Frequency Stabilization of a HeNe Laser via Thermal Feedback

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1 Introduction

When working with lasers, it is often desirable to have an output beam whose frequency remains constant. This can be achieved through various methods of laser stabilization that fall under one of two categories: passive laser stabilization or active laser stabilization. Passive laser stabilization does relies solely on optical effects [2]. An example of this is using a reference cavity, such as the Fabry-Perot interferometer, to lock onto atomic resonance. Active laser stabilization, on the other hand, utilizes an electronic feedback system to control the laser's behavior by converting fluctuations of some kind, such as intensity, to an electronic signal. This signal is then used to monitor and control the laser through various tools, such as PID controllers. Our experiment is utilizing active laser stabilization, where a thermal feedback system is used to stabilize a helium-neon (HeNe) laser.

1.1 HeNe Lasers

A HeNe laser consists of two highly reflective mirrors fixed onto the ends of a glass tube that's filled with gaseous helium and neon atoms. This arrangement forms a laser cavity, where light is only emitted if a reflected beam interferes constructively with an incoming beam after traveling one round trip through the cavity. This condition gives the cavity mode wavelengths, λ_n:

$$2L = n\lambda_n \tag{1}$$

Or in terms of mode frequencies, ν (c = $\lambda\nu$):

$$\nu_n = n\frac{c}{2L} \tag{2}$$

where n is an integer, c is the speed of light, L is the cavity length. The separation between adjacent modes, or the free spectral range (FSR), is given by:

$$\Delta\nu_{FSR} = \nu_{n+1} - \nu_n = \frac{c}{2L} \tag{3}$$

For our cavity of L = 14.1 cm, $\Delta\nu_{FSR}$ = 1.06 GHz.

HeNe light's wavelength is 632.8 nm, which results in a frequency of 474 THz. Because the gain medium is gaseous, the gain curve is Doppler-broadened and has a width of 1.5 GHz [3].

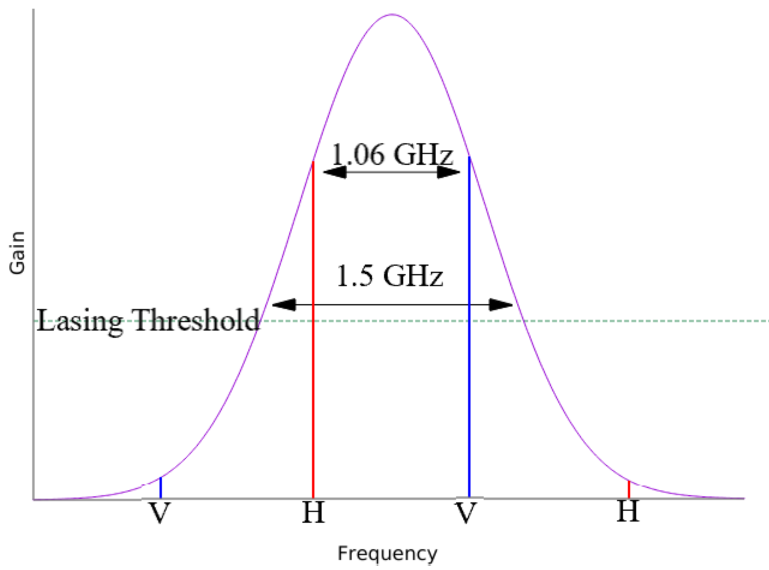

Figure 1: HeNe Gain Curve showing adjacent modes for our laser.

As seen in Fig. 1, our cavity supports two laser modes and the adjacent modes have orthogonal polarizations.

2 Motivation

As the laser warms up, the glass tube begins expand. As a result, the output frequency changes according to equation 2. After some time, the laser will reach an equilibrium point where the tube length remains mostly constant. However, due to ambient temperature fluctuations, the tube length will continue to vary and the frequency will not be completely stable. We want to stabilize the laser using a copper wire heater wrapped around the laser cavity and a PID (proportional, integral, and derivative) controller.

3 Setup

We can exploit the fact that adjacent modes are orthogonally polarized to generate a signal that can be used as a set point for stabilization. This is done by

using a polarizing beam splitter (PBS) and measuring the current of the two modes with photo diodes. We can then convert the current to voltage using an operational amplifier. The difference between the two voltage is sent to the PID via a electric signal. The PID will reduced the difference between the voltages to zero by sending a signal to the heater to adjust the temperature of the tube in order to change the cavity length. The point where the two adjacent modes have equal intensity will be our set point for stabilization.
The stability of the laser can be checked by placing a polarizer and photo detector at the other output of the laser and measuring the intensity of the two modes.

