2019

# Locking a Cavity to a Laser for Laser Phase Noise Measurements

PHYSICS 492R CAPSTONE PROJECT REPORT

PAIGE PRICE

ADVISOR: DR. DALLIN S. DURFEE | April 23, 2019

# Abstract

External cavity diode lasers can mode hop unexpectedly. Based on previous measurements by others in the field, we have theorized that a substantial amount of phase noise occurs when a laser is about to switch modes. By monitoring this phase noise and making necessary adjustments, laser stability could possibly be maintained. We have developed an experiment to measure the phase noise to test our theory and determine the feasibility of this stabilization technique. However, the first step in this process is locking the laser to a reference cavity. The locking system currently being used does not work. This paper outlines the current progress and the steps that will be needed to finish testing whether phase noise increases before a mode hop.

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April 2019

# Introduction

Diode lasers are used in metrology and atomic physics. Applications such as laser spectroscopy and laser cooling require laser beams of stable frequencies and linewidths smaller than atomic resonances. Diode lasers may be preferred over other lasers because they are more durable, less expensive, and frequency adjustable. While diode lasers are used for their ability to adjust frequency quickly, this property also causes the laser to mode hop unpredictably and frequently. Mode hopping occurs because of mode competition. As different wavelengths of light are produced by the gain medium in a diode laser, the wavelengths compete for the finite amount of energy in the laser. Some wavelengths of light will be amplified better than others because of the gain medium and the length of the laser cavity. Because the power is pumped into the gain medium at a finite rate, and because laser cavity modes with higher intensities are more effective at extracting energy from the gain medium, if one mode is favored slightly above the others. It will quickly grow and starve the other modes.

Therefore, a diode laser will produce a particular wavelength unless changes are made to the gain. The gain is affected by both environmental and physical factors. Changing physical factors such as the length of the cavity, the temperature, or the current will change the frequencies and gain of the modes. Unfortunately, these parameters tend to drift with time.

In an external cavity diode laser (ECDL), an optical element such as a diffraction grating is used to direct part of the laser's output back into the cavity. By making this back-coupling wavelength dependent, it is possible to tune the laser to the desired wavelength.[1] But mode hopping still occurs, causing significant complications of experiments using these lasers, and may require a high level of expensive passive stabilization.

There are passive and active ways of countering factors that will affect the gain. Temperature controllers are made to help prevent changes in temperature from affecting the lasers. Special optical tables are used to minimize vibrations that may occur from nearby sources. Some researchers even suggest using vacuum chambers to minimize noise due to environmental factors.[2] These are examples of passively controlling the gain but, this paper will focus on using active control.

Since adjustments to the driving current of the laser or the angle of the ECDL grating can also affect the gain, these factors can be used to control the laser. Environmental factors are harder to control, so the driving current can be actively adjusted so that the diode laser can remain in a specific frequency range. Without an active control, a diode laser would be too unstable to be used in metrology and atomic physics applications. The large shifts in frequency cause the laser to drift away from the atomic resonances.

A method of active control was developed by the lab of Steven Chu at Stanford University. This method was based on the observation of noise. Before a mode hop, they noticed an increase in amplitude noise in the external cavity diode laser (ECDL).[3] Chu's lab designed a feedback system which detected amplitude noise using a photodetector and processed this signal to adjust the current driving the laser. They decided to process the amplitude noise because it would be more convenient than analyzing the frequency noise. Their paper states, "Note that the amplitude noise exhibits a similar behavior as the frequency noise… however, it will be much easier to use the amplitude noise instead."[3] The lab at Stanford was successful in using the amplitude noise in the feedback system such that "the diode current enables 12 days of uninterrupted, mode-hop-free operation (after which the laser was deliberately switched off)."[3]

Therefore, Steve Chu's research group was able to maintain the frequency stability of the laser by analyzing the amplitude noise.

