the rectangular black object in the middle of the bottom of the figure, beneath the light and dark regions.

Various light sources were utilized in this work including white light, a monochromatic flashlight and a helium neon (HeNe) laser. Each source had various pros and cons associated with the Schlieren image it produced.

III.I Light sources: White Light

White light was the original light source used with the Schlieren setup. A Thorlabs adjustable lamp was placed against a pinhole ranging from 100-500 microns in diameter. The white light was advantageous in that it could be placed against a pinhole, didn't require focusing, and had an adjustable intensity. This was useful as pinholes can be interchanged, yielding different results as deemed necessary while light intensity could be adjusted as needed to procure the sharpest image. The primary downside to using white light was that the 75 mm imaging lens seen in Figure 3 was a monochromatic lens while white light contains many wavelengths. This led to somewhat of a smearing effect in the images due to the uneven focusing of light.

III.II Light Sources: Monochromatic Flashlight

To alleviate the smearing effect from the white light, an attempt was made to use a monochromatic green flashlight. While the smearing was eliminated, focusing the flashlight–a device fitted with its own optics–through a pinhole was difficult. In addition there was insufficient light illuminating the mirror and it was impossible to record a detailed image.

III.III Light Sources: HeNe Laser

To fix the problem of smearing while still maintaining sufficient illumination of the mirror, a HeNe laser was used. Since laser light is highly collimated a system of lenses as seen in Figure 5 was used to expand the beam so that it could cover the entirety of the mirror.

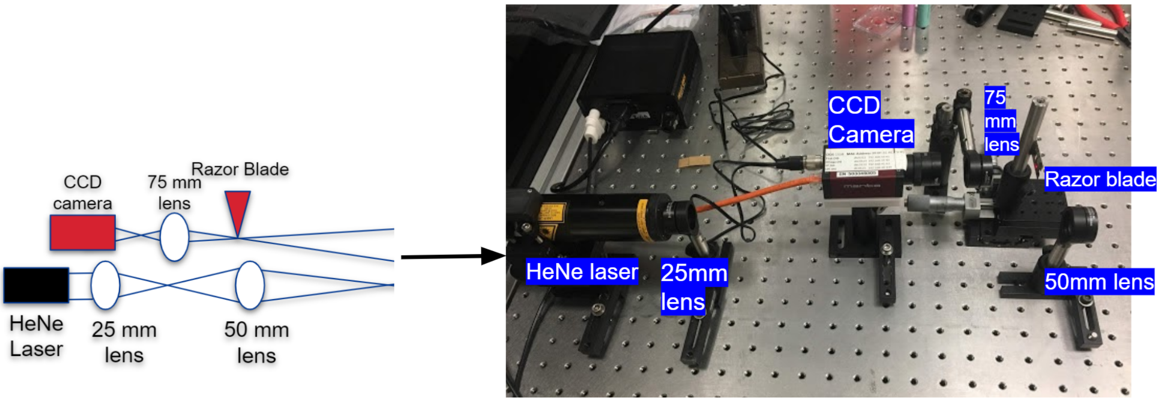


Figure 5: *The setup with the HeNe laser. In this setup, the 50 mm lens represents the point light source. The image on the left breaks down the components of the setup.*

While the HeNe laser had the advantage of eliminating smearing, issues arose regarding the lack of anti-reflection coatings on the various lenses. This led to issues with the image quality leading to a sort of smearing effect. In the end, it was determined that white light with a 500 micron pinhole was ideal for data collected using the hot plate, while either the HeNe system or white light with a 200 micron pinhole was best for collecting data from a nitrogen tube, which will be discussed more in depth in the next section.

IV Data Collection

IV.I Hot Plate

The first set of data was collected using white light and a 500 micron pinhole. The Schlieren signal from the hot plate shown in Figure 4 was analyzed at a set of five temperatures ranging from 40 to 50 degrees Celsius. Using Streampix software, videos were taken of the signal emitted from the hot plate. The CCD camera recorded for 30-45 seconds at a frame-rate of 3 frames per second, garnering videos of around 100 frames. Due to the relatively laminar appearance of the hot plate signal this low frame-rate was deemed acceptable. Single frame examples of the data collected are shown in Figure 6.

