

# **Development of a Stable Laser Lock System**

Pavel Zhuravlev

Advisor: Dr. Eugeny Mikhailov

April 13, 2012

## **1. Abstract**

The purpose of this project was to develop an analog electronic system that will stabilize the frequency of light being output by a laser. This is accomplished using a process called dither locking, which employs a lock-in amplifier in combination with a feedback loop. The lock-in amplifier is used to extract an error signal at a desired point, and the feedback makes corrections in the laser's output frequency to keep it stably locked at the set point. The system we designed and implemented was shown to stably lock the laser light's frequency for over an hour and be able to achieve the lock within 20 seconds of being turned on.

## 2. Introduction

In order to run a controllable experiment, one must often stabilize certain experimental parameters and vary others. In an optics laboratory, many experiments depend on the stable detuning, or shifting, of a laser's frequency. This is especially true of experiments like electromagnetically induced transparency (EIT), transmission through a Fabry-Perot cavity (etalon), and saturated absorption spectra that generate frequency dependent resonance-like signals, shown in the top of Figure 1. Thus, the stable tuning of a laser to the resonance peak is often required for an experiment to yield reliable measurements and results.

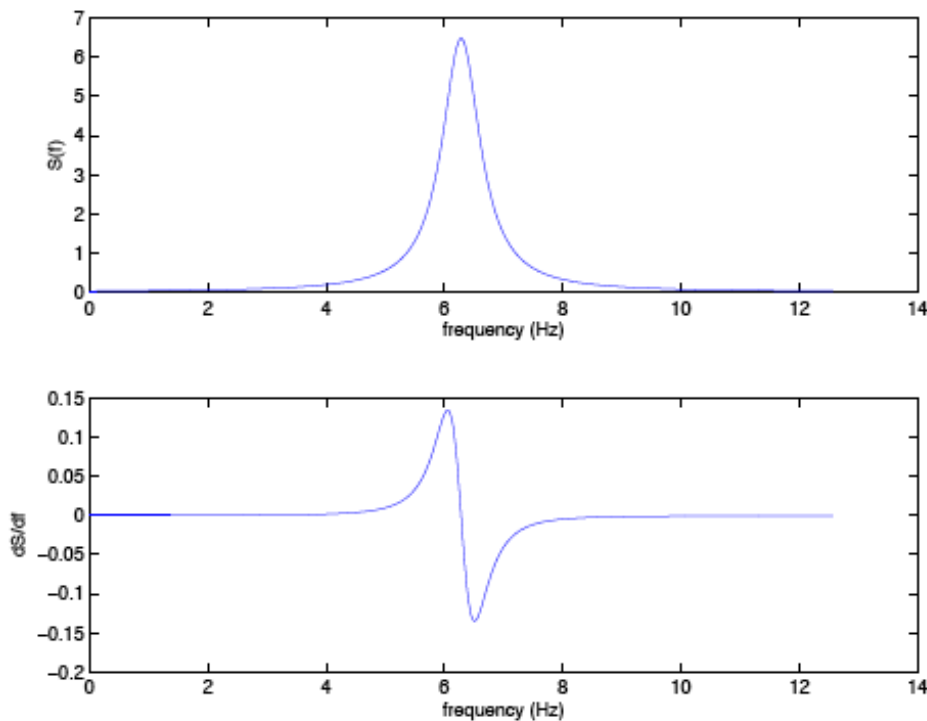


Figure 1: The top graph shows a typical resonance-like signal, with a peak occurring at  $f_0=2\pi$ , which the Laser Lock is designed to lock on to. The bottom graph shows its derivative, which will be used to determine the frequency of our laser relative to the resonant frequency.