While working under the mentorship of Dr. Dallin Durfee, McKinley Pugh was able to demonstrate the correlation between frequency and amplitude noise and mode hopping that the lab at Stanford noticed. Pugh echoed Chu when she stated that "changes in amplitude showed up exactly the same as changes in frequency".[4] However, this correlation was only seen when the laser was locked to the cavity. Therefore, Dr. Durfee hypothesized that the amplitude noise was a byproduct of the feedback system. Any phase/frequency noise was being processed by the feedback system and adjusting the current of the laser. The adjustment of the current produced amplitude noise.

To test this hypothesis, both amplitude and phase noise must be measured. Amplitude noise is measured by looking at the laser power on a photodiode. Phase/frequency noise can be measured by locking a cavity and a laser together so that we can use the cavity to measure high-frequency phase noise relative to the cavity mode.

It takes a series of two types of tests to prove the amplitude noise is a byproduct of the feedback system. First, the laser is locked to the cavity using the noise signal. Amplitude noise is expected in this case. Then, the cavity is locked to the laser. This means the cavity length will be adjusted to keep the laser beam in resonance at a single wavelength within the cavity. Thus, no active adjustments will be made to the laser. If the amplitude noise diminishes, then the conclusion is that the amplitude noise was a byproduct of feedback sent to the laser. Through this experiment, we will identify whether the amplitude noise is a byproduct of locking the laser to the cavity and be able to evaluate how to stabilize the laser frequency by analyzing noise when the cavity is locked to the laser, not only when the laser is locked to the cavity.

However, the locking system is not currently functioning properly. Unexpected noise appears in the error signal in large magnitudes. This has made it difficult for the feedback system to lock the cavity to the laser. We are currently investigating the source of this noise. Therefore, this paper will focus on the progress made so far as well as the next steps we plan to take.

## Methods

In our set up, we have created an external cavity diode laser (ECDL) by placing a diffraction grating in the beam path such that it will affect the frequency of the laser. The grating splits the beam into different wavelengths of light. Some of the wavelengths get reflected back into the laser. However, only the wavelength of light that is also a stable mode of the extended cavity will be amplified by the laser. Therefore, the gain of that wavelength will be greater than the gain of other wavelengths.

To prevent any unwanted reflections back into the laser, an optical isolator is placed in the beam path after the diffraction grating. The optical isolator allows the beam from the laser to pass through to the rest of the optical system. However, any beams that enter through the optical isolator through the side opposite of the laser beam source will not be able to pass through the optical isolator. The optical isolator is able to have this one directional effect because of the Faraday effect. The optical isolator contains a set of orthogonal polarizers and a magnetic field. The light from the laser passes through the first polarizer. Then, the field rotates the light by 45 degrees before the light passes through the second polarizer. As light is reflected back through the optical isolator the second time, it passes through the second polarizer and is rotated 45 degrees more such that it is 90 degrees off from the first polarizer.[4] Thus, these reflections will not be able to pass through the polarizer and enter back into the laser cavity. This prevents unwanted shifts in the gain.

Figure 1 shows the optical setup used to lock the laser to the external optical cavity which will be referred to as the lock cavity. After the laser beam passes through the optical isolator, the beam is split into two beams. One beam goes into the monitor cavity which is used as a reference cavity. The other beam enters the lock cavity. The lock cavity contains a photodetector which creates a current signal that is processed in the feedback system. The feedback system creates an error signal to be evaluated in a proportional-integral controller (PI controller).

