Building a Helium — Neon Gas Laser

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***Abstract*—In this experiment, we will build He-Ne laser cavity using a tube filled with Helium and Neon gas and align it with mirrors such that the Laser is built up from noise having more gain than loss. The single pass gain was measured to have an amplification of 1.03. We determined the angle used to measure maximum output power (Brewster's angle) to be $49^o50^{'}$, this angle has a 12% difference to the expected Brewster's angle. We investigated the cavity longitudinal modes and compared it to the measured cavity length. Also, we attempted to examine the first higher transverse order mode of the cavity TEM_{10}.**

I. Introduction

We all know that light is an electromagnetic wave we use in different aspects of our life, it comes in different frequencies and accordingly in different colors and it carries low energy. However, Laser is different in sense that it emits light coherently, spatially and temporally, so that it produces a very strong ray carries high energy compared to the ordinary light waves. Humans use this strong Laser ray in a lot of fields like medical surgeries, optical communications and many more. The term "laser" is an acronym of the way the Laser ray is produced: "Light Amplification by Stimulated Emission of Radiation". There are many different types of lasers. We get different type of lasers depending on the medium used which can be a solid, gas, liquid or semiconductor.

In our experiment, we are constructing Helium–neon laser cavity using a mixture of gaseous Helium and Neon tube with a ratio of approximately 7:1, by aligning the mirrors with the tube to get it lasing , We will investigate the cavity longitudinal modes and compare it to the measured cavity length. Also, we will examine the first higher transverse order mode of the cavity TEM_{10}.

II. THEORETICAL BACKGROUND [1]

A. Ne-He Laser working principal

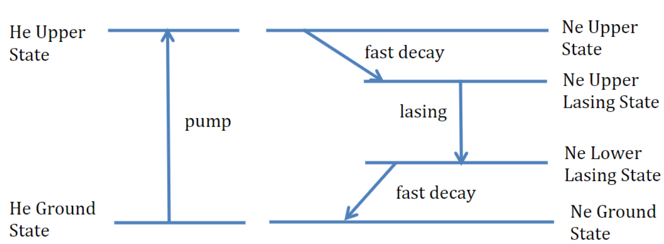

Fig. 1. Ne-He Laser working principal diagram

When high voltage potential is applied across the gas tube , it causes excitation and the stirring of helium and neon atoms. The potential difference works on exciting the helium atoms to higher energy levels such that the excited helium atoms collide inelastically with Neon atoms and transfer their energy. The continuous collision between the helium atoms and the Neon atoms accumulate excited neon atoms in the tube in long-lived metastable state (a relatively long lifespan state). This mode is called population inversion. Then suddenly, some neon atoms drop to a lower energy level and emit photons randomly in all directions.

The emitted photons will be parallel with the tube's axis and will reflect from one of the mirrors and reflects again inside the tube with no escape, then they will interact with the excited Neon atomic electron causing it to drop to a lower energy level, creating a new photon with a similar phase, frequency, and direction of the incident photon such that the atom will emit two photons with the same phase and in the same direction, this process is called Stimulated Emission. This process of reflections is repeated several times and so the number of photons are doubled each time, and that amplifies the intensity of the laser beam to a certain extent, part of which emerges from the partial-reflective mirror in the form of a laser beam, and what remains inside the tube continue the stimulated emission and the production of the laser.

B. Single Pass Gain Measurement

To measure the single Pass Gain measurements, we want to measure the alignment laser signal that passes through the He-Ne tube which acts as laser amplifier and it amplifies the laser signal that passes through.

$$G = \frac{P_{out}}{P_{in}}$$

and the amplitude gain, g, is then given by:

$$g = \sqrt{\frac{P_{out}}{P_{in}}} = \frac{|E_{out}|}{|E_{in}|} = \frac{|E_{in}|}{|E_{in}|}e^{\alpha I_g} = \sqrt{G}$$

C. Cavity power and optimum output coupling [4]

In the figure 2, θ_i is called Brewster angle where the reflected laser beam is completely polarized.