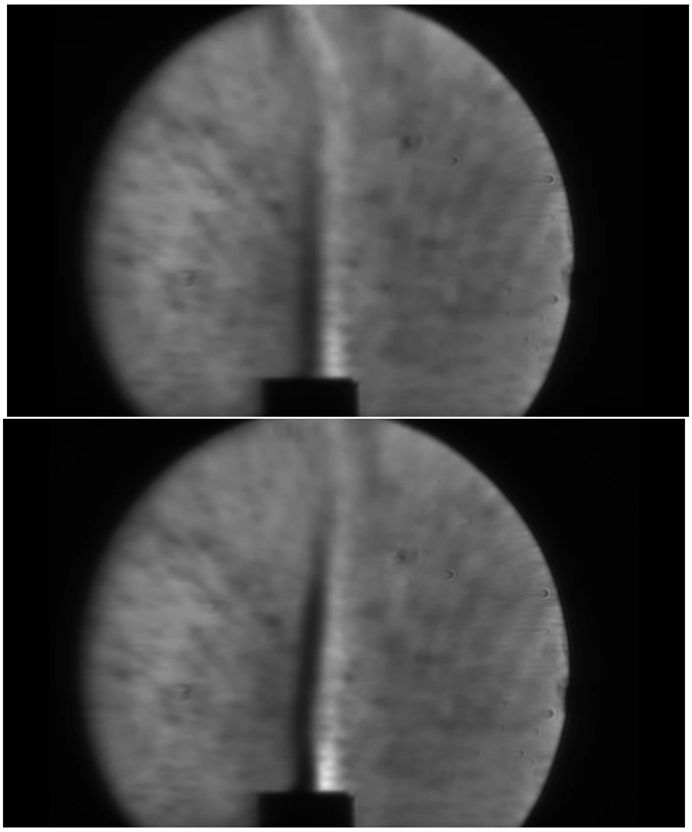


Figure 6: *Two individual frames from videos taken at 40 degrees (top image) and 50 degrees (bottom image). The hot plate is the rectangular black region in the middle of the bottom of the images.*

Air currents caused by human movement, a nearby computer and the room's cooling system contributed to fluctuations in the hot plate signal, causing it to move around and vary its intensity. To account for this, the videos were taken and averaged using a MATLAB function into a single composite image (see Section V).

IV.II Nitrogen Tube

Nitrogen is used in laser systems as a purging gas to eliminate humidity, with little thought given to the disturbances it may cause. As for the heat source, Schlieren has been proposed as a way to identify how nitrogen flow may be affecting laser propagation. To test this, a nitrogen tube was run across the room and mounted in front of the Schlieren system using Thorlabs posts and mounts. Nitrogen flow was controlled by a knob on which three distinct pressures were marked; the initial valve point, quarter turn and half turn. The initial valve point featured a moderate streamlined flow, the quarter turn showed an increase in the nitrogen flow's intensity, and the half turn showed a chaotic fast flowing stream of nitrogen. The signal from nitrogen flow was sharp and unlike the hot plate its shape varied little from convections from the room. With this in mind the sharpest Schlieren images were obtained by recording videos at 18 frames per second for 10-15 seconds.