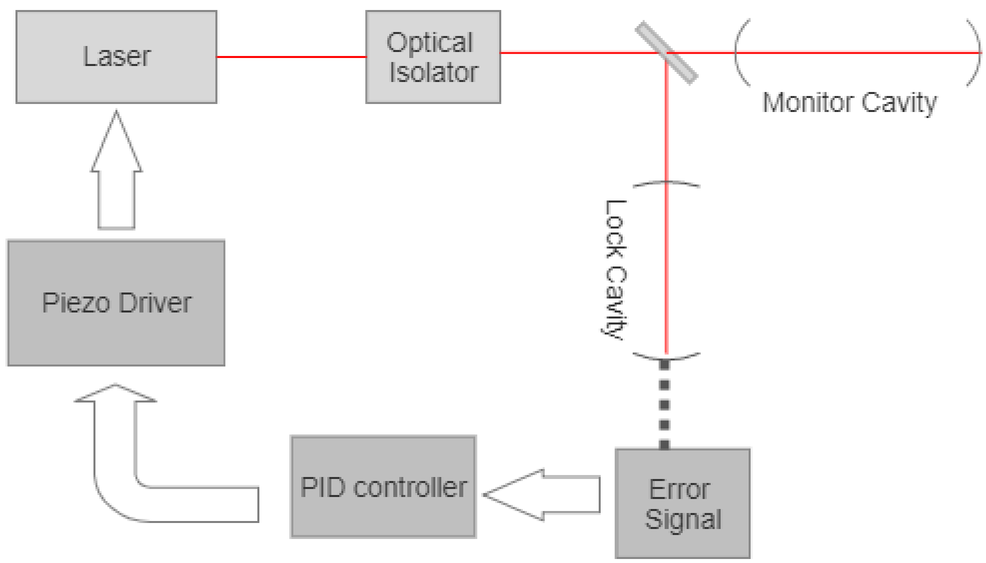



Figure 1. System diagram where the laser is locked to the external optical cavity (the lock cavity).

The PI controller outputs a signal to adjust either the length of the laser cavity or the length of the external optical cavity such that a lock is maintained on a side peak. The PI controller is similar to the electrical system in a car which allows for cruise control. The cruise control evaluates how fast the car is going compared to a desired speed and analyzes the rate at which the speed is changing. Cruise control increases the speed of the car when it is going too slow while preventing the speed from overshooting the desired speed. Similarly, a PI controller in the laser feedback system evaluates the frequency stability of the optical cavity. It determines whether a small or large change needs to be made. The output of the PI controller can be used to adjust different parameters of the system. In some cases, the output of the PI controller is used to adjust the angle of the grating on the laser.[5] This is shown in Figure 1. In other cases, the output is used to change the cavity length of the optical cavity using a Piezoelectric actuator.[6] This is shown in Figure 2.

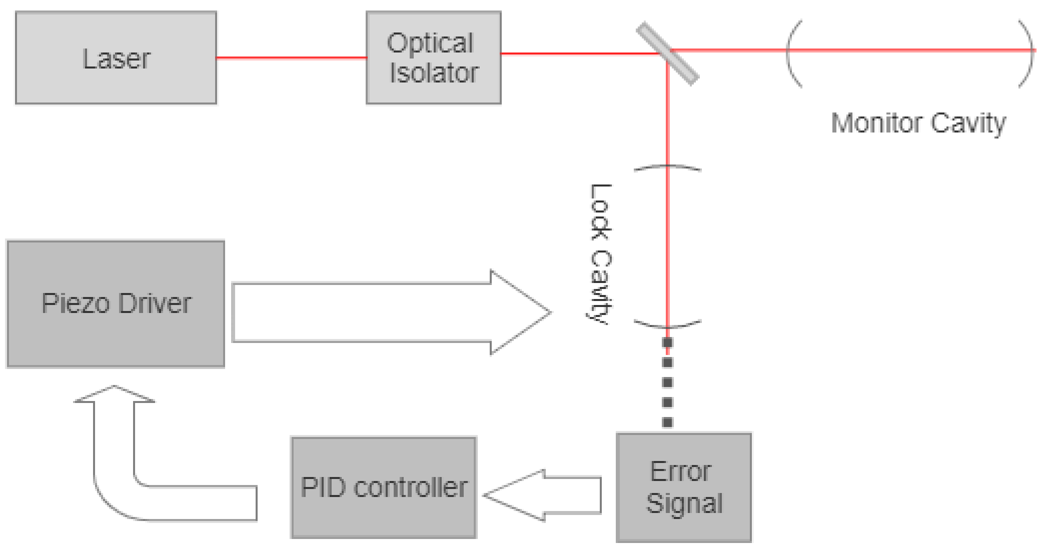



Figure 2. System diagram where the external optical cavity is locked to the laser.