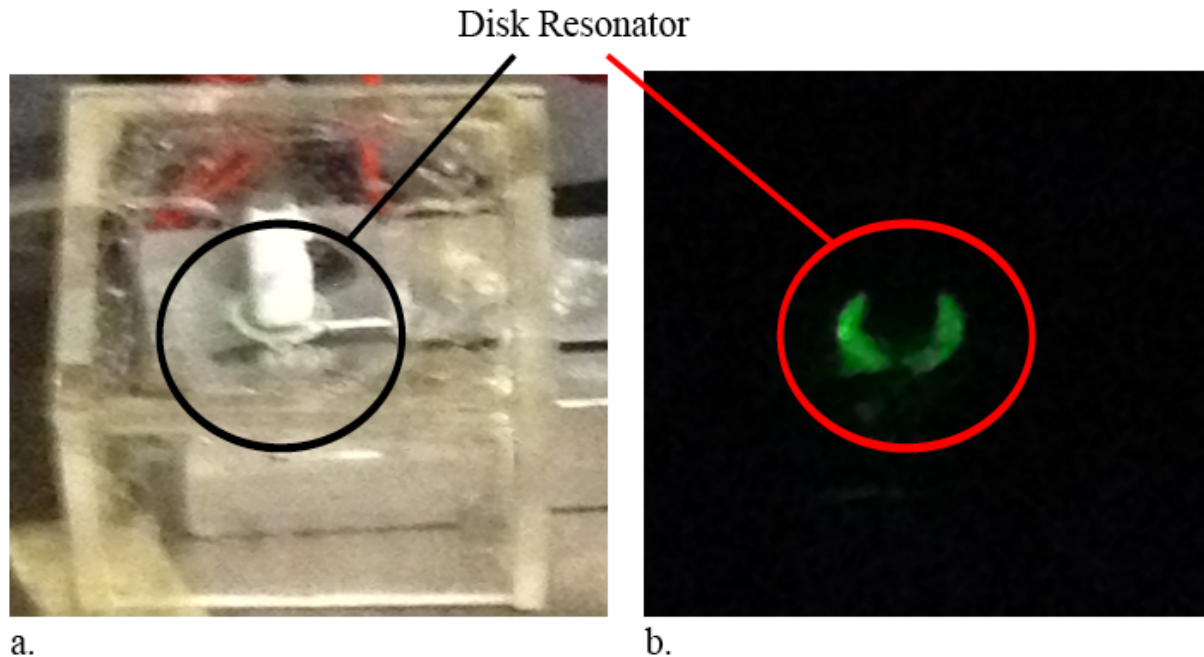


Figure 2: Disk resonator setup and green laser glow due to a second harmonic generation at resonance conditions. <sup>[6]</sup>

Figure 2 depicts an example of an optical experiment that depends on the frequency of the input laser light. The purpose of the experiment is to create a stable second harmonic generator using temperature dependant resonance position tracking. <sup>[6]</sup> In the experiment, an infrared laser is passed through a fiber optic cable followed by a series of lenses and mirrors in order to focus it precisely onto a prism set atop of the crystalline disk shown in Figure 2A. Upon entering the prism, light from the laser refracts and hits the disk, which either reflects or absorbs this light.

The disk is an optical resonator, which at certain resonant frequencies accepts incident light. This produces a strong power buildup as a result of constructive interference. When the frequency of the laser light is properly tuned to the resonant frequency, the disk will begin to glow green, as shown in Figure 2B, due to a doubling of the frequency of light within the disk caused by infrared power buildup. This doubling of frequency corresponds to a halving of the wavelength. Thus, infrared light, which occurs at 1064 nm and is invisible to the human eye,

becomes green light at 532 nm.<sup>[6]</sup> At non-resonant frequencies, however, the disk does not accept light and any waves incident on the disk are reflected straight onto a photodetector. The photodetector converts the incident infrared waves into a voltage proportional to the power of incident light. The voltage signal from the photodetector is then read by an oscilloscope, which, when the laser is properly tuned, produces resonance-like signals similar to those at the top of Figure 1. In our case, however, the signals are inverted so that the minimum corresponds to the maximum acceptance of light by the disk.

The laser must be constantly tuned to resonance because the resonant frequencies of the disk are extremely sensitive to the effects of external variables, especially temperature, because of minute changes in the size of the disk. Small changes in temperature will cause small shifts off of the resonance peaks proportional to the temperature change. It is possible to manually tune the frequency of the incident laser light to resonant frequencies, but in the long run this is time consuming and counterproductive.