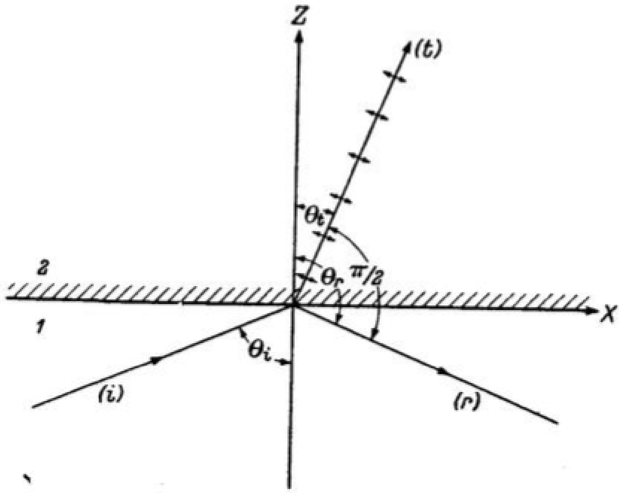

Fig. 2. illustrating the polarizing Brewster's angle

In figure 3, the reflectivity for glass with reflective index n = 1.52, are plotted against the angle of incidence θ_i, such that the Brewster angle will have 0 reflectivity for p-polarization with corresponds to the angle:

$$tan(\theta_i) = n$$

$$tan^{-1}(1.52) = 56^o 40^{'}$$

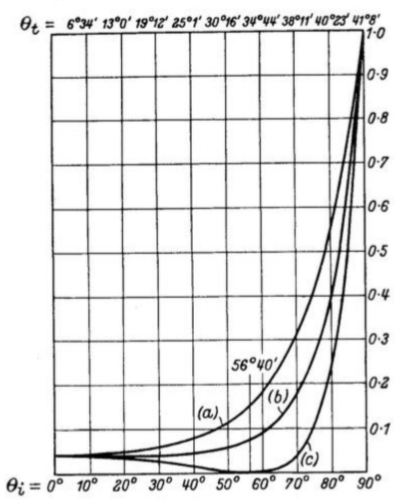

Fig. 3. Intensity of reflected light as a function of the angle of incidence

To determine the power reflectively of the variable output coupler, we can use Fresnel's equation with Snell's law:

$$sin(\theta_i) n_{glass} = sin(\theta_t)$$

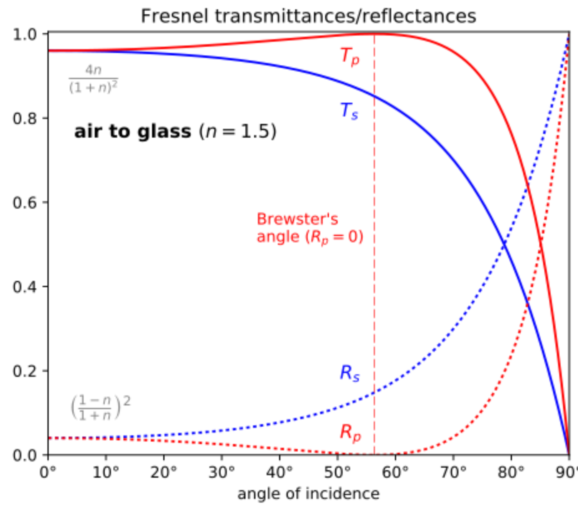

Fig. 4. Power coefficients for the incidence angle in air to the transmitted angle in glass [5]

The power reflectivity for p-polarized light, R_p,is given by:

$$R_p = \frac{tan^2(\theta_i - \theta_t)}{tan^2(\theta_i + \theta_t)}$$

D. Cavity modes

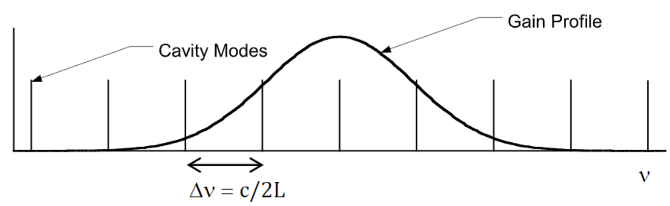

Fig. 5. the frequency domain of the oscillating modes

If we have a laser cavity that is confined between two mirrors, we call it an optical resonator. We Oscillations modes of the cavity are categorized into two categories: longitudinal modes and transverse modes. Such that, Longitudinal modes are the waves which propagate parallel to the axis of the laser cavity, meanwhile, transverse modes are perpendicular to the direction of the wave propagation. For the longitudinal, If we let L to be the length of the laser cavity, then the gap between two consecutive modes is $\frac{c}{2L}$