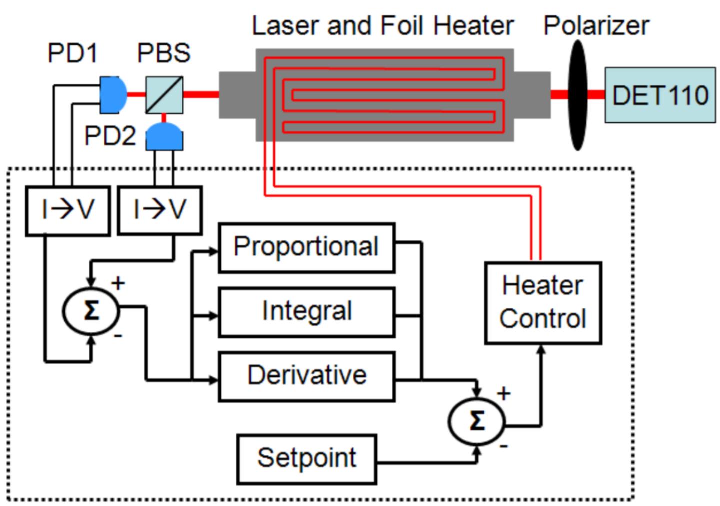

Figure 2: Experimental schematic with general circuit diagram [4].

4 Circuit Components and Laser States

We were able to purchase a programmable Atmega 328 Nano 3.0 Arduino, a circuit board, and components from Laser Sam to carry out this experiment. A link to Laser Sam's website that provides an extremely detailed guide on how to use the circuit and its specifications is provided in reference [1]. Laser Sam also developed a graphical user interface (GUI) to monitor the lasers behavior, which tells you when the laser is locked. However, the GUI is not necessary to use the circuit, as the LEDs on the circuit board will tell you what stage of locking the laser is on. The following list explains the different states of the circuit, as written on Laser Sam's Website [1]:

- **State 0 - Startup**: The firmware is checking that the laser is lit as determined by at least approximately 10 percent of maximum possible amplitude on either the P-Mode or S-Mode signals. Go to State 1 It will wait in State 0 up to 120 seconds for a slow-start tube, else go to State 7.

- **State 1 - Warmup**: The firmware turns on the heater at full power and measures the period of the P-Mode sweep. It will remain here until it exceeds the parameter "Mode Period", which has a default value of around 16 seconds. At this point, the tube should be warm enough to be locked near an optimal temperature. Go to State 3.

- **State 2 - Heating**: The firmware turns on the heater at full power for a fixed length of time, then goes to State 3.

- **State 3 - Locking**: The firmware runs a proportional-only locking algorithm to stabilize the laser. Once the absolute value of the Loop Difference (based on P-Mode - S-Mode amplitudes) has not changed more than the Lock Tolerance threshold for Lock Valid seconds, check the heater power. If within a few percent of 50%, go to State 3; if less than 45-48%, go to State 2 (heating), if more than 52-55%, go to State 4 (cooling). The default duration for heating and cooling differ by 4:1 so that getting into an infinite loop is unlikely.

- **State 4 - Cooling**: The firmware turns on the heater at zero power for a fixed length of time, then goes to State 3.

- **State 5 - Locked**: The firmware runs a PID algorithm and is now stable. It will remain here forever, more or less.

- **State 6 - Hangout**: This is a testing state that can be used to set the heater to a constant value for an unlimited time.

- **State 7 - Error**: Stick here if error occurs. Definition of lock type "error" remains under review but currently includes:

  - Taking too long for the laser to come on in State 0.
  - Loop Difference never going negative in State 1.
  - S-Mode or P-Mode dropping below 5 percent or going above 95 percent in State 5 (which means it's really not locked).
  - Taking too long to lock in State 3.

  Exit from State 7 to State 0 if no laser light after a long time, or to State 1 if the laser beam reappears.

