

THE UNIVERSITY OF BRITISH COLUMBIA

**Laboratory 1:
Construction and Investigation of a
Helium-Neon (HeNe) Laser**

by

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Abstract

Lasers are used in a variety of scientific and industrial applications, they generate long coherence single wavelength, which has a myriad of interesting optical properties. This lab is aimed constructing a Helium-Neon (He-Ne) laser and investigating polarization, spectrum, and the beam arising from the laser light. We started by connecting a mirror setup, a He-Ne gas lamp, and a CCD to create a laser and qualitatively asses the modes of transmission. Then we used a variety of mirrors to establish the regions of stability for the mirror, and a polarizer to confirm the plane of polarization for our laser. We then compared the spectrum of the gas discharge tube and the laser to understand the single wavelength behaviour. Lastly we used a wire to disrupt the standing wave of light established inside the cavity to control the mode of transmission of the laser and also to measure its beam radius. Through this lab we carefully took qualitative and quantitative data to explain various features of laser light, and a laser producing optical setup.

Chapter 1

Introduction

The primary goal of the lab is to investigate the working principals of a Helium-Neon (HeNe) laser. This means that throughout the lab we looked at various aspects and consequences of the optical setup involved in creating laser light. We started by looking at the Transverse Laser Modes, examining the various modes of the laser predicted by the Gauss-Hermite solutions. Then we tried to establish a relationship between the stable cavity size and the radius of curvature of the coupling mirrors. We looked at polarization and spectral output of the laser, which are both important consequences of a laser. Lastly, we used this knowledge and the standing wave equations to control modes by interrupting the beam with a small conductive wire and measure the beam radius inside and outside the cavity.

1. Investigate the dependence of the cavity stability on the radius of curvature of the cavity mirrors
2. Observe and characterize properties of the laser output.
3. Measure the beam radius at different locations inside and outside the cavity and compare with the expected size given the chosen cavity length and mirrors.

Chapter 2

Methods

2.1 Transverse Laser Modes

Our primary objective was to get the laser lasing in the lab, and then do a qualitative analysis of the transverse laser modes achievable in its current state. To do this we used a high-reflectivity planar mirror to achieve stimulated emission from the gain medium. The most challenging aspect here was getting the laser lasing, but once we had gotten more familiar with the apparatus we were able to quickly establish a laser. We setup and used the CCD/DAQ combination to look at the various mode of the laser that were achievable by slight adjustment to the angle of the planar mirror. Since our objective was to qualitative exploration, we merely took captures of the CCD.

2.2 Mirror Curvature

We used the spherical-mirror resonator equations to come up with a way of measuring the radius of curvature of the back mirror.

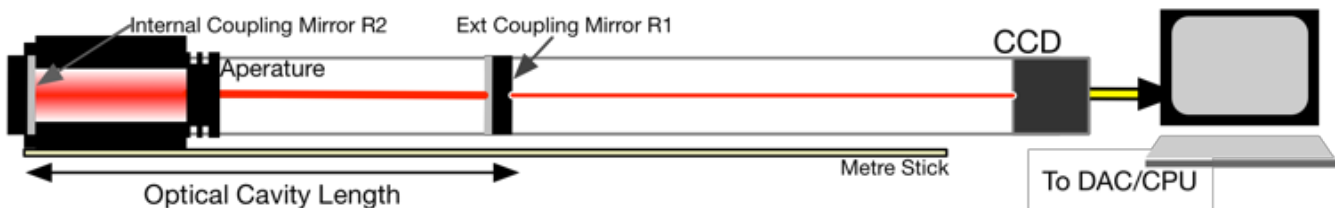


FIGURE 2.1

$$0 \leq \left(1 + \frac{d}{R_1}\right)\left(1 + \frac{d}{R_2}\right) \leq 1 \quad R_1 = \infty \implies R_2 = d$$

Once we came up with the radius of the back mirror we could figure out the region of stability for the laser cavity size and any limitations on the possible mirror curvature. We could also use the regions to verify the stated mirror curvatures.

2.3 Polarization

This primarily involved finding if the laser had any sort of polarization and trying to characterize this polarization. To do this we used a linear polarizer and our CCD. Viewing the laser spot on the CCD camera let us figure out points of minimum and maximum intensity. By rotating through the polarizer angles and observing the change in intensity we were able to verify that the light was linearly polarized and could work out the plane of polarization.