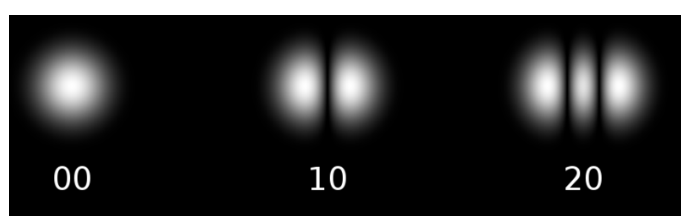

Fig. 6. first three Transverse modes orders, Wikipedia: Hermite-gaussian

For the transverse modes, they are called TEM, which stands for Transverse Electro-Magnetic. Only in the case of the first order mode TEM_{00}, as shown in figure 6, is the continuous region of the highest intensity, However, for the rest of the modes, two or more regions of high intensity are shown in which they are separated by regions of lower intensity.

E. Cavity Stability

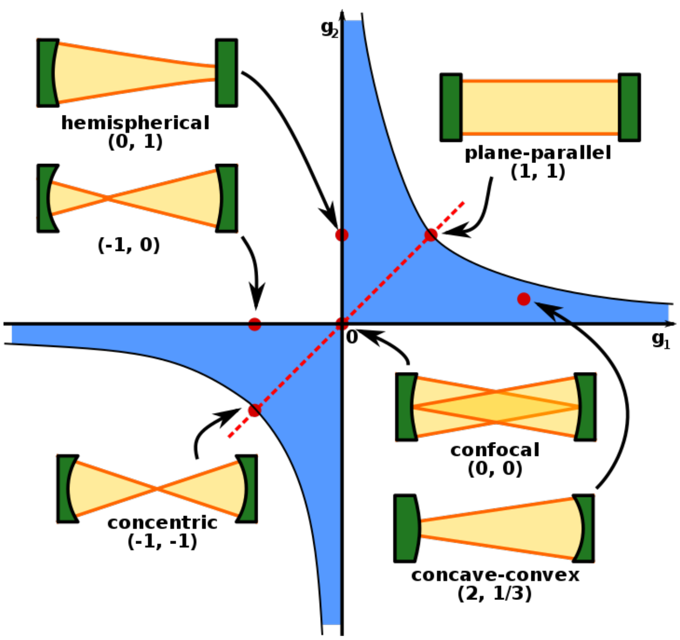

Fig. 7. Stability diagram for a two-mirror that correspond to stable configurations, Wikipedia: Optical cavity

To produce stable modes, in which the beam is produced without being lost, we need these quantities: stability parameter g, radii R of curvature of mirrors 1,2 and the cavity length L, to satisfy this inequality:

$$0 \leq g_1 g_2 \leq$$

such that:

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

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

As shown in Diagram 7, the configuration is stable in the area bounded by the line g_1 g_2 = 1. However, cavities that exist on the line exactly are "almost" stable; such that any tiny change in the length of the cavity can result in an unstable modes. [6]

III. EXPERIMENTAL DESIGN AND PROCEDURE

A. Description of the apparatus

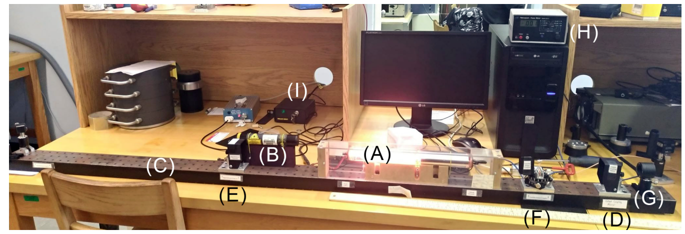

Fig. 8. The laser Alignment Setup

The used apparatus consists of :

A) He-Ne laser tube
B) Alignment laser
C) optical breadboard
D) partially reflective output-coupling mirror
E) Curved high reflecting cavity mirror
F) Variable output coupling
G) power meter detector
H) Power meter
I) High voltage power supply for the He-Ne laser tube

B. Description of the experimental procedure [2] [3]

As shown in Figure 9, we used a commercial He-Ne laser to align the experimental He-Ne laser tube. To do that, we used two turning flat mirrors to reflect the beam inside the tube and then for the beam to come out from the tube. However, this step was already established by our lab instructor.