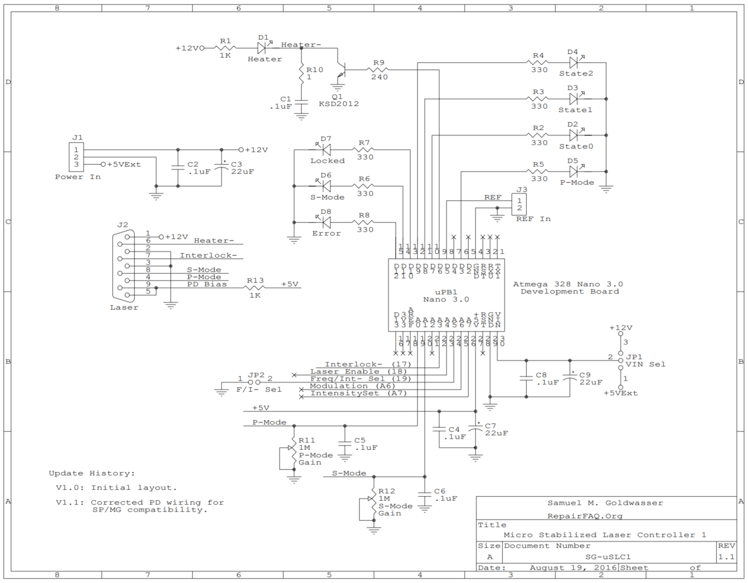

Figure 3: Circuit Diagram from Laser Sam [1]

5 Results

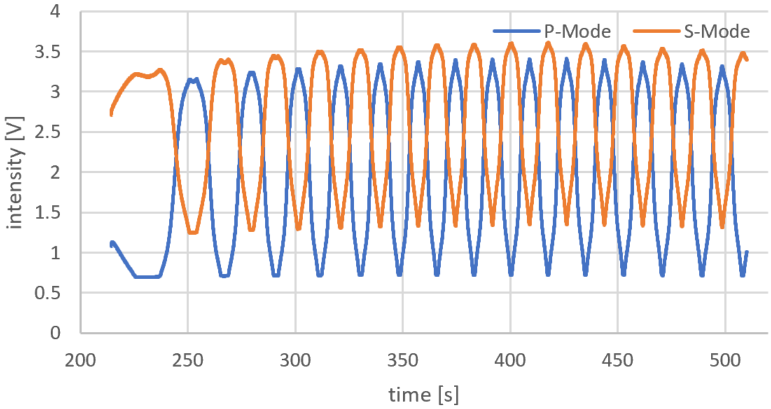

Figure 4: The plot above shows the output of the two modes, measured in intensity, for the first five minutes of the laser being on. The modes' intensity fluctuates very frequently as the expanding glass tube causes the laser to sweep across the modes.

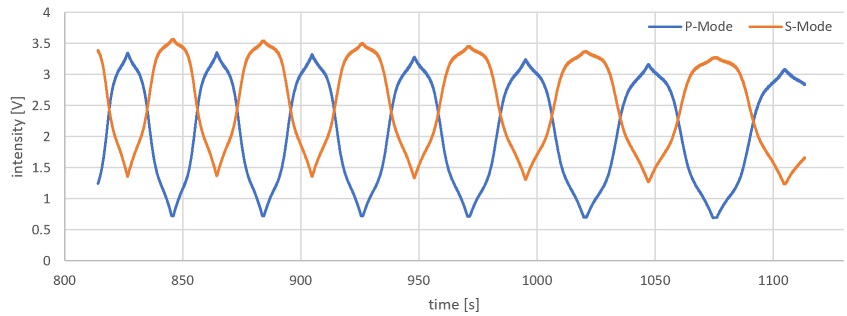

Figure 5: The plot above shows the output of the two modes after the laser has been on for 15 minutes. The data is taken over the span of about 5 minutes and 30 seconds. As the tube length changes less rapidly, the mode sweeping begins to slow down.

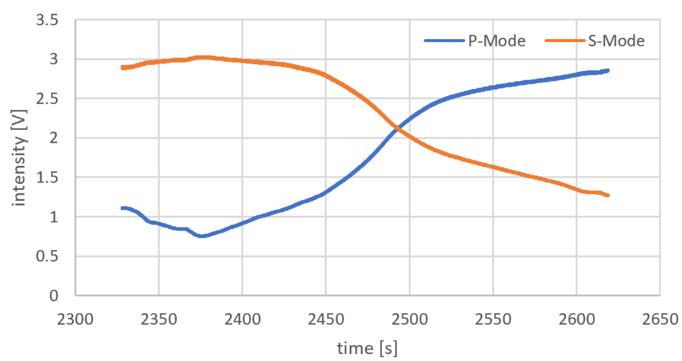

Figure 6: The plot above shows output of the two modes after the laser has been on for 35 minutes. The laser tube is getting close to equilibrium, as the mode sweeping has slowed down significantly as compared to Fig. 4 and 5.