2.4 Spectral Output

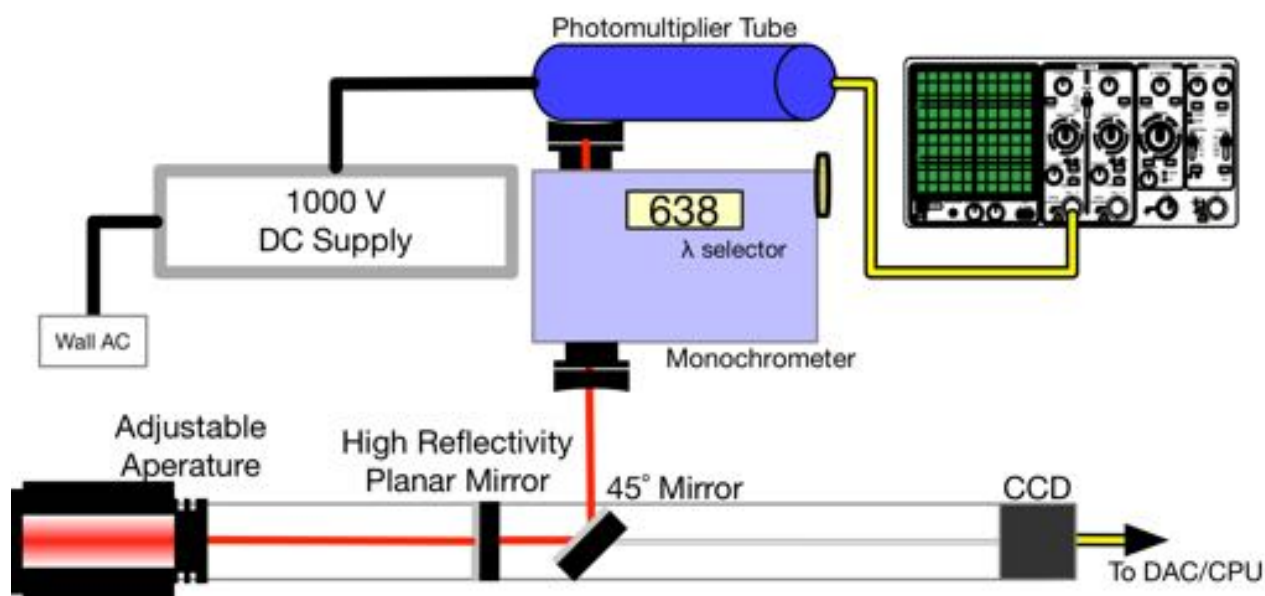


FIGURE 2.2

We put laser light through the monochromator with its diffracting setup to accept light at wavelength of 638nm. We used the photo-multiplier tube (PMT) and the 1000V power supply to amplify the signal out the back. Using the scope we were able to get a DC level from the PMT, and we adjusted alignment for maximum signal. Then we swept over the wavelengths from 580-642, advancing by increments of 2nm. We followed the same procedure to collect the spectrum for the HeNe lamp, but we used a lens to

focus a spot into the monochrometer to get a noticeable signal. In addition we swept over all frequencies in the same range.

2.5 Mode Control and Beam Radius Measurements

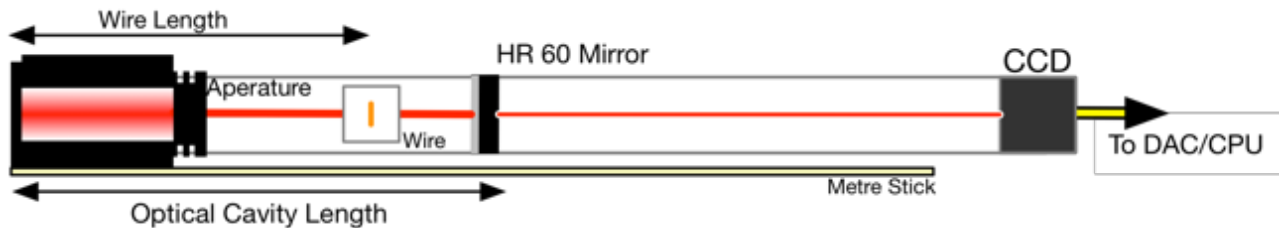


FIGURE 2.3

In this last section, we measured the beam radius at one location inside the cavity and at two locations outside the cavity and compared with expected values.

The HeNe laser was adjusted to lase with the curved (60 mm) output coupler (OC) mirror positioned to make a larger optical cavity length (552 mm). Next the CCD camera was placed at the end of the rail so that the CCD was about 1110 mm from the opposite end of the laser cavity. The OC mirror was adjusted to achieve TEM_{20} .

To measure the beam radius within the cavity a thin, vertically-orientated, conductive wire mounted on a translation stage on a carriage was placed inside the cavity between the OC mirror and the iris. Starting from one side, the wire was translated across the center of the cavity and the micrometer position was measured and recorded for where each mode change occurred.

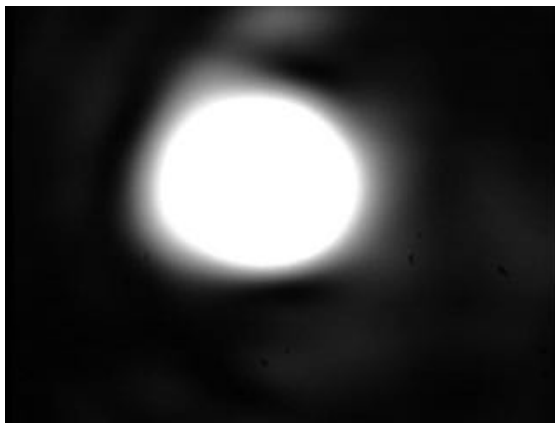
For measuring the beam radius outside the cavity the CCD camera was placed at a known location and images of the TEM_{00} , TEM_{10} , and TEM_{20} modes were taken. The images were analyzed with MATLAB to find the intensity of the pixels and relate that to the radius of the beam. This was repeated for another camera position and compared to theory.

Chapter 3

Summary of Results

3.1 Transverse Laser Modes

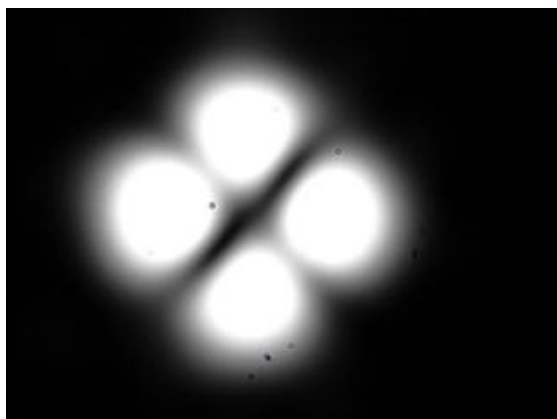
Once the Laser was successfully lasing, we were able to adjust the angle of the OC mirror in two planar directions to obtain different spatial modes of the laser. These modes were captured using the CCD camera and compared against know images of different spatial modes such as Laguerre–Gaussian and Hermite–Gaussian. The following modes were found:



Modes: TEM_{00} Laguerre–Gaussian
or TEM_{00} Hermite–Gaussian



Modes: TEM_{01} Laguerre–Gaussian
or TEM_{10} Hermite–Gaussian
Skew: $\frac{\pi}{4}$ rad
or TEM_{01} Hermite–Gaussian
Skew: $-\frac{\pi}{4}$



Modes: TEM_{02} Laguerre–Gaussian

Skew: 0 rad

or TEM_{11} Hermite–Gaussian

Skew: $\frac{\pm\pi}{4}$ rad

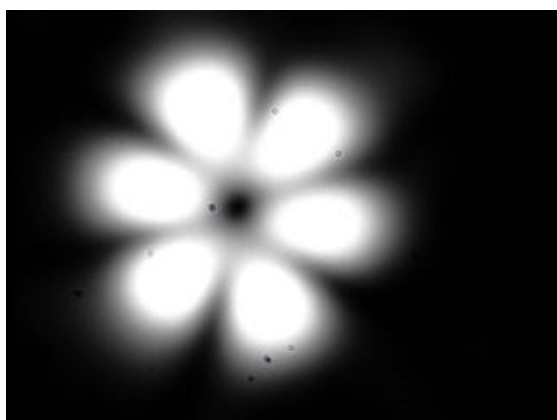


Modes: TEM_{20} Hermite–Gaussian

Skew: $\frac{\pi}{4}$ rad

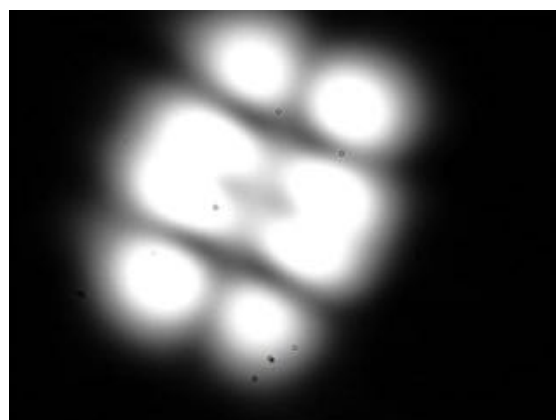
or TEM_{02} Hermite–Gaussian

Skew: $\frac{-\pi}{4}$ rad



Modes: TEM_{03} Laguerre–Gaussian

Skew: $[0 \text{ to } \frac{-\pi}{6}]$ rad



Modes: TEM_{31} Hermite–Gaussian

Skew: $[0 \text{ to } \frac{-\pi}{6}]$ rad

3.2 Mirror Curvature

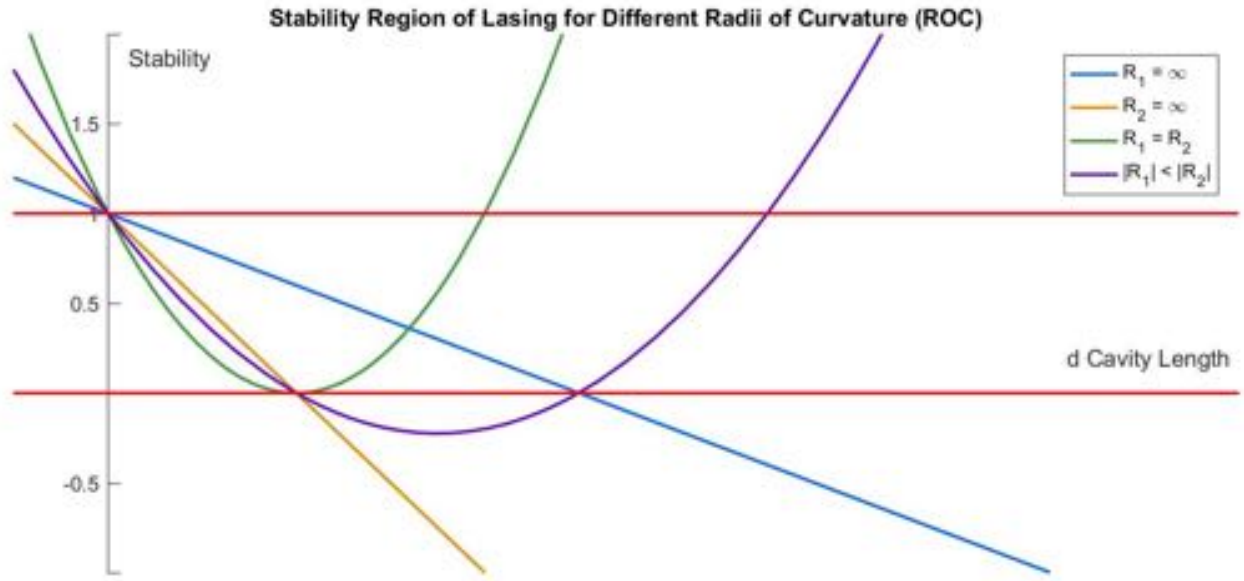


FIGURE 3.1: Here is the figure

Using the planar mirror we found the radius of curvature of the back mirror to be

$$R1 = 55.60 \pm 0.07cm$$

Using the two concave mirrors, we found that the restrictions on the cavity size were as follows:

$$0 \leq d < R1; R2 < d < R1 + R2$$

assuming that

$$|R1| < |R2|$$

with the high reflectively coupling mirror always being concave. We also could use our setup to verify the radius of curvature of the two provided concave mirrors.

3.3 Polarization

By measuring the angle of the polarizer at points where the throughput laser had minima intensities we were able to determine the plane of polarization. The throughput laser was almost completely blocked at polarization angles of $33 \pm 0.5^\circ$ and $213 \pm 0.5^\circ$. These results are 180° apart from each other which is expected for a linearly polarized wave. Furthermore, the max intensity of the throughput beam was measured at $122.5 \pm 1^\circ$ and $304 \pm 1^\circ$. These values are roughly 180° apart from each other and 90° from the

minimum intensities, which also conforms to the theory. From these results we can also estimate that the angle of the Brewster window inside the cavity was near 123° .