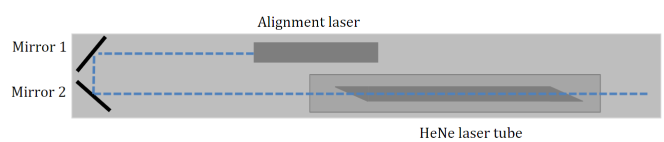

Fig. 9. The laser Alignment Setup diagram

1) Measuring Single Pass Gain: In the first part of the experiment, we wanted to take the single Pass Gain measurements, to do that, we want to measure the alignment laser signal that passes through the He-Ne tube which acts as laser amplifier and it amplifies the laser signal that passes through. However, we want to minimize the losses to measure the gain without any losses, so we placed a polarizer in front of the beam and then we rotated it until we minimized the reflection we saw on the wall of the tube's window. Finally, we placed the Power Meter in front of the beam after it passes from the tube to measure its power. We did that by turning off the Laser tube and blocking the laser beam and zeroing the power meter, then we allowed the beam through and measured the power, and then we turned on the laser tube back and blocked the beam and re-zero the power meter. Lastly, we let the beam pass through the tube and then we measured the amplified power.

2) Lasing setup: As shown in Figure 10, to get the bean lasing, we placed the output coupling mirror at the end of the laser cavity and we placed the high reflector mirror at the opposite end of the laser cavity. We placed the coupling mirror first, so we needed to adjust the mirror such that the beam should reflect back through the tube, we adjusted it using the two knobs (vertical and horizontal adjustment). Then we placed the high reflector mirror as shown in figure 10, again we used the using the adjustment knobs to reflect the beam back to the alignment laser so that the we get its reflection in the centre of the alignment laser output hole.

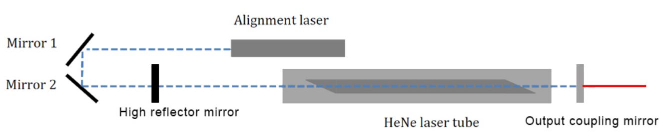

Fig. 10. Lasing Alignment Setup diagram

We watched the output end of the output coupling mirror to see if it started lasing or not, as the output coupling mirror is partially reflective, so part of the alignment beam will be transmitted and this is when we get the alignment for the cavity to start lasing. Finally, we turned off the alignment laser and just left the laser tube turned on for the laser beam to appear.

3) Measuring Brewster's angle: In this part, we want to find Brewster's angle where the reflected laser beam will be completely polarized. To do that, we placed the variable output coupler on the "output" side of the laser cavity.

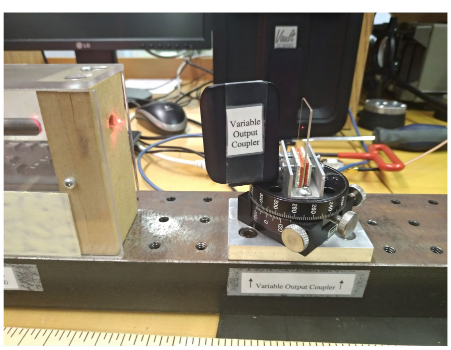

Fig. 11. variable output coupler

After we place the variable output coupler, we need to get the beam lasing again by rotating the variable output coupler, we observed that light is reflected from both surfaces of the glass plate. However, we should get one beam to be completely blocked and the other beam is reflected to the other way in which we placed the power meter in front of it, then we adjusted the angle to maximize the power coming out from the variable output coupler and this is what we call Brewster's angle.