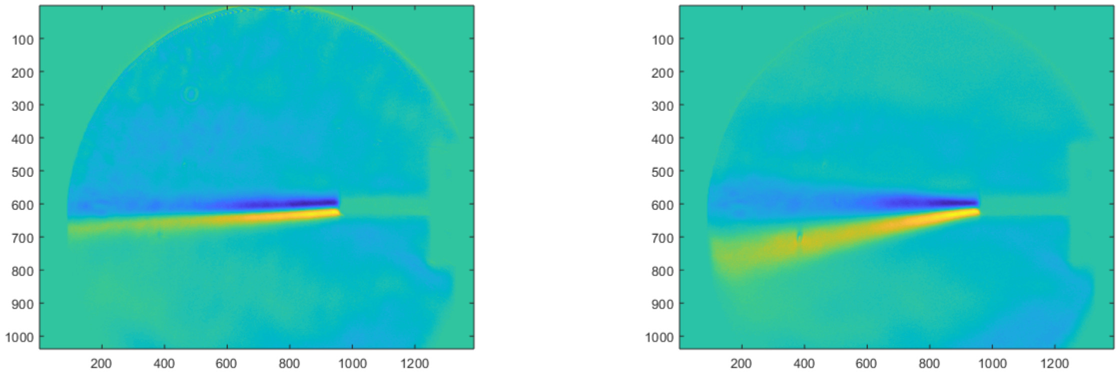


Figure 7: *Two individual frames from videos taken at the initial valve point (left image) and half turned valve (right image). Images have been background subtracted in MATLAB for greater clarity. The darker blue and yellow regions represent areas of nitrogen flow and the turquoise region directly to the right of that represents the nitrogen tube.*

V Analysis in MATLAB

A MATLAB script was created, aiming to complete the following goals for the data discussed in Section IV.

1. Average all frames of the Schlieren video into a composite image.
    (a) To accomplish this, a for loop was written which individually reads each frame of the video as a matrix and then finds the average of all of the matrices. The final matrix represents an averaged image of all the frames in the video.
2. Eliminate background noise from the image discussed in step 1.

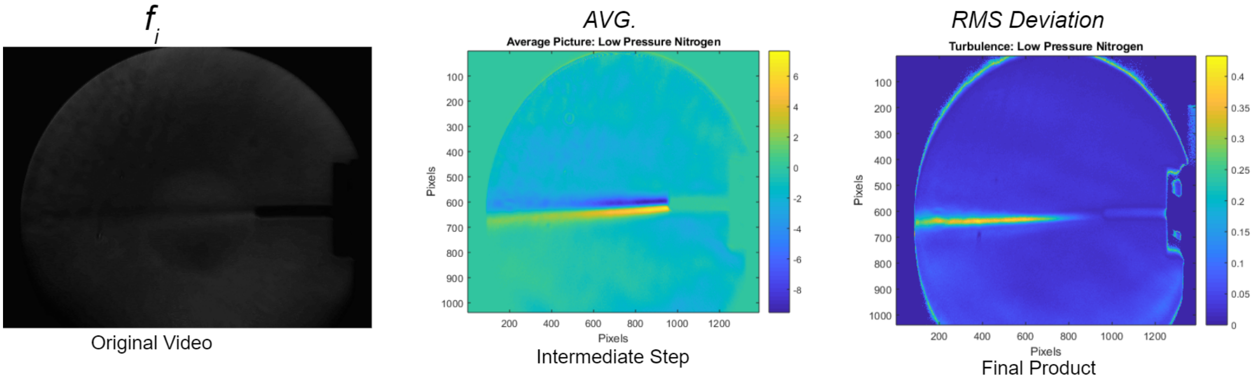
(a) To accomplish this step, an image is taken with the Schlieren system without any signal (no hot plate or nitrogen flow). This data is then subtracted from the averaged image from step 1. This step removes stationary sources of signal (air currents, heat from computer, etc.) that are not the direct result of the source being studied. This ultimately provides a clearer image of the targeted signal.

3. Identify specific areas of both uniform (laminar) index gradients and turbulent index gradients.

   (a) Stopping after step 2 reveals areas of laminar index gradients. To identify areas of turbulent flow a for loop was written in MATLAB to find the root-mean-square deviation between the image from step 2 and each individual frame in the video.

$$RMSDeviation = \sqrt{\frac{1}{n}\Sigma_{i=1}^{n}(AVG. - f_i)^2}$$

   where n is the number of frames in a video, $AVG.$ is the background subtracted average image from step 2, and f_i is an individual frame from the video. The background is again subtracted, and the resulting image depicts turbulent flow (see Figure 8).



Original Video

Intermediate Step

Final Product

Figure 8: *A frame from a Schlieren video of nitrogen flow as it goes through the MATLAB program. The leftmost image shows a frame of a video taken with the Schlieren system. The middle image depicts an averaged video with the background subtracted (see step 2 above). The rightmost image shows the root-mean-square deviation between the middle image and the video with adjustment for background subtraction (see step 3).*

VI Comparison of the Nitrogen and Hot Plate

Upon recording data for both the nitrogen flow and the hot plate, various observations were made regarding the two and differences in their respective signals. Differences in the appearances of light and dark regions provide information about refractive index gradients. Figure 9 illustrates some of these differences. The nitrogen tube is mounted vertically in Figure 9 rather than horizontally as in Figure 7, in order to more directly compare it to the hot plate.