3.4 Spectral Output

After collecting the average intensity of each wavelength for both the laser and the fluorescence of the He-Ne tube we plotted the data. From the plot we are able to clearly see that the laser beam is primarily comprised of 638 nm light and that the fluorescence of the tube is a combination of several different wavelengths of light. It should be noted that the most prominent wavelengths in the fluorescence were at about 582 and 590 nm and not at 638 nm like the laser.

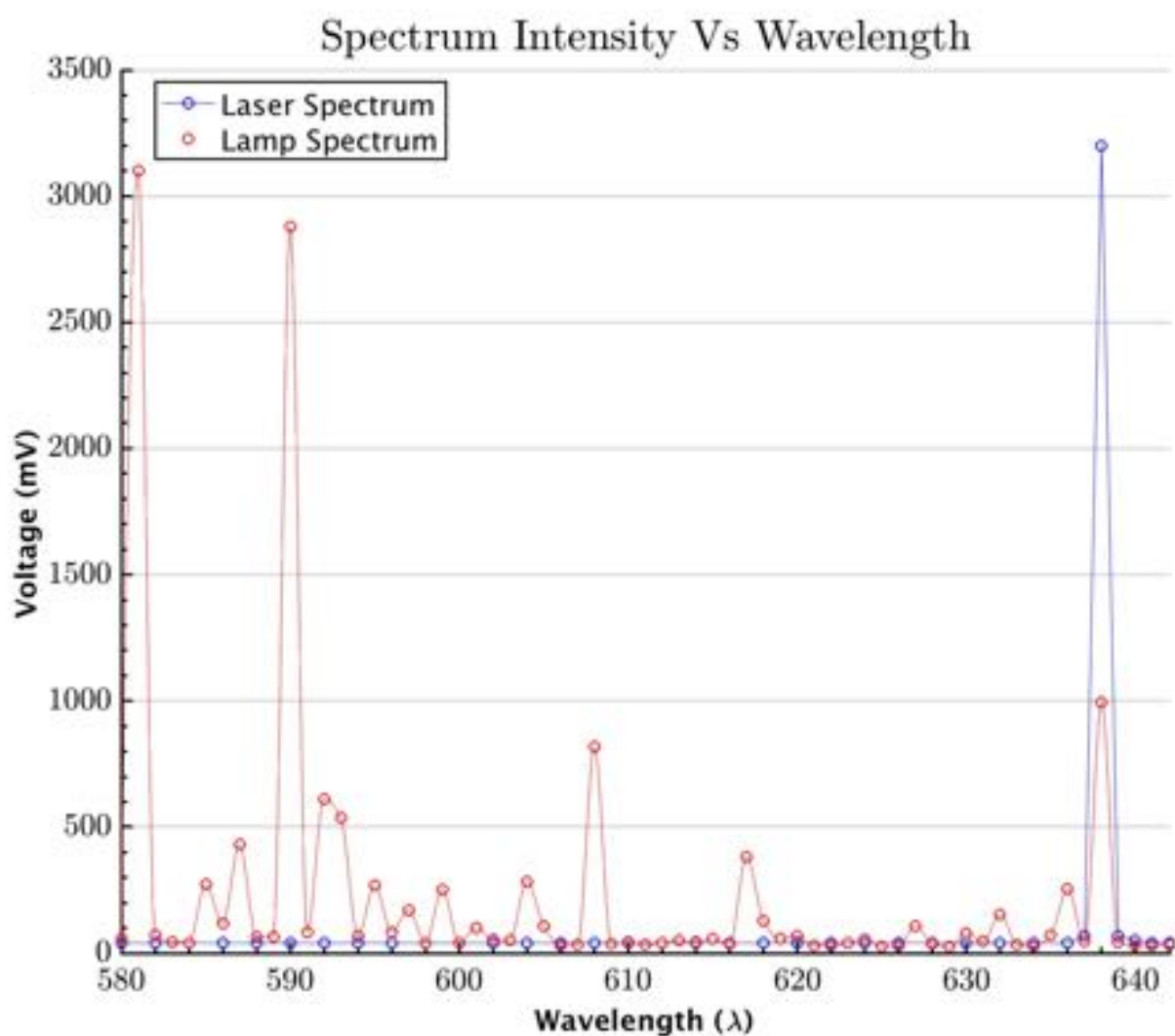


FIGURE 3.2

The reason that these two sources have different major components is because of the working principle of a laser. The point of the laser is to create long coherence light that is all at the same wavelength. We see essentially a single line in the laser. The He-Ne gas lamp has multiple different energy transitions going on as electrons are kicked up to empty energy levels past where the laser is operating. As these electrons come back down they emit high energy photons forming the lower wavelength bumps on the He-Ne spectrum.

3.5 Mode Control and Beam Radius Measurements

As the wire was passed across the beam path, the laser was forced into different TEM. Here we see the output laser change from modes:

$$TEM_{10} \rightarrow TEM_{20} \rightarrow TEM_{10} \rightarrow TEM_{11} \rightarrow TEM_{10} \rightarrow TEM_{20} \rightarrow TEM_{10}$$

This pattern is symmetric about the TEM_{11} mode where the wire is directly in the center of the beam path. Also, the wire blocked the laser from lasing at positions on both sides of TEM_{11} between it and TEM_{10} .

Using the first wire position for TEM_{20} (9.44 ± 0.01 mm) and the second wire position for TEM_{20} (7.82 ± 0.01 mm) we can approximate the beam diameter inside the cavity. This is because at these two wire positions the laser is forced into the two modes because its position is coexistent with the nulls of the mode.