4) Determining Cavity longitudinal and transverse modes: Because we can't measure the frequency of the laser longitudinal cavity modes, we will only measure the beat frequency between the modes. To do that, we removed the variable output coupler and placed the photodiode detector in front of the output beam of the laser cavity then we connected the photodiode detector to the RF analyzer on the Lab PC. We repeated that same procedure for different position of the high reflector mirror so we can compare it with the expected value from the new value for the new cavity length.

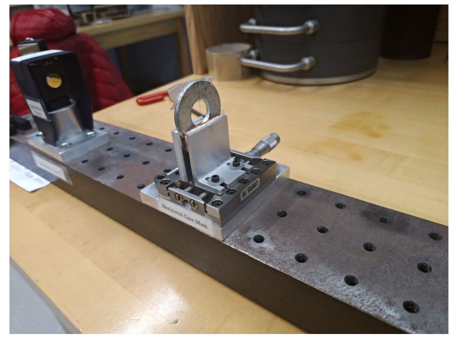

Fig. 12. Horizontal Gain Mask

To observe the transverse modes, we need to change the spatial distribution of the pumping energy and so we did that but using Horizontal Gain Mask. The beam we are getting from lasing is is the zero order transverse mode. However, in this case we are introducing the mask to observe the first order transverse mode. Using the knobs of the Gain Mask, we moved it left and right till we observe a split in the beam and this is the first order transverse mode TEM_{10}

IV. Analysis and Discussion [2]

A. Single Pass Gain Measurement

$$P_{out} = 0.121mW$$

$$P_{in} = 0.118mW$$

The power being output from the commercial HeNe laser was measured to determine the input power using a photodiode. The amplified single pass gain measurement was obtained using the same HeNe laser and is the output power in the following calculation.

The single-pass power gain has an amplification of:

$$G = \frac{P_{out}}{P_{in}} = 1.03$$

The amplification for a single pass is not very great as expected. Over many iterations this amplification becomes significant.

$$g = \sqrt{\frac{P_{out}}{P_{in}}} = \frac{|E_{in}|}{|E_{in}|} e^{\alpha I_g}$$

$$\alpha = \frac{ln(\sqrt{\frac{P_{out}}{P_{in}}})}{I_g}$$

where $I_g = 0.32m$ and $\alpha = 0.0785$

Power Gain Constant = 0.157

There was a fluctuation of readings for the input and output measurements for the commercial HeNe laser. The resulting uncertainty for these measurements is $\pm$ 0.002 mW. This as well as an uncertainty in the measurement of the laser tube length ($\pm$ 0.005 m) result in an uncertainty for the resulting calculated Power Gain Constant. The calculation for this error was carried out as outlined in the manual for Assessment of Experimental Errors and was calculated to be $\pm$ 2%.

The ends of the laser tube are cased in some opaque material only allowing a measurement for its length precise to the nearest half centimeter

Maximum Measured Power Output of Experimental Laser = 0615 $\pm$ 0.003 mW.

The error in the measured maximum power output of the experimental laser is due to observing the measurement to fluctuate upon reading. This was the most stable measurement obtained.

The experiment took place in an environment with substantial ambient light and the intensity of this ambient light was not monitored or kept constant. Without knowing the rate at which the intensity of ambient light may change or fluctuate an uncertainty results. There was also visibly noticeable dust which was moving through the air which the laser travels through, blocking some intensity of the laser at times.

B. Cavity Power and Optimum Output Coupling

The angle used to maximize the power coming out of the original output coupling mirror to ensure the plate is at Brewster's angle is: $49^o50^{'}$

Brewster's angle is $56^o40^{'}$, this measured angle has a percent difference of 12% to the theoretical Brewster's angle.

The maximum power recorded for this angle was 0.440 $\pm$ 0.010 mW, the uncertainty is due to significant fluctuation in measurement readings.