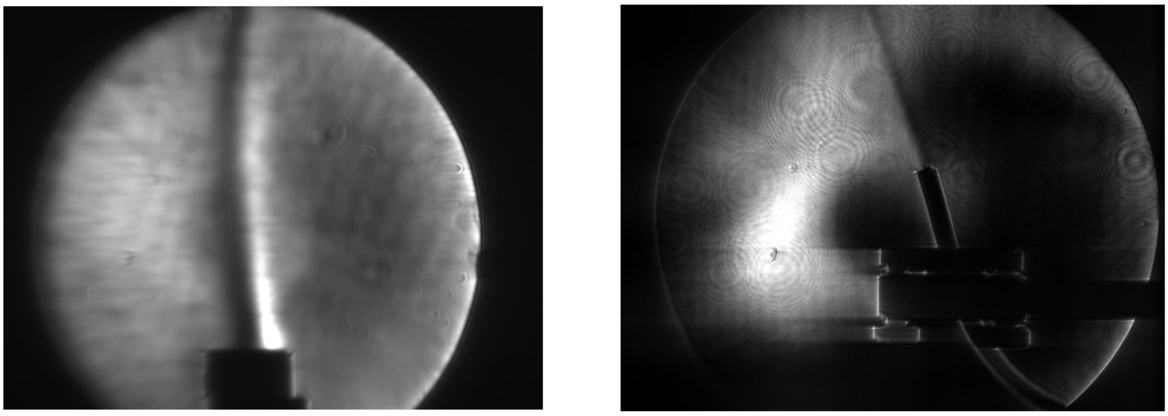


Figure 9: *Images of the hot plate (left) and nitrogen flow (right). The hot plate signal is dark on the left and white on the right while this is the opposite for the nitrogen flow (the faint signal coming off the end of the tube) which is at the initial valve point setting.*

This difference in the position of light and dark regions is due to differences in index of refraction between the nitrogen and the warm air from the hot plate. Figure 10 illustrates this in terms of Snell's law: $N_1 * Sin\theta_1 = N_2 * Sin\theta_2$.

