Laser Physics

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Abstract

In this lab we used a 4 level laser HeNe tube and achieved lasing. In the process of alignment we obtained an exponential growth constant of $(75 \pm 3x10^{-3}\frac{l}{m})$ and power constant of $(150 \pm 6)x10^{-3}\frac{l}{m}$. Next the reflectivity was calculated using two methods: from the cavity power and using the Fresnel equation, to which we obtained 0.0740 ± 0.0002 and 0.20 respectively. In our last experiment were found the two beat frequencies $185.83 \pm 0.05Mhz$ with 1.5% error and the other $182.5 \pm 0.2MHz$ had 2.4% error. We also concluded that the first cavity had 8 nodes while the second had 13.

Introduction

The term LASER actually stands for "light amplification by stimulated emission of radiation". In space odysseys are a hallmark of mass destruction but their usefulness transcends science fiction. In every day lives we see laser in bar code scanner at the local market to laser nuclear fusion. So it's important for us to understand how it work.

We used a Helium-Neon tube to amplify the power of a standard laser. By doing so we are able to calculate the power gain constant. Next we calculated the cavity mode spacing of the HeNe tube and compared it with cavity length measurements (Phys 360AB/460AB..). Lastly found the optimum output for the HeNe laser (Phys 360AB/460AB..)

Theory

In this lab a Helium-Neon (HeNe) Laser was used, the first gas laser created. When first created the laser emitted infrared light at a wavelength of 1.15 micrometers but due to demand of visible light lasers a version was created that operated at 633 nm's. These lasers work on a mixture of 85% helium and 15% neon or about 7:1. To operate, the helium atoms are excited by a high-voltage electrical discharge which in turn collide with the neon atoms transferring the energy. These neon atoms then discharge over a 3-step process, starting at the upper state they quickly decay into the upper lasing stage. Then they will lase until they reach the lower lasing stage until ultimately decaying quickly into their ground state. Due to the neon atoms passing through 4 energy levels, this laser is known as a four-level laser. Lasers do exist at other levels, for example the first laser was a three-level laser using ruby as a medium. It was eventually proven that the transition rate from the lower to upper state was the same as the rate from the upper to the lower. This discovery was made by Einstein 1917, leading to this rate being called the Einstein B coefficient. Since the rate of emission is equal to the B coefficient times the number of atoms in the upper state, it showed that you need more atoms in the upper state in order to have more photons produced then lost. This idea is called population inversion and can be used to show that it is not possible to have steady state emission in a two-level system as the upper state decreases by two processes (stimulate emission and spontaneous emission) and the lower by one (absorption). Most

lasers use a three-level or four-level system because of these issues.
Three and four level systems also have issues related to the transitions. Four level systems must have fast decays at the upper level and the lower level otherwise there may be direct transition between the upper level and the ground state (thus creating a two-level system). But there are other challenges as well (for any laser), some light may be diffracted by the mirrors, light can be absorbed by all materials in the laser, reflections from sources outside the system may also interfere.
The cavity of the laser also has some requirements as it must allow the linewidth of the laser to be less then the maximum gain bandwidth created by the upper laser level. The cavity also has multiple modes which are based on the fundamental frequency of the cavity, this can be given by:

$$L = \frac{\lambda}{2} \tag{1}$$

Where is the fundamental frequency of the cavity, and L is the length of the cavity. This also allows us to show that the fundamental frequency of the cavity is twice the length of the cavity. If the length of the cavity is chosen so that a single mode over laps the gain region, the frequency between one of the modes can found using the following equation:

$$\Delta v = \frac{c}{\lambda} = \frac{c}{2L} \tag{2}$$

This frequency can also be called the beat frequency, this value can also be used to determine the number of modes if given the gain bandwidth of the laser.
The laser inside the cavity loses definition as it reflects off each end of the cavity and thus must be focused as it reflects. This causes an issue with using solely parallel mirrors and thus requires one to use a concave mirror as well to help focus the beam. In order for the reflected beam to continue to be reflected it must be identical in phase and amplitude to the initial beam so it does not interfere. This also allows modes to be created within in the space of the cavity. These nodes are called Transverse Electro-Magnetic or TEMlm, with the subscripts indicating the coordinates in the space. Certain directions can be blocked or polarized, thus changing the coordinates of the beam. The cavity must also be stable enough for it to generate a laser mode. While it is not necessary for cavities to be stable in order to generate a laser (thus why it is possible to form laser using two flat mirrors) it is ideal for a consistent laser. The stability is based off two factors:

$$g_1 = 1 - \frac{L}{R_1} \tag{3}$$

$$g_2 = 1 - \frac{L}{R_2} \tag{4}$$

Where L is the cavity length and R is the radius of curvature of a mirror. In order for the cavity to be stable, multiplying these values together must be greater or equal to 0 and less then or equal 1 one. Thus, since flat mirrors have a radius of infinity and thus land right

on 0 making them unstable.
There will also be a partially reflective mirror at the output end of the cavity, this is also called an Output Coupler. This mirror allows some of the light to escape so it can be used for a desired purpose. These is an ideal angle that allows the most light to escape but also allows enough light to continue lasing. There is also an ideal angle to keep all the light inside the cavity to continue lasing, this angle is known as the Brewster Angle. These angles can be used to calculate the power of reflectivity by using:

$$R_{\mathrm{p}} = \frac{tan^2(\theta_{\mathrm{i}} - \theta_{\mathrm{t}})}{tan^2(\theta_{\mathrm{i}} + \theta_{\mathrm{t}})} \tag{5}$$

Where Rp is the reflective power, θ_{i} is the angle of incidence and θ_{t} is the angle of transmission. The power from the beam escaping through the coupler can also be calculate using:

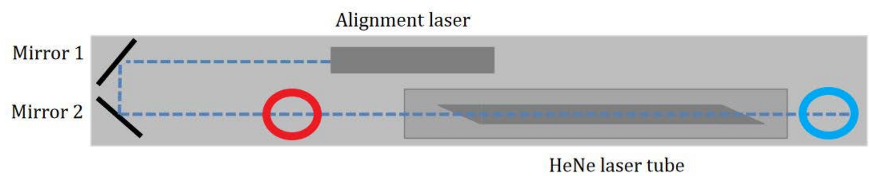
$$P_{\mathrm{p}} = P_{\mathrm{sat}}(\frac{\gamma_2}{2})(\frac{P_{\mathrm{pump}}}{P_{\mathrm{threshold}}} - 1) \tag{6}$$

Where P_{sat} is the saturation power of the gain medium, P_{pump} is the pump power, $P_{\mathrm{threshold}}$ is the pump power that allows lasing to occur, and γ_2 is the coupling loss of the coupler.

Procedure

Equipment List:
- 2 flat mirrors
- commercial grade laser
- HeNe Laser tube
- Curved High Reflecting Cavity Mirror (HR-C)
-Partially Reflective Output Coupling Mirror (OC)
- Variable Output Coupler
- Photodiode Detector
- RF Analyzer
- Meter Stick
- Mask (Wire and washer)
- Power Meter

The first step of the experiment is to align the laser. To do this one needs to use the alignment laser seen in the above diagram. Turn this laser on, then adjust Mirror 1 so the beam enters the laser tube and then adjust Mirror 2 so that the beam is able to make it all the way through the tube. To adjust the mirrors, one needs to walk the mirrors, which is to say slowly adjust the knobs one at a time until the desired setting is achieved. Use the Power meter and the detector to measure the strength of the laser and adjust the mirrors to get the highest value. The next step is to measure the Single Pass Gain, to do this turn on



the laser tube and then place the power meter in the beam after the laser tube. Then take multiple measurements of the beam and without the beam (block the beam or turn it off), this will allow accurate measurements to take place.