Because of this, we have decided to construct a lock-in based laser lock system. This system allows us to lock-in to the peak of a signal, at either its minimum or its maximum, output by an experiment. It will do so by measuring the derivative of the experimental output signal, shown at the bottom of Figure 1. Measuring the derivative of the experimental output signal allows us to determine how far and in which direction the laser's frequency needs to be tuned in order to be on resonance with the resonant frequency corresponding to the zero point of the derivative. The system will then generate an error signal that is proportional to the deviation of the derivative of the experimental signal from its zero point. This error signal is the crucial part of the feedback loop. It adjusts the laser's frequency in order to stabilize it and prevent it from deviating from the experimental output signal's peak.

The general procedure for determining the derivative of the resonance signal is shown in Figure 3. This process is known as dithering, because we will oscillate the frequency of the laser's light. These oscillations in frequency,  $\Delta f$ , will cause corresponding oscillations in the amount of light incident on the photodiode ( $\Delta A$ ), and thus in the output voltage of the photodetector. Assuming that the response of the system is approximately linear about small changes in frequency ( $\Delta f$ ), the amplitude ( $\Delta A$ ) of the signal oscillations can be found.

$$\Delta A = \frac{dS}{df} \Delta f \quad \text{Equation 1}$$

Where  $dS/df$  is the slope (derivative), of the resonance peak. Because it is proportional to the derivative, the amplitude of the oscillations is the quality of interest to us.

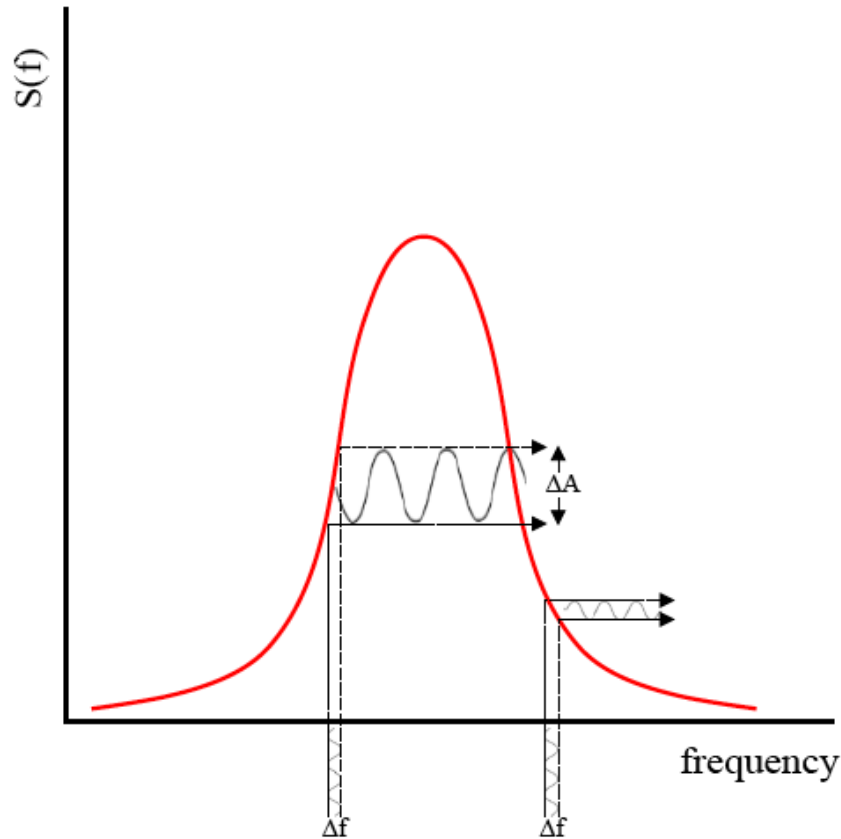


Figure 3: Determining the derivative of the resonance peak by dithering the laser's frequency.

Dithering the laser's frequency about the resonant frequency is shown in Figure 4. This output can still be approximated using a sine wave with a doubled frequency. Sufficiently small amplitudes in the dithering frequency will allow Equation 1 to hold, making the dither output zero at resonance. In order to determine the amplitude of the sinusoid ( $\Delta A$ ) at the dither frequency ( $\Delta f$ ) the laser lock system will employ a lock-in amplifier.