Beam Diameter inside the cavity: 1.62 ± 0.014 mm

Lower bound on Beam Diameter: 0.84 ± 0.014 mm (almost half of the other measurement)

The following figure shows the different modes that the laser was forced into using the wire for control:

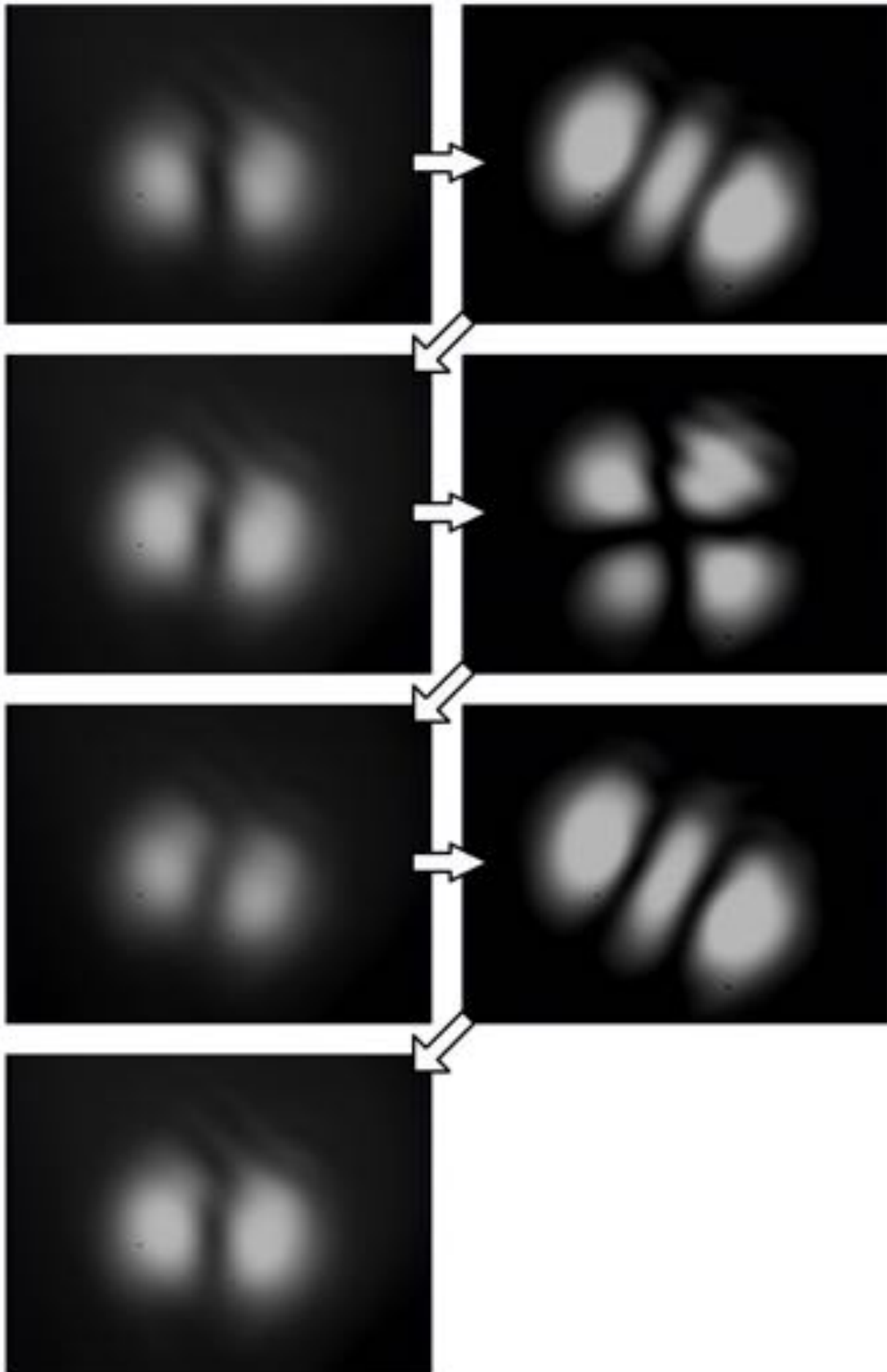


FIGURE 3.3

Next we measured the beam diameter at two locations outside of the optical cavity.

The CCD camera was placed at positions 1110 mm and 700 mm to record the radius at two different locations. Pictures of the TEM_{00} , TEM_{10} , and TEM_{20} modes were taken and the pixel data was analyzed in MATLAB. For the TEM_{00} , the Full Width at Half Maximum (FWHM) was taken to determine the beam radius. Next the spacing between the two nulls in the TEM_{20} was taken to determine the beam radius. These values were both compared against the theory for the two different points. These results are shown in the following figure:

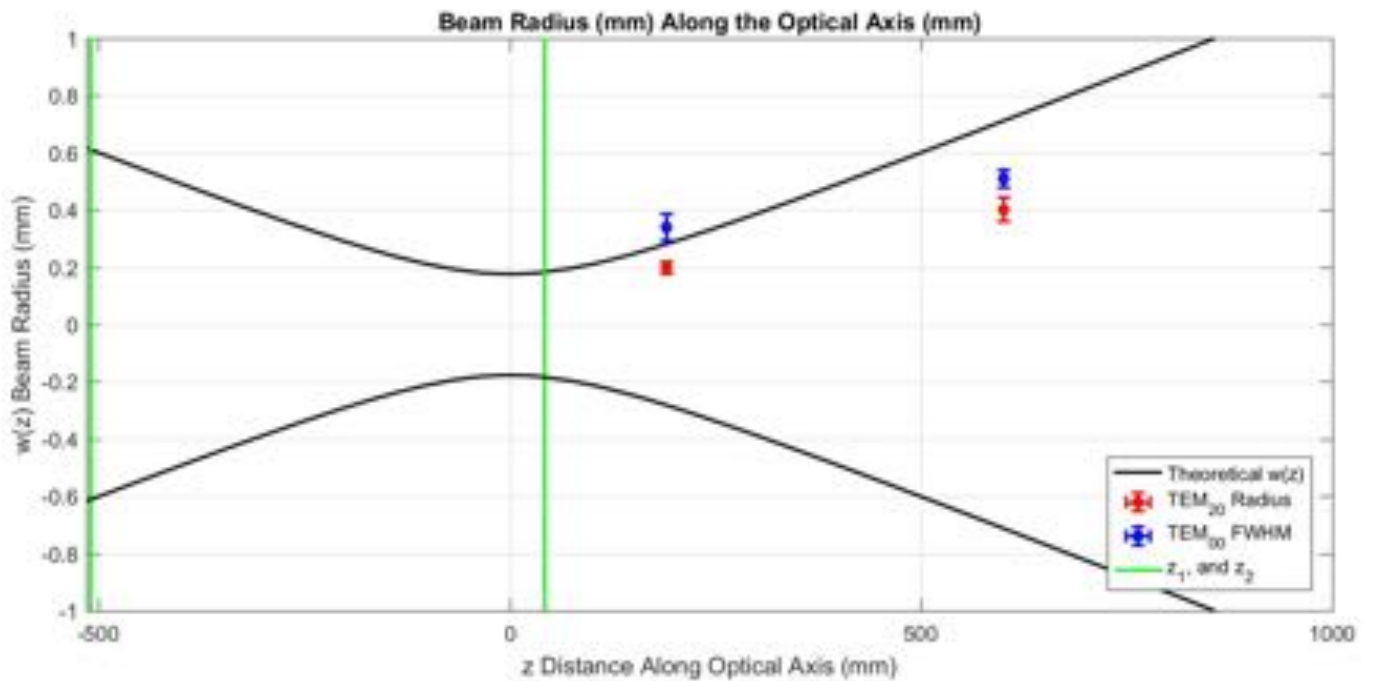


FIGURE 3.4

This plot shows the two theoretical ends of the optical cavity as z_1 and z_2 , respectively (shown in green). This also shows the focus point of the laser beam is inside the optical cavity, which is essential for lasing to occur.

The values for the beam radius that we measured are on the same order of magnitude as the values we expect from the theory. These values are off by 20-30% on average.

Chapter 4

Conclusions

Below are the answers to the most relevant problems posted in the lab

4.1 Questions

4.1.1 Transverse Laser Modes

What is the highest order mode you could see?

Using the Planar mirror the highest mode that we were able to achieve was TEM₃₁ after that further small adjustments to the planar mirror caused the laser to stop lasing. Perhaps it is feasible that using a curved mirror would allow use to access higher order modes, because it could collect light coming in at a steeper angle.

With the laser lasing in any mode that is not the TEM₀₀ mode, slowly open and close the iris near the Brewster window. What happens? Explain why.

We placed the laser in the TEM₂₀ mode a tried to open and close the adjustable aperture in front of the Brewster window. As we closed the iris the laser would drop in mode first to the 1,0 mode, to the 0,0 mode, and finally turned off all together. This is due to the 2-dimensional standing wave nature of the laser. In order to be in a particular mode the beam must be able to have zeros in particular places in relation to its wavelength. As we close the aperture, we force the beam into a smaller space making a higher order standing wave impossible. This forces the mode to drop to the next most stable state. Eventually, the wave cant support a standing wave at all even though the aperture is slightly open, because the standing wave cant place the its nodes in the right location.

Why do you usually see the laser has only one transverse spatial mode at a time?

4.1.2 Mirror Curvature

Measure the stability regions of the laser using the curved output coupler mirror. How does your measured region of stability compare with what you expect? Use your measurements to verify experimentally the advertised ROC of the curved output coupling mirror.

Using the planar mirror we found the radius of curvature of the back mirror to be

$$R1 = 55.60 \pm 0.07cm$$

Using the two concave mirrors, we found that the restrictions on the cavity size were as follows:

$$0 \leq d < R1; R2 < d < R1 + R2$$

assuming that $|R1| < |R2|$ We found using this method that the 60cm mirror had a ROC of 59.3 ± 0.2 cm and the 66cm mirror had an ROC of 65.5 ± 0.2

Could you use a convex ($R < 0$) mirror in this setup? If so, are there any constraints on the radius of curvature that this mirror could have? We found that convex mirrors were not possible to use in the current configuration. To use them we would need a negative cavity length, this would involve replacing the back mirror to make this possible.

4.1.3 Polarization

What does it mean for the laser to be polarized? Check the polarization of the He-Ne laser beam

Laser light is polarized if all of the light is a single plane. That is the transmission vectors of all of the light are contained in some plane. We checked the plane polarization of the laser by using our 60mm concave mirror and adding a polarizer after the mirror. When we looked at this beam on the CCD, we could get the intensity of the light to change significantly by rotating the angle of the polarizer through 90 of rotation. This means that the light was plane polarized.

Why might the output of the laser be polarized? Are there any elements in the laser that could cause the output beam to be polarized?

The laser is being polarized because of the Brewster window. The window is at the Brewster angle which means that only light at one particular plan polarization is transmitted at full power, and the light $\frac{\pi}{2}$ out of phase with the Brewster angle is not transmitted at all. We could build a laser with mirrors internal to the He-Ne lamp and then that

would get rid of the need of the Brewster windows. This new laser would not have any plane polarization.

4.1.4 Spectrum Output

Why are the results different between the He-Ne lamp and the laser? By overlaying the spectrum we saw that the laser amplifies the bump at 638nm. The two spectra should be different because of the working principle of a laser. The point of the laser is to create long coherence light that is all at the same wavelength. So we see essentially a single line in the laser. The He-Ne gas lamp has multiple random energy transitions going on as electrons are kicked up to empty energy levels past where the laser is operating. As these electrons come back down they emit high energy photons forming the lower wavelength bumps on the He-Ne spectrum.