In our experiment specifically, the photodetector creates a current which is transformed into a voltage signal using a transimpedance amplifier. A summer is then used to create an error signal. When the frequency begins to shift, this error signal determines whether an increase or decrease in voltage is required for the piezo to properly adjust to maintain frequency stability. Then the error signal is inverted so that the output of the PI controller will be in the correct direction to move the laser or cavity closer to, rather than further from, the cavity resonance. The final operational amplifier is powered from 0 V to 15 V so that the signal will never become negative. To prevent damaging the piezo, the voltage output must never go negative.

All operational amplifiers used were model type TL072. These operational amplifiers were chosen because of their high slew rate. However, these operational amplifiers are not rail-to-rail. Therefore, the operational amplifier that is powered from 0 V to 15 V cannot have its non-inverting input at 0 V. This is because no matter how hard the operational amplifier tries, it will never be able to make the inverting input match the non-inverting input while the non-inverting input is at the same value as the lower supply voltage. Therefore, a voltage divider was used to supply the non-inverting input with 3.46 V. This allows the operational amplifier to work to make the inverting input match the non-inverting output while also preventing the output voltage from going negative. See Appendix A.1 for the full schematic.

Our first circuit, which used only an integral gain stage, was unable to lock the cavity to the laser, so a second circuit was developed. This circuit added a proportional gain in parallel to the integrator. Another adjustment was also made to the circuit. The transimpedance amplifier had a 10 MΩ feedback resistor which was used to convert the current signal from the photodiode into a voltage signal with a relatively high bandwidth. This resistor was switched out for a 100kΩ variable resistor to give us a way to control the overall gain of the system. By having a tunable overall gain, we tested if we had too much gain. These adjustments are recorded in the circuit diagram in Appendix A.2.

## Results and Discussion

With both proportional and integral feedback, and with better control of the feedback parameters, we tried again to lock the cavity to the laser. Figure 3 shows the error signal produced when feedback is not being sent to the cavity as the laser is scanned through a cavity resonance. When feedback is applied, the error signal will oscillate about zero. However, Figures 4 and 5 show that the feedback signal does not make the error signal go to zero. Figure 4 shows when all variable resistors are set to maximum value while Figure 5 represents the signals that result when the proportional gain is set to half its value. Neither case is successful at locking the cavity.