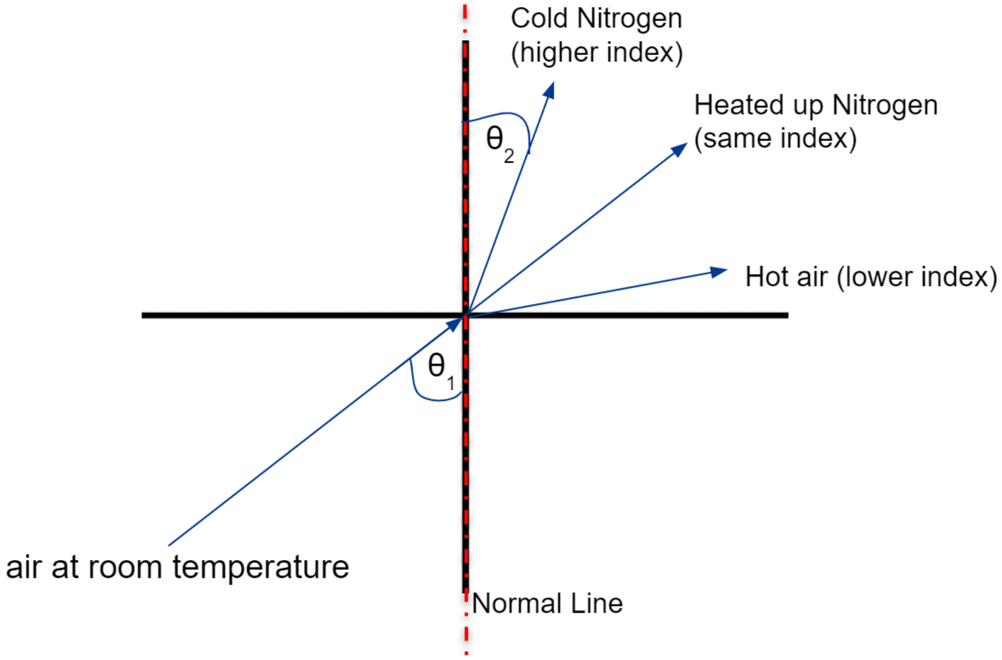


Figure 10: *Light refracting as it goes between two media. The x-axis represents the border between the media and the y-axis represents the interface normal which the light refracts relative to. As light passes from air at room temperature to cold nitrogen, it refracts at a smaller angle relative to the normal, while as light passes from air at room temperature to hot air, it refracts at a larger angle. The area below the x-axis represents air at room temperature and that above the x-axis represents the listed media.*

Cold nitrogen has a higher index of refraction than hot air and therefore light refracts at a smaller angle relative to the normal line. The index of refraction of a given medium is dependent on temperature. Heating a medium lowers its index of refraction and therefore increases the angle that light refracts to relative to the normal. It should therefore be possible to eliminate a signal from the nitrogen through heating it until its index of refraction is the same as that of room temperature air. If heating nitrogen eliminates the signal, than this tactic could be used in laser systems where nitrogen is present in order to avoid problems caused from turbulence related to nitrogen. Using data from Ref. 3 the required temperature of nitrogen was found to be around 20 degrees more than room temperature (23 degrees Celsius). It was then attempted to heat the nitrogen to this temperature, but, with limited time and materials, it was not possible to heat the nitrogen by a significant amount. Future work can be done in this area to find the exact temperature at which the signal from the nitrogen disappears.

VII Testing Laser Parts

Nitrogen is often used as a purging gas to reduce humidity in laser systems. Various laser parts were tested using nitrogen and the Schlieren system to see how they may be contributing to gas-related turbulence. Two examples of devices that use nitrogen are laser crystal cells and a gas diffuser, shown in Figure 11. Both parts were put in front of the Schlieren system and nitrogen was run through them to see how they interact with the gas. This test helped users understand how the parts may contribute to turbulence, before using them in a laser system.

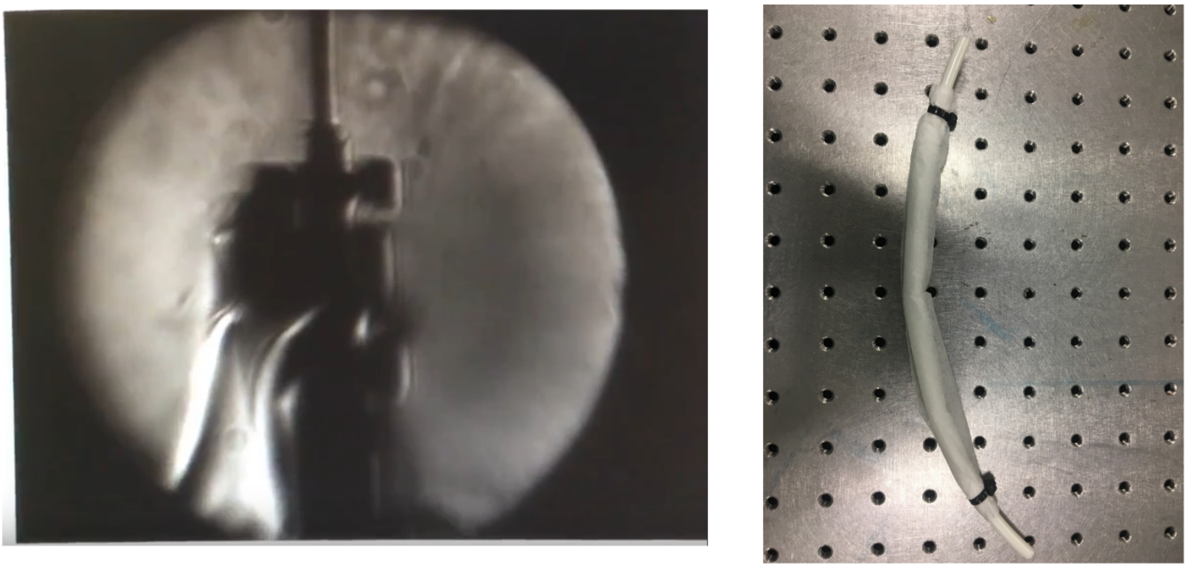


Figure 11: *Two laser parts that were tested. A Schlieren image of a laser crystal cell with nitrogen going through it (left) and a gas diffuser (right). The gas diffuser is a piece of a plastic tube with holes poked in it and mesh wrapped around it. The one pictured is used to release nitrogen in a laser system.*