4.1.5 Mode Control and Beam Radius

Describe what you see as you translate the wire through the location of the beam. Explain why you see this behavior.

The laser is forced into different TEM as the wire is passed across the beam. This occurs because the wire acts like a null in the spatial mode and thus forces the beam to conform to fit the geometry and location that it is in. The beam does this by matching its spatial mode.

You should see the TEM₂₀ modes occur twice. Why is this? Which mode occurs when the wire is at the (transverse) center of the cavity?

The TEM₂₀ spatial mode has two distinct spatial nodes. When the wire is positioned into these nulls, the mode of the laser is constrained to this output mode. As the wire passes across the entirety of the beam it hits both locations of these nodes and that is why they are seen twice.

4.1.6 Final Questions

Show that the allowable laser frequencies are given by

$$f_m = m \frac{c}{2L}$$

where L is the length of the laser cavity, and m is the number of half-wavelengths that fit between the mirrors. Why can you only get red light out of this laser? In other words,

the equation suggests that many frequencies should be possible, so why do you only see one color?

The photons from the laser must all be in phase. This is because if there is a phase separation between photons then they will reflect by different amounts and overtime there will be enough destructive interference to get rid of all of the light (the HR mirrors reflect about 1000 times before transmission). This means that the light in the cavity must be in a standing wave, which implies $f = \frac{c}{\lambda}$. Then we know that at the boundaries there is perfect reflection, which forces us to have to spacial nodes at the end (analogous to a closed pipe). This means that the only allowable wavelengths are $\lambda = 2L/m$, where m is an integer. These two quantities taken together gives us our result.

$$f_m = m \frac{c}{2L}$$

This is simply the allowable frequencies for a standing wave inside the cavity, but we actually need to stimulate the gain medium correctly to be able to get light emission. There is the physical phenomenon of population inversion and gain pump that create the coherent light all at one wavelength. Other wavelengths of light are not in phase and thus destructive interfere with themselves. This gives us the single red colour that we see.

Do you see that the laser only lases for specific mirror separations, as predicted by the equation? Why or why not? It might be useful to know that the full width half max of the gain medium in the He-Ne laser is about 1 GHz.

We observed that within the stability region we were able to keep the laser lasing continuously. This is because this standing wave calculation is true for planar mirrors, rather than the concave setup that we actually have. By being able to use the concavity we can adjust the path length as the mirror separation changes and keep the laser inside the correct standing wave.

If we consider the 1GHz as the f_m frequency, and set the cavity length to be 500mm (a typical size for cavity in the experiment) we can calculate for allowable values of m .

$$m = \frac{2f_m L}{c} = 3.33$$

This helps give us a good upper bound for the number of modes allowable. We expect to be able to put the laser into a up to 3 higher than the base TEM_{00} .

4.2 Learning Objectives

What was the most challenging part of this lab? Is it what you thought it would be (i.e., what you wrote in your outline)? Comment (i.e., write more than yes or no). It turned out that the monochromator spectrum was the most challenging part of this lab. In the outline we assumed this would be the easiest part of the lab. This was largely due to our issues aligning the monochromator with the beam. Once we had done this correctly this section took no time at all. We thought that the hardest part of the lab would be the beam radius measurement. This turned out to be the most data/measurement intensive part of the lab, so we think it would still been the hardest had we not had to wrestle with the monochromator for so long. The lab outline could not have foreseen the spectrum challenges because they were very apparatus specific and were not obvious to us until we started to do the actual lab.

Chapter 5

Discussion

The radius of curvature measurement are not a perfect science because of the poor tolerance of the optical equipment. Because we were able to line up the planar mirror several times, we feel fairly confident in our measurement of the back coupling mirror (R1), but the verification of the ROC of the other two mirrors is more suspect. As a qualitative metric however, the measured ROCs are close enough that we feel comfortable accepting the manufacturer values.

Plane polarization angle is reported with the optical table and its perpendicular taken as the coordinated axes in this setup the table is a 0 degrees. The angle we report is in this coordinate frame and is also the numerical value reported through the polarizer. We could pick a new set of axes such that the maximum intensity of light was at 0 degrees and the minimum at 90 degrees, but for the sake of repeatably we left the values as is.

Generally, He-Ne lasers operate at a wavelength of 632.8 nm, this is from the most common gas tube setup. We measured a significantly different wavelength using our monochromator. This is either because we have considerably different gas composition, or because there the monochromator is no longer aligned well. Either way the results are consistent with the expected spectrum for a laser device.

Lastly, our beam radius measurements don't line up with our theoretical function. We believe that this is because the theory makes the assumption that all of the optical components are thin, but the real components have a nontrivial thickness. This adds some optical delay and reduces the value. There may be some other effects, which we have failed to model, but we believe this is the major source for the discrepancy. It is also possible that because of the difficulty with measuring the ROC, the theoretical trend is shifted away from the data.