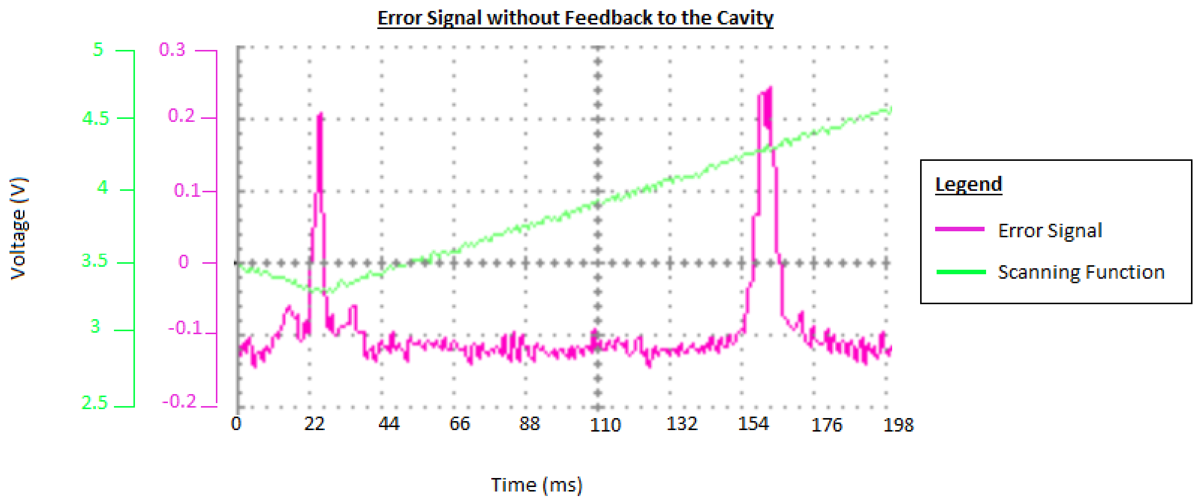



Fig 3. Pink is error signal produced by the circuit without any feedback. The green line is the function being used to scan the laser.

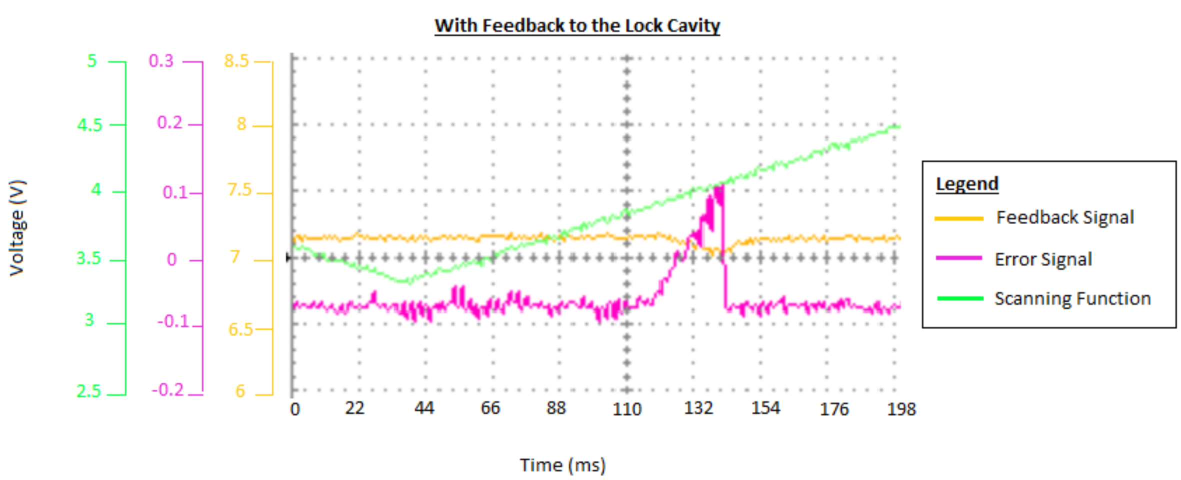


Fig 4. The error signal is created as a result of the feedback signal. The graph corresponds to data using the Appendix A.2 circuit diagram where all variable resistors are set to maximum resistance.