Next, one needs to create the laser cavity. This will be done using the OC and HR-C. First place and bolt down the OC in the specified location (should be around the blue circle on the diagram). There will be two knobs, one for vertical adjustment and one for horizontal adjustment. Adjust these knobs until a red spot is seen on the front of the alignment laser. Then place and bolt the HR-C in the specified location (around the red circle), then similar to before, adjust the mirror so the laser reflects and hits the alignment laser resulting in a red dot centered on the output hole. Then, fine tune the cavity by "walking" the mirrors again, starting with the vertical adjustment. Adjust one knob at a time until peak power is reached, if the value starts lowering return the adjusted knob to the prior position. Then repeat this process again with the horizontal knobs. Once peak power is achieved record the value multiple times similarly to how it was done in the first part.

The next step is to identify the Brewster Angle of the laser tube. Place the Variable Output coupler next to the output of the laser tube with the scale facing out. Adjust the angle until the laser beam is completely blocked, then adjust the angle and after each adjustment record the power of the beam leaving the cavity and the beam being reflected out of the cavity. Do this for multiple angles get more accurate data. Now for the next part, remove the coupler and place the photodiode detector in the output beam of the laser and connect it to the RF analyser. Use the RF analyser to identify the beat frequency and then measure the length of the cavity. Then compare the measured frequency to the calculated value. Now move the HR-C towards Mirror 2 away from the tube. Re-align the HR-C like before. Then remeasure the beat frequency and length of the cavity, and once again compare to the calculated beat frequency. Then using the knowledge that the HeNe gain bandwidth is 1.5GHz, calculate the maximum value of ΔL. For the last part, take the mask and place it in front of the back mirror of the cavity and move the wire into the beam. The slowly move the wire into the middle of the beam and record the shape of the patter.

Analysis

Alignment 1

Once we have set up the alignment outlined in the procedure we started recording background, unamplified laser beam and also the amplified beam as it passes through the HeNe laser tube. In the appendix is the table of raw data we obtained by taking 10 trials of the background, beam, and amplified beam. In the following table i subtracted off the background from both the amplified and unamplified beam to get the power input and output. In the following table to get input power i took the difference of the beam with the background and output power with the difference between amplified beam and the background.

Input Power (mW) $\pm(1x10^{-3})$	Output Power (mW)$\pm(1x10^{-3})$	Amplitude Gain $\pm(4x10^{-3})$
0.249	0.264	1.03
0.249	0.275	1.05
0.248	0.272	1.05
0.248	0.260	1.02
0.249	0.261	1.02
0.257	0.261	1.01
0.248	0.274	1.05
0.248	0.261	1.03
0.249	0.277	1.05
0.248	0.261	1.03

Table 1: Table of Input Power,Output Power, and Amplitude Gain

An example calculation of how the amplitude gain was calculated will be done below: Using the equation:

$$g = \sqrt{\frac{P_{\text{out}}}{P_{\text{in}}}} \tag{7}$$

Plugging in the values $0.249 = P_{\text{in}}$ and $0.264 = P_{\text{out}}$

$$g = \sqrt{\frac{0.264}{0.249}} = 1.0296 = 1.03 \pm (4x10^{-3}) \tag{8}$$

Next the error was calculated as follows:

First find the percentage error of P $_{in}$ and P $_{out}$ which gives you 0.53% and 0.57% respectively.

Next take the square root of the sum of squares

$$\sqrt{(0.53)^2 + (0.57)^2} = 0.7793/ \tag{9}$$

This gives you the error after dividing P $_{out}$ by P $_{in}$ however when you take the square root of that you need to divide the error by 2 resulting in:

$$\frac{1}{2} * 0.7793\% = 0.3895\% = 0.4\% \tag{10}$$

Lastly you multiply 0.4% to the gain amplitude to obtain the error $4x10^{-3}$

With the value of amplitude gain for each trial we can then calculate and find the average amplitude gain which gives 1.03 $\pm 1x10^{-3}$. Next by using the following equation:

$$g = e^{\alpha l} \tag{11}$$

Rearranging to solve for α

$$\alpha = \frac{ln(g)}{l} \tag{12}$$

The tube length we measured was $l = 39.5 \pm 1cm$

Inputting values for g and l we get that $\alpha = (75 \pm 3)x10^-3\frac{1}{m}$

The method of finding the error of α is done below:

First the error of ln function is:

$$\frac{\delta x}{x} = \frac{1x10^-3}{1.03} = 9.708x10^-4 \tag{13}$$

Next computing ln(g) = 0.02955. Then the percent error of ln(g) becomes $\frac{9.708x10^-4}{0.02955}x100\% =$ 3.3%. Finally we found the percent error of the tube length measurement and applied the standard error propagation methods:

$$uncertainty = \sqrt{(3.3\%)^2 + (2.5\%)^2} = 4.14\% = \tag{14}$$

Finally multiplying 4.14% to α gives $3x10^-3$

To conclude we found we found the amplitude exponential growth constant to be $\alpha = (75 \pm 3)x10^{-}3\frac{1}{m}$ meaning the power gain constant is $(150 \pm 6)x10^{-}3\frac{1}{m}$

Alignment 2

To begin some qualitative analysis will be made. Once we had the curved mirrors aligned and we achieved lasing outside of the tubes in-between the mirror and the tube entrance at times you were able to laser filaments in the air. There would be small red sparks flashing once lasing occurs.

Next a more quantitative is looking at the maximum power of the HeNe laser tube. Similarly to the first alignment the raw data is in the appendix. Averaging the Power after taking the background difference results in 0.676 $\pm 4x10^{-4}$mW. To minimize the fluctuation between trials we tried not to move too much as power meter was extremely sensitive to small changes in light. For the most part throughout all 10 trials we didn't move much however at the same time around us there were other labs going and people coming in and out was unavoidable. During the set-up we saw the power meter peaked to 700's however it quickly dived back down to 680. We tried the method of "Master and Slave" in adjusting the mirrors however everyone in our group peaked at around 670-680. A variety of factors put a upper limit on the maximum power attainable on the meter. To name a few, the amount of sunlight outside can change the readings on the power meter. Also mentioned earlier human traffic around the lab also significantly effect the readings.

Cavity power and optimum output coupling

Starting off with a bit of qualitative analysis, the initial power was about 0.004J/s when it should be zero. This is however, likely due to ambient light in the room. The value is low since the light is not directed and focused to one point, unlike a laser. The value of the reflected beam is lower then the beam going straight. Even the peaks of the reflecting beam is lower then the peak of the straight beam.

As expected, the direct laser has a single peak and the value is 0.626J/s at an angle of 79 degrees.

Also, as expected there is two peaks, although, it would be expected to be maximized at the same value. The first peak is 0.265J/s at 72 degrees and 0.329J/s at 87 degrees

To find the reflectivity, there are two methods. One with the transmittion power and cavity power and another with Fresnel equation.

The first method is:

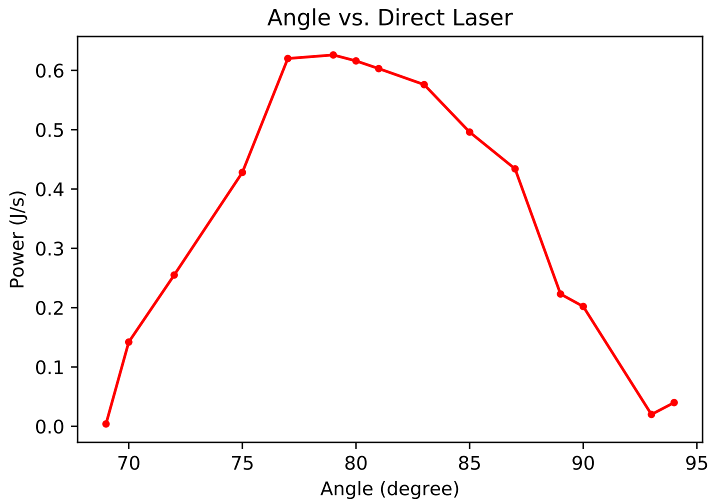


Figure 1: Direct Laser

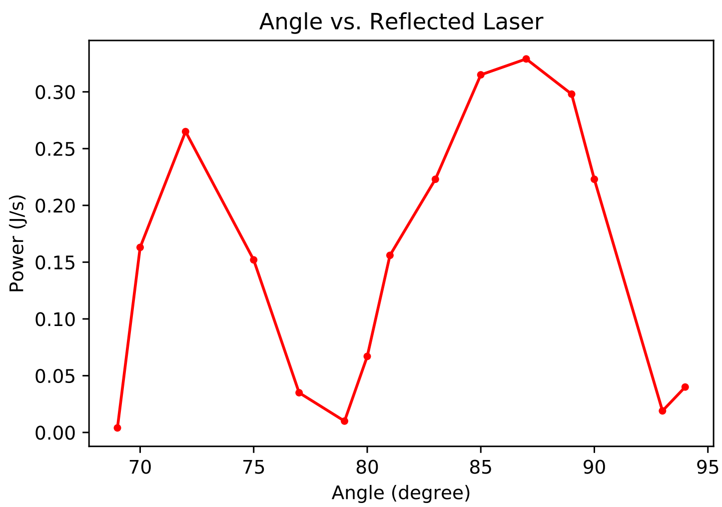


Figure 2: Reflecting Laser

$$R = 1 - T = 1 - \frac{P_{direct}}{p_{cavity}} \tag{15}$$

The average for the cavity is: $0.676 \pm 0.001 J/s$ and the peak power transmited was $0.626 \pm 0.001 J/s$.

$$R = 1 - \frac{0.626}{0.676} = 0.0740 \pm 0.0002$$

Using the second method:

$$R = \frac{Tan^2(\theta_i - \theta_t)}{Tan^2(\theta_i + \theta_t)} \tag{16}$$

The incident angle would be 79 degrees and the transmited angle can be determined using snells law with an refraction index of the glass being 1.5.

$$n_{air}Sin(\theta_i) = n_{glass}Sin(\theta_t) \tag{17}$$

$$\theta_t = arcsin(sin(79)/1.5) = 41 degrees$$

Plugging the values in the Fresnel Equantion:

$$R = \frac{Tan^2(80 - 41)}{Tan^2(80 + 41)} = 0.20$$

The first reflectivity was 0.0740 ± 0.0002 and the second reflectivity was 0.20 which is about 20% as expected (Phys 360AB/460AB..).

The output power is determined by:

$$P_{out} = P_{sat}(\frac{\gamma_2}{2})(\frac{P_{pump}}{P_{threshold}} - 1) \tag{18}$$

Cavity Modes

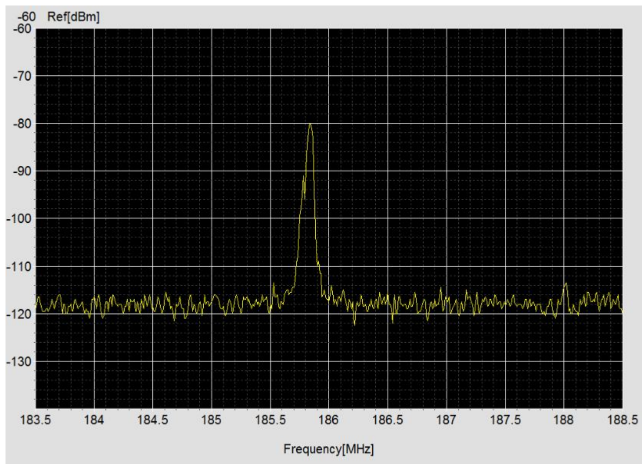


Figure 3: RF Analyzer data for small cavity

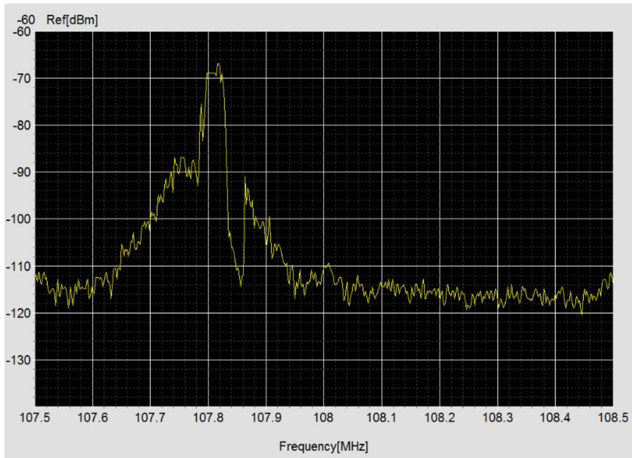


Figure 4: RF Analyzer data for large cavity

Looking at the graphs from the RF analyzer the Beat Frequency for the smaller cavity length is about 185.83 $\pm$ 0.05 MHz (Fig 3) and for the larger cavity it is about 107.82 $\pm$ 0.02 MHz (Fig 4). Using the equation:

$$\Delta v = \frac{c}{2L} \tag{19}$$

where Δv is the beat frequency, c is the speed of light $\left(2.99x10^8 \frac{m}{s}\right)$ and L is the length of the cavity, the beat frequencies can be calculated. For the small cavity:

$$\Delta v = \frac{2.99x10^8 \frac{m}{s}}{2x(0.819 \pm 0.001)m} = 182.5 \pm 0.2MHz \tag{20}$$

This value can be seen to be smaller then the value determined from the graph as there is about a 1.5% difference between the two values. For the large cavity with a length of 1.42 m, the beat frequency would be 105.3 $\pm$ 0.07 MHz, which again is smaller then the value measured of 107.82 MHz with a 2.4% difference. Using both the beat frequencies and the gain bandwidth of the HeNe laser (1.5 GHz), the number of nodes can also be calculated:

$$n = \frac{f_{\text{HeNe}}}{f_{\text{beat}}} = \frac{1.5GHz}{0.18583GHz} = 8.1 \approx 8nodes \tag{21}$$

Thus there are about 8 nodes in the small cavity arrangement. For the large cavity there would be about 13 nodes. Thus neither of them give single mode, in order for them to give single mode the beat frequency would have to be the same as the bandwidth which means (by equation 2) that the length of the cavity would have to be about 10 cm long. So, in order for the commercial laser to have single mode it would need to have a rather smaller cavity.

It is also possible to determine the stability of the laser using the comparison of g_1 and g_2 which can be calculated using the following equation:

$$g_{\text{n}} = 1 - \frac{L}{R_{\text{n}}} \tag{22}$$

Where L is the length of the cavity, n is the mirror number and R is the radius of the curvature of the mirror. The radius of both mirror 1 and mirror 2 is 1.44 m. So, in the case of the small cavity:

$$g_1 = 1 - \frac{(0.819 \pm 0.001)m}{1.44m} = 1 - 0.56875 = 0.43 \tag{23}$$

Since both mirrors have the same radius g_1 = g_2 = g. One check that can be made to make sure cavity was stable is to use the relation:

$$0 \leq g_1 g_2 \leq 1 \tag{24}$$

$$0 \leq g^2 \leq 1 \tag{25}$$

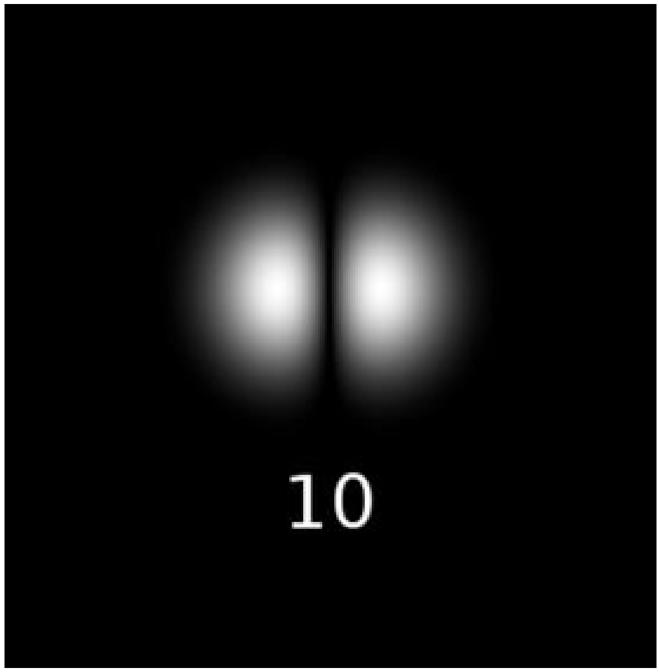
In the case of the small cavity:

$$0 \leq (0.43)^2 \leq 1 \tag{26}$$

$$0 \leq 0.18 \leq 1 \tag{27}$$

Thus, it can be seen that the small cavity is stable as the value 0.18 is between 0 and 1. For the large cavity it has a g value of 0.01, which would have a g_2 value of $1.9x10^{-4}$. Since for a cavity to be stable it must fall between 1 and 0 the closer g_2 gets to either one the higher possibility it has to go past either bound, which means it is unstable. So, comparing the two values, it can be seen that the longer cavity is much more unstable as it is much closer to either bound, specifically 0.

In our experiment we were unable to achieve the TEM10 mode, but the mode should have looked like:



There are many reasons why the laser did not achieve the mode, the water content in the air, the temperature, movement of the air, etc. These may have caused the medium (air) that the laser would transfer through to interfere with beam, affecting the modes.

Conclusion

The first part was to do alignments. The first alignment lead to a exponential growth constant of $(75 \pm 3x10^{-3}\frac{1}{m})$. This gave a power gain constant of $(150 \pm 6)x10^{-3}\frac{1}{m}$. For the second alignment, the background different was $0.676 \pm 4x10^{-4}mW$. After this, the system was aligned for the next parts.

For the cavity power and optimum output coupling, the two graphs were as expected with the direct beam having one peak and the reflecting beam having two peaks. Quantitatively, the two reflective values are 0.0740 ± 0.0002 and 0.20. The latter being 20%, like the expected ≈20%.

The last part, two beat frequnecies where determined. The first beats value was $185.83 \pm 0.05 Mhz$ and the calculated frequnecy was $182.5 \pm 0.2 MHz$,which has a percent error of 1.5%. The second beat value was $107.82 MHz \pm 0.02$ and the calculated value was $105.3 \pm 0.07 MHz$ with a percent error of 2.4%. The first cavity had 8 nodes and the second cavity had 13 nodes. Both cavities are stable, however, the longer cavity is more stable then the shorter one.

Appendix

Background (mW)	Laser Beam (mW)	Amplified Laser Beam (mW)
0.018 $\pm$0.001	0.266 $\pm$0.001	0.281$\pm$0.001
0.016$\pm$0.001	0.265$\pm$0.001	0.291$\pm$0.001
0.017$\pm$0.001	0.265$\pm$0.001	0.289$\pm$0.001
0.016$\pm$0.001	0.264$\pm$0.001	0.276$\pm$0.001
0.014$\pm$0.001	0.263$\pm$0.001	0.275$\pm$0.001
0.013$\pm$0.001	0.270$\pm$0.001	0.274$\pm$0.001
0.012$\pm$0.001	0.260$\pm$0.001	0.286$\pm$0.001
0.012$\pm$0.001	0.260$\pm$0.001	0.273$\pm$0.001
0.012$\pm$0.001	0.260$\pm$0.001	0.273$\pm$0.001

Table 2: Table of Background, Laser Beam, and Amplified Laser Beam For Alignment 1.

Background (mW)	Laser Beam (mW)
0.005$\pm$0.001	0.680$\pm$0.001
0.006$\pm$0.001	0.682$\pm$0.001
0.006$\pm$0.001	0.682$\pm$0.001
0.008$\pm$0.001	0.682$\pm$0.001
0.008$\pm$0.001	0.682$\pm$0.001
0.006$\pm$0.001	0.683$\pm$0.001
0.005$\pm$0.001	0.681$\pm$0.001
0.004$\pm$0.001	0.683$\pm$0.001
0.005$\pm$0.001	0.682$\pm$0.001
0.004$\pm$0.001	0.682$\pm$0.001

Table 3: Table of Background and Laser Beam For Alignment 2.

References

Phys 360AB/460AB Intermediate Physics Laboratory Experiment 21: Laser Physics. Date Unknown. PHYS 360A Modern Physics Laboratory 1. Waterloo(ON): University of Waterloo.