The output coupler reflected beam was not observed to have gone to zero because the maximum power recorded for the transmitted beam was much less than the maximum power output of the laser and so some power must have been reflected. The maximum power was measured at $49^o50^{'}$ rather than at $56^o40^{'}$ and so the variable output coupler had a reflectivity power greater than 0 resulting in a reflected beam. The power output reading had very unstable fluctuations and the measurement recorded (even though the error is quite high due to its fluctuation) was the most stable measurement we could find on the scale. It could be due to these instabilities that the maximum power was not found at Brewster's angle. A Possible cause for these fluctuations could be from increased dust/particles from our bodies being near the beam and the variable output coupler while changing its angle.

The angle used to maximize the power coming out of the reflected output beam is: $47^o40^{'}$

The maximum power recorded for the reflected beam this angle was 0.270 $\pm$ 0.010 mW, the uncertainty is due to significant fluctuation in measurement readings.

From Snell's law the angle of transmission was determined to be:

$$\theta_t = sin^{-1}(\frac{47^o40^{'}}{1.5}) = 29^o30^{'}$$

The reflectivity power is therefore:

$$R_p = \frac{tan^2(\theta_i - \theta_t)}{tan^2(\theta_i + \theta_t)}$$

$$R_p = 5.60 \times 10^{-3}$$

Using the measured output powers:

$$P_{cav} = \frac{Max.\ Measured\ P\ Output\ of\ Experimental\ Laser}{Transmissity\ of\ Output\ Coupler}$$

$$R_p = \frac{Maximum\ Measured\ Reflected\ Output\ Power}{P_{cav}}$$

$$R_p = \frac{(0.015)(0.270mW)}{0.615mW} = 6.59 \times 10^{-3}$$

The measured maximum reflected power as well as the maximum output power of the experimental laser have an uncertainty which carries over to the reflectivity power calculation using these output powers. The uncertainty in this calculation is $\pm$ 4% (calculated as outlined in the lab manual on Learn using the measurement uncertainties).

The power reflectivity calculated from output power has a 15% difference to the value calculated using the Fresnel equations, there is a $\pm$ 4% uncertainty in this calculation but the difference is not within this expected uncertainty.