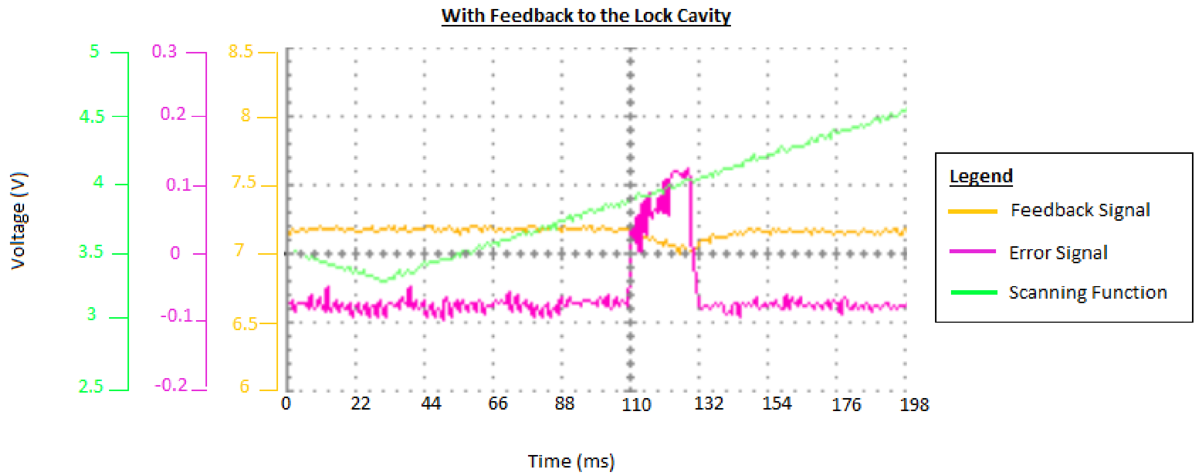



Figure 5. Error signal (pink) is created as a result of the feedback signal (yellow). The graph corresponds to data using the Appendix A.2 circuit diagram where the transimpedance amplifier and the integrator are set to maximum gain but the proportional gain is set to half of the maximum value.

In some cases, extra oscillations of magnitudes greater than 0.3 V occur on the error signal. These oscillations make it impossible to lock the cavity. While one would expect oscillations with too much feedback, strangely these oscillations were not centered around the lock point. When the gain was reduced enough, the oscillations would go away. But when the gain was reduced, there seemed to be very little feedback. The feedback was insufficient to lock the cavity to the laser.

We believe that there is not enough bandwidth to successfully lock the cavity, and this could be causing the oscillations. The noise is at frequencies higher than we are able to feedback. Therefore, a piezo actuator with higher bandwidth or a setup with more passive stability will be required to successfully lock the cavity.