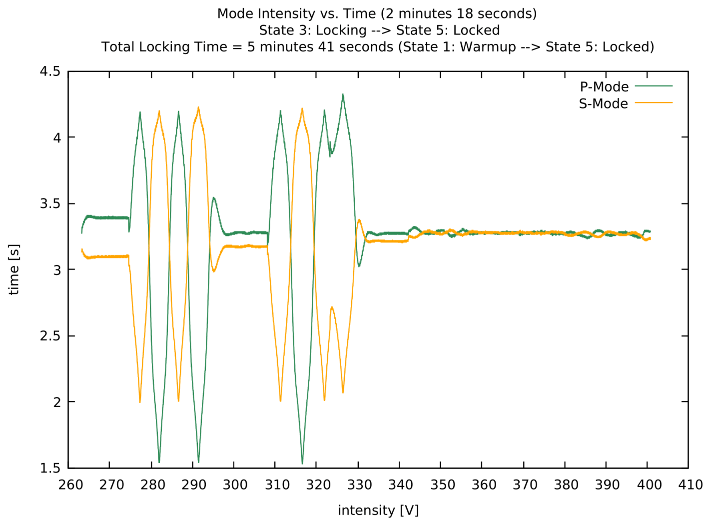

Figure 7: Plot of mode intensity versus time when the laser goes from locking (State 3) to locked (state 5).

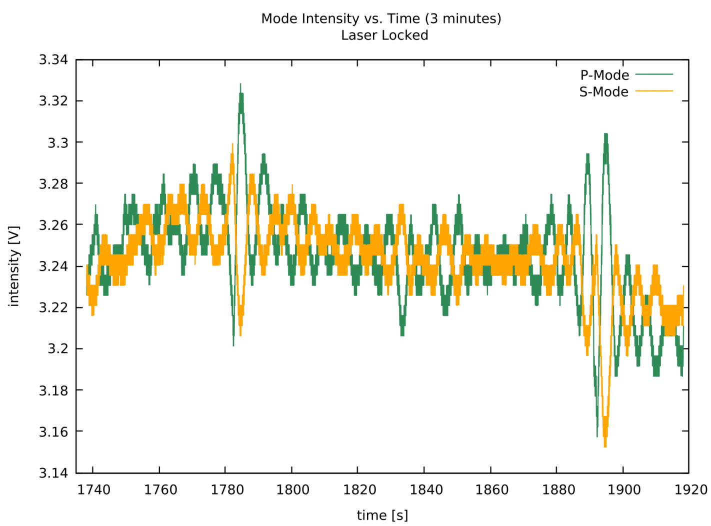

Figure 8: Plot of mode intensity versus time (axis titles are reversed) when the laser is locked, over a period of 3 minutes. This is the desired output, as intensity fluctuations remain small, approximately 0.10V.

6 Conclusion

A circuit that utilizes PID controllers and operational amplifiers were used to stabilize the frequency of a helium-neon laser. Plots of intensity of the two modes versus time were graphed to observe the laser behavior. From figure 4, it can be observed the intensity of the two modes of the laser fluctuates for the first five minutes when the laser was turned on. Thirty minutes later, the laser, without locking, continued to fluctuate but at a slower rate compare to the first five minute as seen from figure 6. However, when the laser is locked, the fluctuation decreased dramatically, as shown in figure 8.

References

[1] Sam Goldwasser *Micro Stablized Laser Controller 1 (μSLC1)* `http://repairfaq.cis.upenn.edu/Misc/uSLC1/uSLC1.htm#uSLC1pcb`

[2] RP Photonics Encyclopedia: Stabilization of Lasers, `https://www.rp-photonics.com/stabilization_of_lasers.html`

[3] Ståhlberg, B., et al. "A Very Simple Stabilized Single-Mode He–Ne Laser for Student Laboratories and Wave Meters." American Journal of Physics, vol. 58, no. 9, 1990, pp. 878–881., doi:10.1119/1.16354.

[4] Yuanchi Zhao. *Implementing Thermal Feedback Control of a Helium-Neon Laser for Frequency Stabilization.* `https://laser.physics.sunysb.edu/_victorz/paper/index.html`