C. Cavity Modes

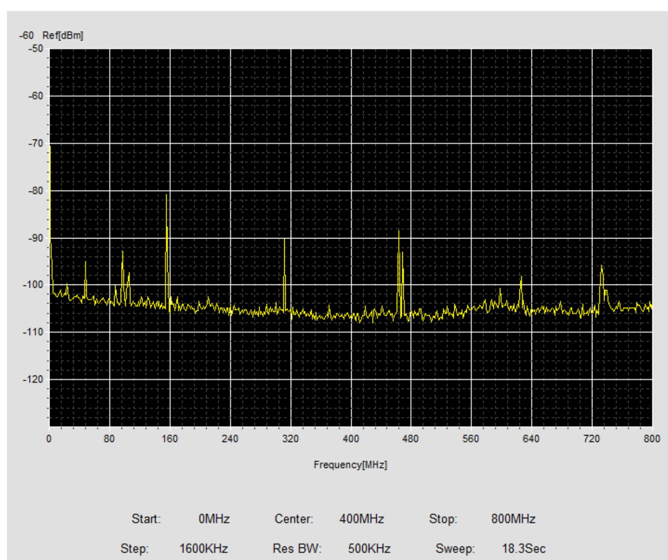

Fig. 13. Beat Frequency Between Modes at High Reflector Position 1

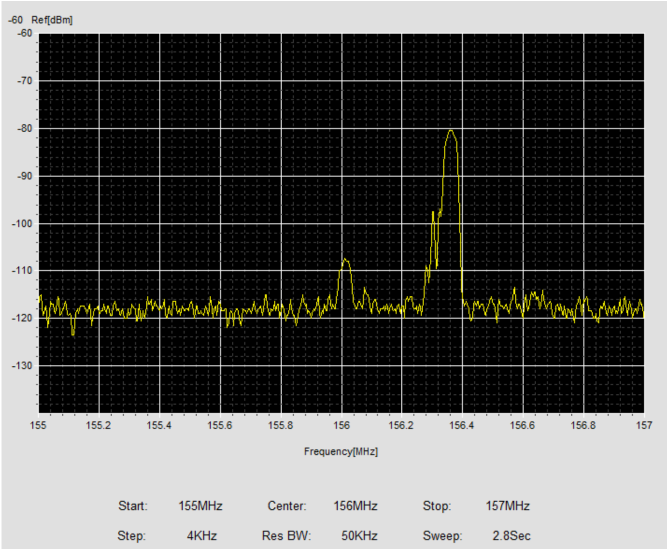

Fig. 14. Zoom at Beat Frequency Between Modes at High Reflector Position 1

From both Figures 13 and 14, the beat frequency at position 1 is determined to be 156.38 MHz using the RF analyzer. The length of the laser cavity at position 1 was measured to be 0.955 $\pm$ 0.005 m. The uncertainty in this length measurement is due to the fact that the reflective surfaces could not be touched and so the distance between reflective surfaces could not directly be measured from the surface. Comparing the value determined using the RF analyzer to the calculated beat frequency:

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

$$\Delta v = \frac{3.0 \times 10^8 m/s}{2 \times 0.955m} = 157MHz$$

The measured beat frequency for the modes at position 1 has a percent difference of 0.4% to the expected theoretical value determined from the measured laser cavity length. There was an uncertainty in the length measurement which will then carry over to the beat frequency calculation and the uncertainty is $\pm$ 0.5%. This calculated value is within its range of uncertainty to the measured value of the beat frequency.

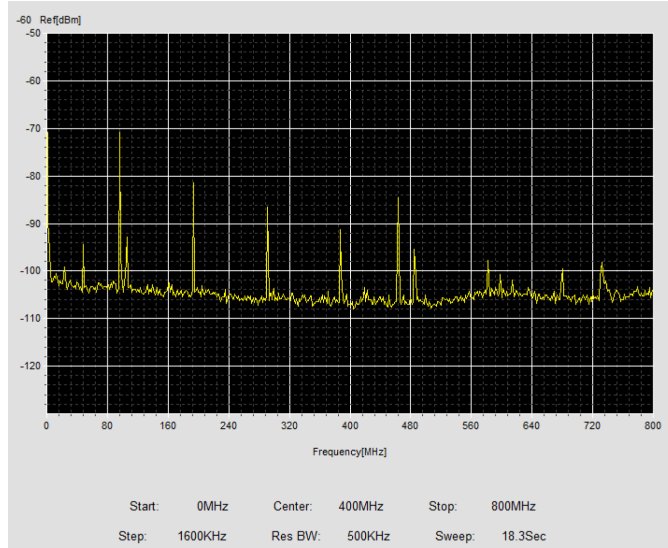

Fig. 15. Beat Frequency Between Modes at High Reflector Position 2

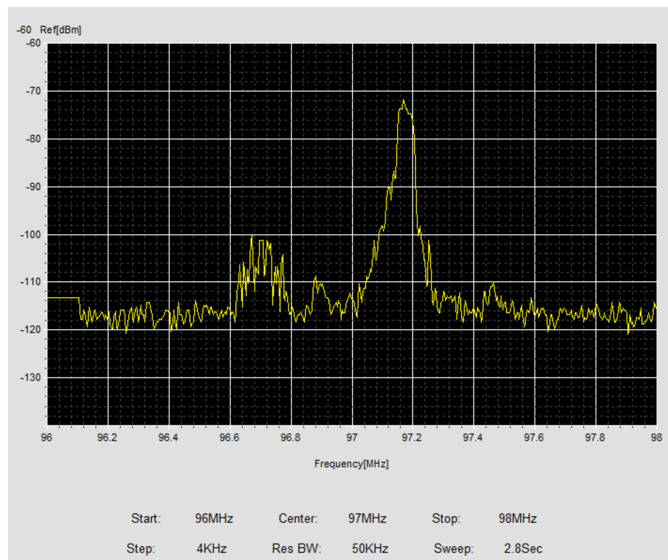

Fig. 16. Zoom at Beat Frequency Between Modes at High Reflector Position 2

From both Figures 15 and 16 the beat frequency at position 2 is determined to be 97.16 MHz using the RF analyzer. The length of the laser cavity at position 2 was measured to be 1.560 $\pm$ 0.005 m. similarly the uncertainty in this measurement comes from the inability to touch the reflectors. Comparing this measured value to the calculated beat frequency value:

$$\Delta v = \frac{3.0 \times 10^8 m/s}{2 \times 1.560m} = 96.2MHz$$

The measured beat frequency for the modes at position 2 has a percent difference of 1% to the expected theoretical calculated value determined from the measured laser cavity length. The uncertainty in this calculation is $\pm$ 0.5%. The difference between these values exceeds the expected range of measurement error.