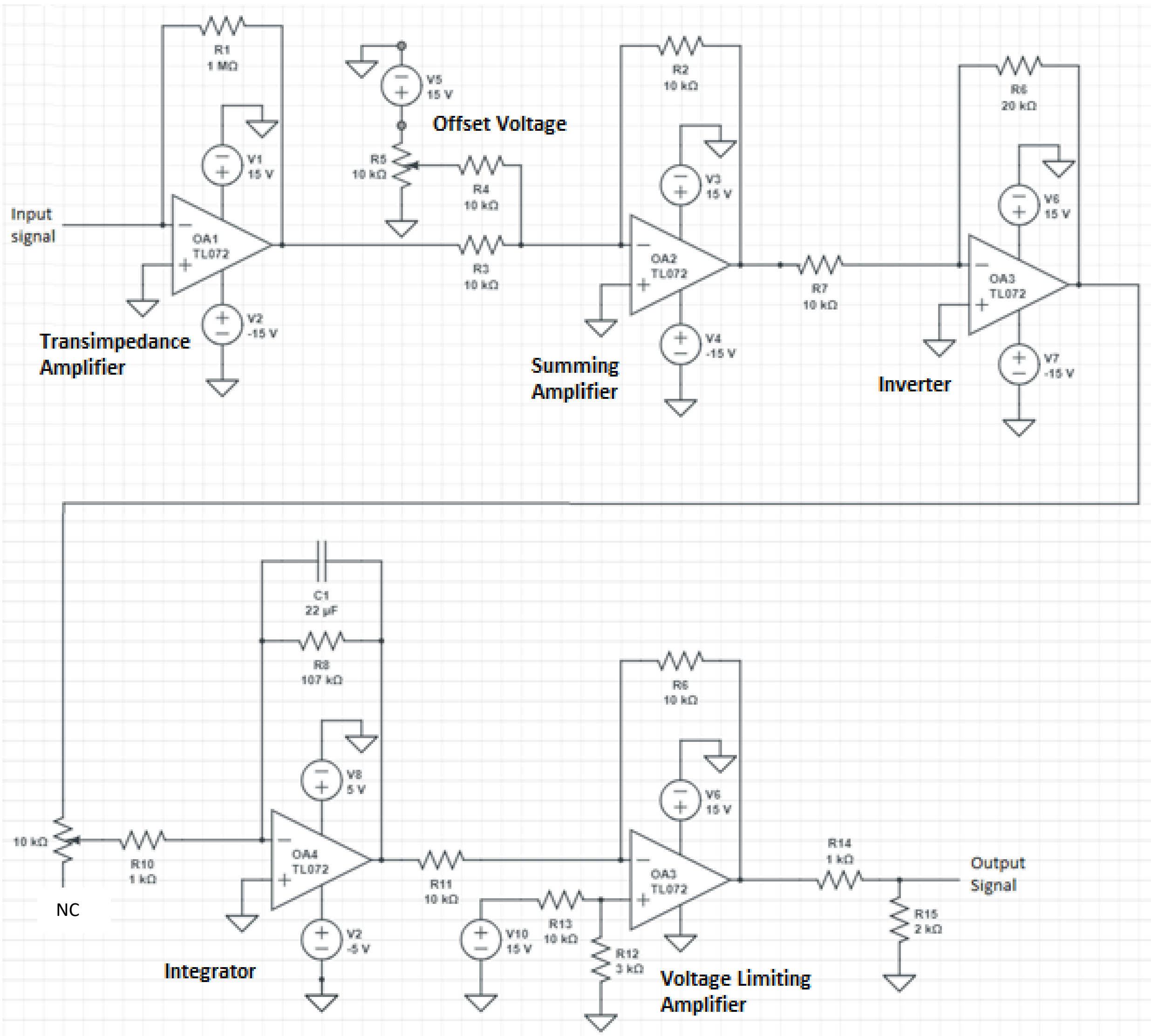
# Conclusions

There could be many reasons why this system was unable to lock. The most probable solutions are an error in the circuit or limited bandwidth of the piezo mirror mount. The circuit has undergone many tests, however, there may still be circuitry errors. There may be a poor connection somewhere in the circuit, and the wires may be acting as antennas picking up and amplifying noise. However, the circuit appears to work properly when the feedback is not sent. It is only after the feedback is adjusting the cavity length that unexpected results occur. Therefore, the problem may be due to the piezo actuator not being able to process the feedback fast enough. A piezo actuator with higher bandwidth may be required to successfully mode-lock. Future work is required to create a locking system that can be used to test our hypothesis that the amplitude noise in the work of Chiow, et. al.[3] was a byproduct of the feedback system.