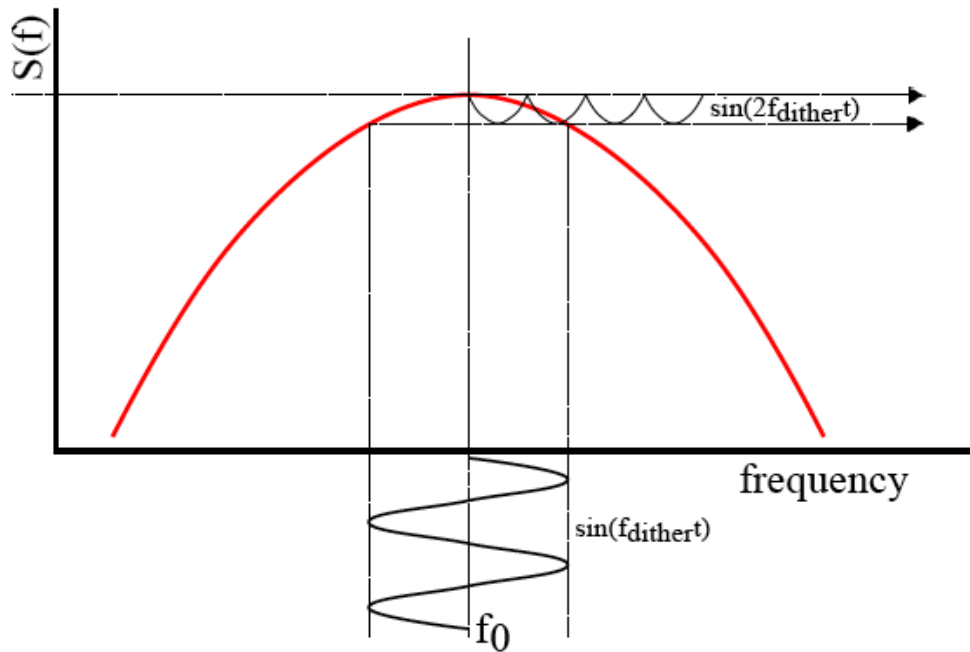


Figure 4: Dithering the laser's frequency at the resonant frequency,  $f_0$ .

### 3. The Laser Lock System

Figure 5 shows a block diagram of the Laser Lock System. A function generator is used to set the frequency with which the laser is dithered. The laser light is then sent into an experimental system. The output signal from the experiment is then sent into a variable gain amplifier, which passes it into a demodulator. Simultaneously, a square wave reference signal at the same frequency is phase-shifted to compensate for lags due to the different paths of the signal and the reference. It is then sent as a reference signal into the demodulator. The demodulator will output a DC signal whose amplitude is proportional to the amplitude of the dithered signal. The

demodulator's output is then fed into another output buffer and into a PID feedback loop. The PID feedback will determine how far the experiment is from our desired set point and output a correction signal. This correction signal is then summed with the dithering signal from the function generator and sent back into the laser stabilizing its output.