VIII Pinhole Images and Aberrations

A concern with Schlieren imaging is that optical aberrations may distort the final image. In the setup used here (Figure 3) a concave parabolic mirror was used, avoiding spherical aberrations. However, the mirror is subject to comatic aberrations. Comatic aberrations come when light rays from any one of the sources hit the mirror at a nonzero angle to the normal, causing individual rays to not reflect back to the desired point at the edge of the razor blade. To test the effect of this on the imaging system the mirror was placed at an angle and images were recorded of the pinhole light sources' reflection to see how aberrations affected their image.

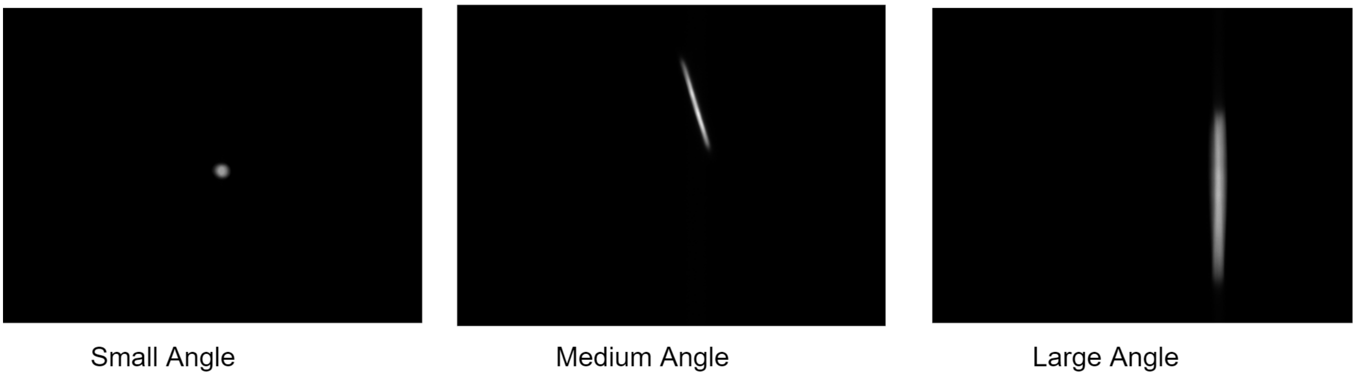


Figure 12: *Images showing the relationship between mirror angle and the image of the pinhole light source reflected in the mirror of Figure 3.*

The small angle image shown in Figure 12 accurately depicts the pinhole image when light rays are reflected 2.5-13 cm to the side of the original light source. The image becomes distorted, as shown in the middle image, when light rays are reflected at a medium angle 15-25 cm to the side of the light source. Beyond this, at 25+ cm to the side of the original light source, the pinhole reflection becomes quite distorted and difficult to focus as shown in the large angle picture in Figure 12. To alleviate the effect of these distorted pinhole images, the Schlieren system was typically set up with the pinhole reflection around 2.5-7.6 cm to the side of the original light source.

IX Conclusions

A Schlieren imaging system was built and various parameters were experimented with to optimize it. The system was also demonstrated using a hot plate and nitrogen gas flow. A MATLAB program was written which together with the Schlieren reveals areas of thermal and gaseous turbulence. Future work could be done to explore whether the effects from turbulence from nitrogen and other gasses can be accurately and consistently reduced through heating them. Work could also be done with the Schlieren system to reduce its size and increase its portability, enabling it to be implemented into laser systems to better understand and quantify how disturbances may be affecting them.

X Acknowledgments

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XI References

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[3] H. Johns and J. Wilhelm, "The refractive indices of liquid oxygen, nitrogen, and hydrogen," *Canadian Journal of Research*, vol. 15, pp. 101–108, 04 2011.