Appendix A

Appendix

A.1 Radius of Curvature MATLAB Code

```
clear;clc;close all;
R1 = -2;
R2 = -5;

z0 = @(d) (1+d/R1)*(1+d/R1);
z2 = @(d) (1+d/R1)*(1+d/R2);
z1 = @(d) (1+d/R2);
z3 = @(d) (1+d/R1);

width = 10;      % Width in inches
height = 4;      % Height in inches
alw = 0.75;      % AxesLineWidth
fsz = 11;        % Fontsize
lw = 1.5;        % LineWidth
msz = 9;         % MarkerSize

figure(2)
pos = get(gcf, 'Position');
set(gcf, 'Position', [pos(1) pos(2) width*100, height*100]); %<- Set size
set(gca, 'FontSize', fsz, 'LineWidth', alw); %<- Set properties
fplot(z1, 'Color', [0 102/255 1], 'LineWidth', lw, 'MarkerSize', msz)
hold on
fplot(z3, 'Color', [230/255 138/255 0], 'LineWidth', lw, 'MarkerSize', msz)
fplot(z0, 'Color', [51/255 153/255 51/255], 'LineWidth', lw, 'MarkerSize', msz)
fplot(z2, 'Color', [102/255 0 204/255], 'LineWidth', lw, 'MarkerSize', msz)

xlim([-1 12])
ylim([-1 2])

plot([-12,12],[1,1], 'r', 'LineWidth', lw, 'MarkerSize', msz)
plot([-12,12],[0,0], 'r', 'LineWidth', lw, 'MarkerSize', msz)

ax = gca;
ax.XAxisLocation = 'origin';
```

```

ax.YAxisLocation = 'origin';
set(ax,'xtick',[ ])
grid off
box off

legend('R_1 = \infty','R_2 = \infty','R_1 = R_2', '|R_1| < |R_2|', 'Location', 'NorthEast');
xlabel('d Cavity Length');
ylabel('Stability');
title('Stability Region of Lasing for Different Radii of Curvature (ROC)');
hold off

```

A.2 Beam Radius Theoretical and Measured MATLAB Code

```

clear; clc; close all;

R1 = -556;
R2 = -600;
d = 552;

z0 = sqrt(-d*(R1+d)*(R2+d)*(R1+R2+d)/(R1+R2+2*d)^2)
z1 = -d*(R2+d)/(R1+R2+2*d)
z2 = d*(R1+d)/(R1+R2+2*d)

lambda = 638e-6;

w0 = sqrt(lambda*z0/pi)

w = @(z) w0*sqrt(1+(z/z0)^2)
w_neg = @(z) -w0*sqrt(1+(z/z0)^2)

x = [1110+z1,700+z1,1110+z1,700+z1]
y = [0.802/2, 0.3975/2, 1.021/2, 0.680/2]
err_x = [0.7 0.7 0.7 0.7];
err_y = [0.042 0.021 0.031 0.047];

width = 10; % Width in inches
height = 4; % Height in inches
alw = 0.75; % AxesLineWidth
fsz = 11; % Fontsize
lw = 1.5; % LineWidth
msz = 8; % MarkerSize

figure(2)
pos = get(gcf, 'Position');
set(gcf, 'Position', [pos(1) pos(2) width*100, height*100]); %<- Set size
set(gca, 'FontSize', fsz, 'LineWidth', alw); %<- Set properties

fplot(w,'k','LineWidth',lw,'MarkerSize',msz)
hold on
xlim([z1+0.01*z1 1000])

```

```

ylim([-1 1])
errorbar(x(1:2),y(1:2),-err_y(1:2),err_y(1:2),-err_x(1:2),err_x(1:2),'or','LineWidth',lw,'Marker
errorbar(x(3:4),y(3:4),-err_y(3:4),err_y(3:4),-err_x(3:4),err_x(3:4),'ob','LineWidth',lw,'Marker
plot([z1,z1],[-1,1],'g','LineWidth',lw,'MarkerSize',msz)
plot([z2,z2],[-1,1],'g','LineWidth',lw,'MarkerSize',msz)
fplot(w_neg,'k','LineWidth',lw,'MarkerSize',msz)
grid on
legend('Theoretical w(z)', 'TEM_{20} Radius', 'TEM_{00} FWHM', 'z_1, and z_2', 'Location', 'Sou
xlabel('z Distance Along Optical Axis (mm)');
ylabel('w(z) Beam Radius (mm)');
title('Beam Radius (mm) Along the Optical Axis (mm)');
hold off

```

A.3 CCD Camera Image Analysis MATLAB Code

```

function [x ,y] = DiffractionData(imagefile, savefile_, line, option)
% this function takes an image file and returns a text file that contains
% the intensity data along a user inputted horizontal or vertical
% scan line. It will also plot the line segment you have choosen.

% imagefile = name of the image file
% savefile = file name for the saved data. An extension _hor or _ver will
% be added depending on which type of line cut is taken
% line = row or column to take the line out
% option = 'hor' or 'ver' to choose to take a horizontal line or vertical
% line segment.
%
% an example usage would be

% DiffractionData_v2('wire.jpeg','wire_cut', 250, 'hor')

%This would import the image wire.jpeg and output the intensity as a
%function of pixel position along the y=250 horizontal line to the data
%file wire_cut_hor.txt.

%The image files captured will usually be 480x640 (horizontal x vertical)

image = rgb2gray(imread(imagefile));
x = [0];
y = [0];

if option=='hor'
    savefile_hor = [savefile_,'_hor.txt'];
    output_hor = fopen(savefile_hor,'w');
    if (line >= 0) && (line <= 480)
        for j=1:640
            diffractionarray(1,j)=(j);
            diffractionarray(2,j)=(image(line,j));
        end

        fprintf(output_hor,'\n %i, %i',diffractionarray(1:2,:));
        plot(diffractionarray(1,:),diffractionarray(2,:));

```

```
        x = diffractionarray(1,:);
        y = diffractionarray(2,:);

    else
        disp('ERROR: line out of range')
    end
end

if option=='ver'
    savefile_ver = [savefile_,'_ver.txt'];
    output_ver = fopen(savefile_ver,'w');
    if (line >= 0) & (line <= 640)
        for j=1:480
            diffractionarray(1,j)=(j);
            diffractionarray(2,j)=(image(j,line));
        end

        fprintf(output_ver,'\n %i, %i',diffractionarray(1:2,:));
        plot(diffractionarray(1,:),diffractionarray(2,:));
        x = diffractionarray(1,:);
        y = diffractionarray(2,:);

    else
        disp('ERROR: line out of range')
    end
end

end

status = fclose('all');
```

Unless otherwise indicated, all images were either drawn by us or taken directly from the Physics 408 lab manual during the course of the lab.