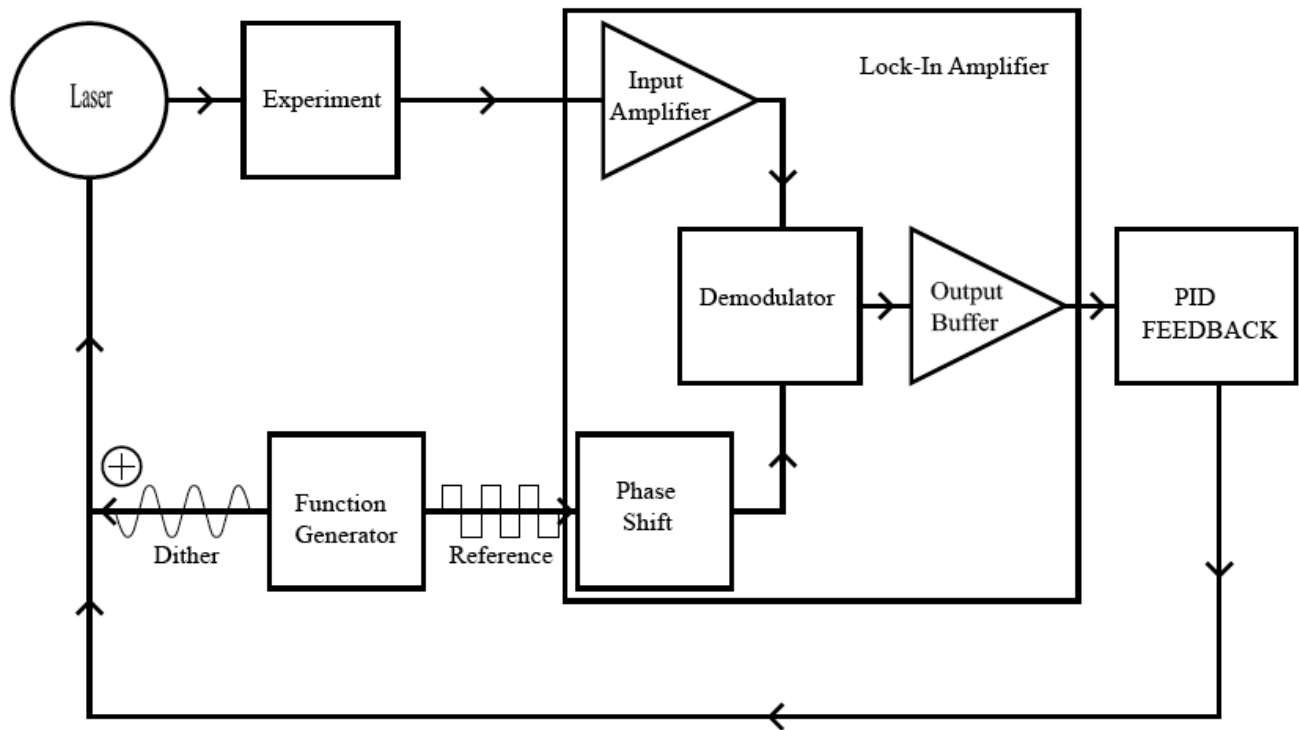


Figure 5: Block Diagram of the Laser Lock System

### 3.1 Lock-In Amplifier Theory <sup>[3, 7]</sup>

Lock-in amplifiers are used to detect and accurately measure very small AC amplitudes that are masked by noise sources many times larger or to measure the derivatives of a signal. This is accomplished using phase-sensitive detection to single out the signal component that has the same frequency and phase as the reference signal, and rejecting those components that are not at this frequency. Usually, an experiment is excited at a fixed frequency and then the lock-in

is used to detect the response of the experiment at this reference frequency.

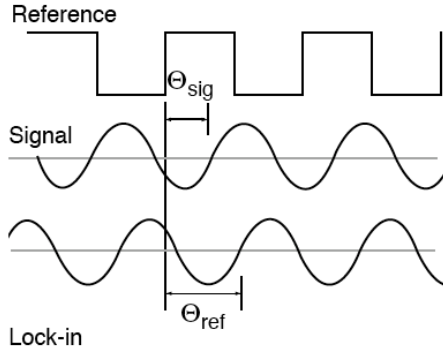


Figure 6: A typical input signal, reference signal, and internal lock-in reference signal.<sup>[7]</sup>

Figure 6 shows what a typical set of inputs into a lock-in amplifier may look like. In this case, Equation 2 gives the input signal where  $A_{sig}$  is the amplitude,  $\omega_{sig}$  is the signal frequency and  $\theta_{sig}$  is the signal's phase.

$$S(t) = A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \quad \text{Equation 2}$$

A lock-in amplifier creates its own internal reference signal, shown in Figure 6, using a phase-locked-loop that is locked to the external reference. Equation 3 gives the internal reference signal.