The precision of this method could have been improved by measuring the frequency of multiple beats and averaging them for a more accurate beat frequency determination with the RF analyzer.

Within the bandwidth of 1.5 GHz there are:

Position 1:

$$\frac{1500MHz}{96.2MHz} = 15\, excitable\ modes$$

Each longitudinal mode results in a sinusoid output wave of unique frequency and since the RF analyzer only detected one beat frequency there must only be one mode excited and so each of these arrangements gives single mode. A Gaussian beam was observed when the laser was pointed at a surface which is consistent with the fundamental transverse mode. A single mode Gaussian beam would be most ideal and expected for commercial alignment lasers because of its narrow linewidth which results in precise alignment.

D. Spatial Modes

The conditions for a stable cavity are:

$$0 \leq g_1 g_2 \leq 1$$

In the experimental cavity both mirrors have the same radius of curvature so:

$$0 \leq g^2 \leq 1$$

For the cavity length of position 1 at 0.955 m:

$$g^2 = \frac{1 - (0.955m)}{(1.44m)^2} = 0.133$$

For the cavity length of position 2 at 1.560 m:

$$g^2 = \frac{1 - (1.560m)}{(1.44m)^2} = 6.94 \times 10^{-3}$$

The shorter mode at position 1 is more stable because its stability is closer to 0 and therefore farther from the edge of the stability curve than the stability at position 2, past which the cavity mode cannot form. The shorter of the two modes was easiest to align due to its superior stability which supports this theory.

E. Higher Order Spatial Modes

Despite attempts, the first order TEM_{10} mode was not observed. It is noted that other unsuccessful attempts have been made using the mask by previous groups. The failure to observe the TEM_{10} could be due to a flaw with the equipment such as the wire not being properly aligned so that the vertical wire will not line up with the horizontal center such that the loss does not become infinite at that center. This would prevent the node from forming at the center of the beam and prevent the laser from lasing in TEM_{10}.

V. Conclusion

The single pass laser gain was found to have an amplification of 1.03, a small amplification as expected but more significant over large numbers of iterations. The amplitude exponential growth constant was then calculated to be 0.0785 with an uncertainty of $\pm 2\%$.

The angle used to measure maximum output power using the variable output coupler was measured to be $49^o 50^{'}$, this angle has a 12% difference to the expected Brewster's angle. A reflected beam was noted upon observing this measurement which supports theory that even though maximum output power was observed, the variable output coupler was not at Brewster's angle. Measurements were noted to be highly fluctuant in this part of the experiment using the variable output coupler.

The power reflectively of the variable output coupler was determined using two methods, one using Fresnel's equation with Snell's law and another by measuring power outputs. The two methods yielded values with a percent difference of 15% and only an uncertainty of $\pm 4\%$. The fluctuations of output power measurements was a major source of uncertainty in the output power calculation method.

The beat frequency determined using the RF analyzer for the shorter of the two cavity length modes was within expected uncertainty of it's theoretically calculated value with a percent difference of 0.4% with an expected uncertainty of 0.5%. The longer of the two cavity length modes was not within the expected $\pm 0.5\%$ uncertainty range with a percent difference of 1%.

The shorter mode was determined to have frequency 156.38 MHz and has a total of 9 excitable modes over the gain bandwidth. The longer mode was determined to have frequency 96.2 MHz and has a total of 15 excitable modes over the gain bandwidth. Both arrangements were determined to give single mode.

The shorter of the two spatial modes was determined to be most stable as expected, the shorter the cavity length the greater stability.

Attempts were made to produce the TEM_{10} pattern using the mask but the pattern was not observed and the TEM_{10} mode was not successfully produced, most likely due to flaws with the mask.

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