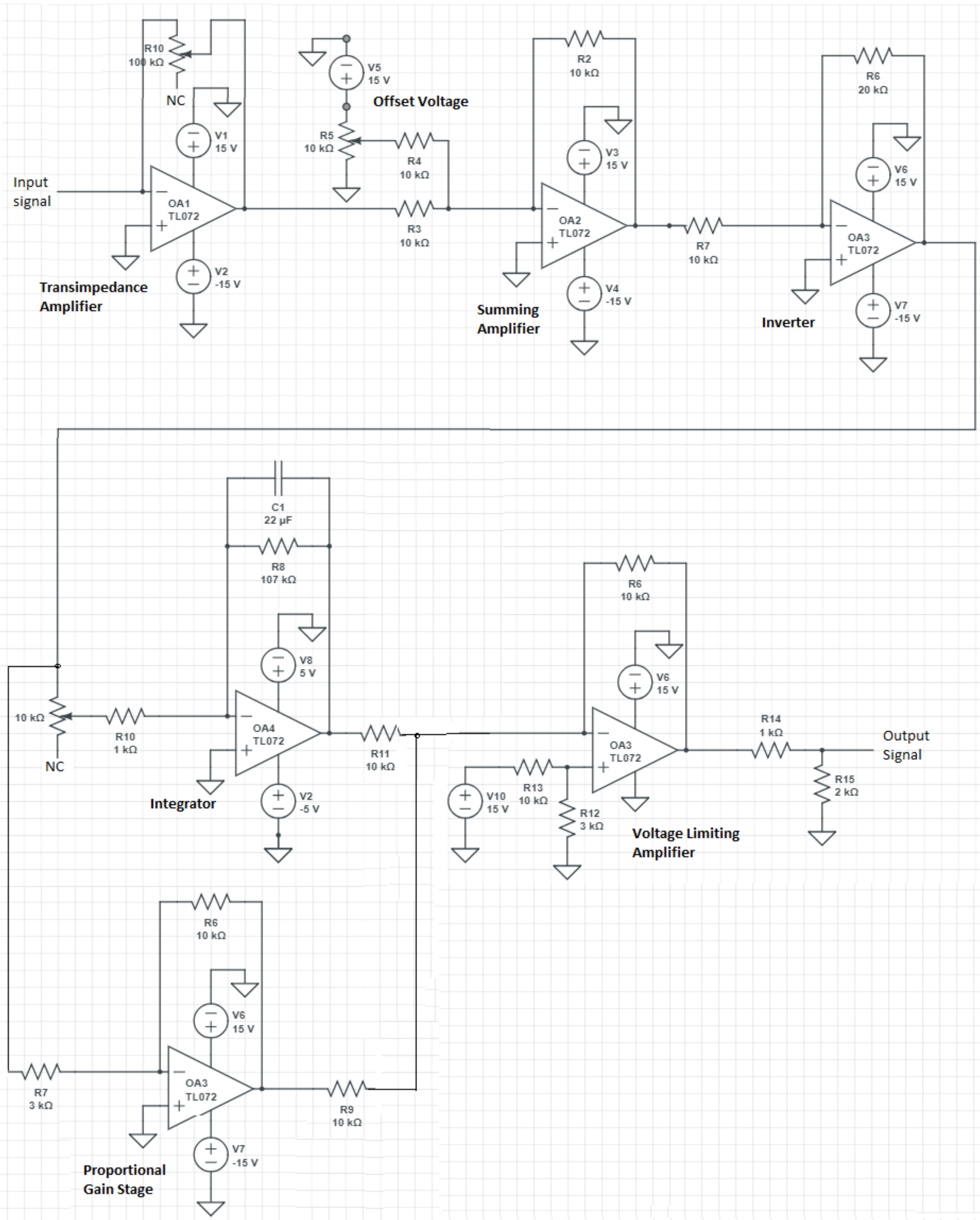
# Appendix A

These are the circuit diagrams outlined in the methods section.

A.1)



A.2)


R10
100 kΩ
NC
V1
15 V
OA1
TL072
V2
-15 V
Input signal
Transimpedance Amplifier
V5
15 V
Offset Voltage
R5
10 kΩ
R4
10 kΩ
R3
10 kΩ
R2
10 kΩ
V3
15 V
OA2
TL072
V4
-15 V
Summing Amplifier
R7
10 kΩ
R6
20 kΩ
V6
15 V
OA3
TL072
V7
-15 V
Inverter
C1
22 µF
R8
107 kΩ
V8
5 V
10 kΩ
NC
R10
1 kΩ
OA4
TL072
V2
-5 V
Integrator
R11
10 kΩ
R6
10 kΩ
V6
15 V
OA3
TL072
V10
15 V
R13
10 kΩ
R12
3 kΩ
Voltage Limiting Amplifier
R14
1 kΩ
R15
2 kΩ
Output Signal
R6
10 kΩ
V6
15 V
R7
3 kΩ
OA3
TL072
V7
-15 V
R9
10 kΩ
Proportional Gain Stage

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# Acknowledgements

Dr. Dallin Durfee has guided me in this project. Jarom Jackson and David McKenna have also been wonderful mentors. I am grateful for the time they have set aside to assist me in trying to figure out why the system was not locking. Their knowledge of circuitry and lasers has been invaluable. I am grateful to have had the opportunity to learn from them.