$$L(t) = A_{Lock} \sin(\omega_{ref} t + \theta_{ref}) \quad \text{Equation 3}$$

The lock-in amplifier amplifies the signal and then multiplies it by its internal reference using either a phase-sensitive detector (PSD) or multiplier. This produces an output,  $V_{out}$ , given by Equation 4 and composed of two AC signals.

$$\begin{aligned} V_{out} &= S(t)L(t) \\ V_{out} &= A_{sig} A_{Lock} \sin(\omega_{sig} t + \theta_{sig}) \sin(\omega_{ref} t + \theta_{ref}) \\ V_{out} &= \frac{1}{2} A_{sig} A_{Lock} \cos([\omega_{sig} - \omega_{ref}]t + \theta_{sig} - \theta_{ref}) - \frac{1}{2} A_{sig} A_{Lock} \cos([\omega_{sig} + \omega_{ref}]t + \theta_{sig} + \theta_{ref}) \end{aligned} \quad \text{Equation 4}$$

Passing this output through a low-pass filter will remove the AC signals, leaving nothing unless the two signals  $S(t)$  and  $L(t)$  are at the same frequency. In this case, the first term at the

difference frequency ( $\omega_{sig} - \omega_{ref}$ ), becomes a time-independent DC signal and the output of the lock-in is given by Equation 5:

$$V_{out} = \frac{1}{2} A_{sig} A_{Lock} \cos(\theta_{sig} - \theta_{ref}) \quad \text{Equation 5}$$

The two AC signals have become a single DC signal proportional to the signal amplitude,  $A_{sig}$ . This can be further simplified by adjusting the phase of the reference signal using the phase-shift construction described in section 3.5. When the signal and reference are phase-matched the cosine term in Equation 5 becomes one, allowing for the measurement of  $A_{sig}$ .

A typical input, however, is usually made up of the desired signal combined with noise. The combination of the PSD and low-pass filter will only detect signals at frequencies very close to that of the lock-in reference. Signals at frequencies far from the reference frequency will be attenuated at the output by the low-pass filter, and only the desired signals at frequencies close to the reference frequency pass through the low-pass filter unchanged.

### 3.2 Feedback Theory <sup>[2, 3]</sup>

The output of the lock-in amplifier is fed into a feedback loop, which stabilizes the frequency of the laser's output. Feedback works by measuring the current state of a physical system, determining how far this current state deviates from the desired state, and then applying a control signal to bring the current state closer to the desired state. Successive repetitions of this process will bring the system to its desired state and keep it there.

A generic feedback model can be thought of as a simple system characterized by the variable  $f$ , in our case the laser's frequency. Normally, this system has a steady state value of  $f = f_0$ , the value of which may vary and drift over time as a result of changes in environmental variables ( $v$ ). We are able to both measure the system, and modify it with a control input ( $u$ ). Functionally, the system can be considered as  $f(u, v, t)$ . We will also assume that the system ( $f$ ) is

monotonic in the vicinity of  $f_0$ . The feedback will set the system to the desired state ( $f = f_d$ ) by measuring the current state of  $f$ , calculating an error variable ( $e = f - f_d$ ), then it will feed a trial control input ( $u = u(e)$ ) back into the system thereby altering  $f$ . This will be done iteratively until  $f$  is equal to  $f_d$ .

Feedback in our system was achieved using a PID controller. PID control operates by generating a control signal given by Equation 6.

$$u(e, t) = g_P e(t) + g_I \int_0^t e(t) dt + g_D \frac{de(t)}{dt} \quad \text{Equation 6}$$

Where  $g_P, g_I$ , and  $g_D$  are the proportional, integral and derivative gains, and  $e = f - f_d$ . Without feedback, the system would remain in the state  $f_{no\ feedback}(t) = f_0$ . When feedback is applied, the system evolves according to Equation 7.

$$f(t + \Delta t) = f_0 + u(e, t) \quad \text{Equation 7}$$

If we consider the system as having a small characteristic response time,  $r_t$ , this can be converted to Equation 8.

$$f(t) + r_t \frac{df(t)}{dt} = f_0 + g_P e(t) + g_I \int_0^t e(t) dt + g_D \frac{de(t)}{dt} \quad \text{Equation 8}$$

In typical feedback applications the derivative term is normally eliminated, i.e.,  $g_D = 0$ . The derivative gain serves to improve the time response of the system, allowing it to converge more quickly to its steady state value, but this is often unnecessary and difficult to deal with in practice. Eliminating the derivative gain, taking the time derivative of Equation 8, and substituting  $e(t) = f(t) - f_d$  converts Equation 8 to a 2<sup>nd</sup> order linear differential equation with constant coefficients.

$$\frac{df}{dt} + r_t \frac{d^2 f}{dt^2} = g_P \frac{df}{dt} + g_I f - g_I f_d \quad \text{Equation 9}$$



Combining like terms, Equation 9 becomes:

$$r_t \frac{d^2 f}{dt^2} + (1 - g_p) \frac{df}{dt} - g_I f = -g_I f_d \quad \text{Equation 10}$$

Equation 10 is an 2<sup>nd</sup> order inhomogeneous differential equation with constant coefficients.

Equation 11 gives its solution:

$$f(t) = a_+ e^{b_+ t} + a_- e^{b_- t} + f_d$$

$$b_{\pm} = \frac{(g_p - 1) \pm \sqrt{(g_p - 1)^2 + 4g_I r_t}}{2r_t} \quad \text{Equation 11}$$

The first two terms are the homogenous solution to Equation 10. The third term is the inhomogeneous solution, which is independent of the initial conditions, and the constants  $a_+$  and  $a_-$  can be determined from the initial conditions. Most importantly, Equation 11 shows that if  $b_{\pm}$  are negative, as is the case in negative feedback, then over time  $f$  will converge to  $f_d$  and the error signal  $(f - f_d)$  will be equal to zero. Otherwise,  $f$  will diverge.

### 3.3 Schematic of the Lock-In Amplifier

Figure 7 shows the schematic of the lock-in amplifier composed of the input amplifier, the phase shifter, the demodulator, and the output buffer/low-pass filter. A high-pass resistor-capacitor filter is used to eliminate any low frequency noise from both the input signal and the reference signal. Equation 14 gives the cutoff frequencies for these high-pass filters. The input amplifier is a variable gain operational amplifier (op amp) setup in the non-inverting configuration. The phase-shift of the reference signal is achieved using either the combination of an op amp all-pass filter and inverting amplifier, or simply the op amp all-pass filter on its own. This option is regulated by a switch and allows for the phase of the reference signal to be shifted by anything between 0° and 360°.

The lock-in functionality of the Laser Lock was achieved using an AD630 chip. The AD630 is a high precision balanced modulator, which, when used in a lock-in amplifier configuration, is capable of recovering a small signal from 100dB of interfering noise, i.e., a signal to noise ratio of  $10^{-5}$ . The chip was wired as shown in the ‘Lock-In Amplifier Applications’ section of the AD630 Datasheet.<sup>[1]</sup> The output is then fed into three sequential low-pass RC filters and an output buffer. Three filters were used in order to more rapidly attenuate high frequency non-DC signals. OP27G operational amplifiers were used in constructing this circuit.

### 3.4 The Input Buffer and Pre-Amplifier<sup>[3]</sup>

Pre-amplification of the experimental output signal was achieved using an operational amplifier setup in the non-inverting configuration, shown in Figure 7, in combination with a unity gain op amp buffer/high-pass Resistor-Capacitor Filter. RC filters will be discussed in a moment. The op amp is 3-pin device with 1 inverting input, 1 non-inverting input, and one output. The inputs of an ideal op amp have an infinite resistance and therefore draw no current. It is designed to keep the signal at both inputs the same by outputting a voltage that is connected to one of the inputs through a feedback loop. Equation 12 gives the gain for an op amp in a non-inverting configuration:

$$G = 1 + \frac{R_2}{R_1} \quad \text{Equation 12}$$

In the case of our input amplifier,  $R_2$  is replaced with a potentiometer with variable resistance ( $R_V$ ). This allows us to vary the gain of our amplifier depending on the strength of our input signal. The potentiometer can be adjusted to have a resistance from 0 k $\Omega$  to 100 k $\Omega$ .

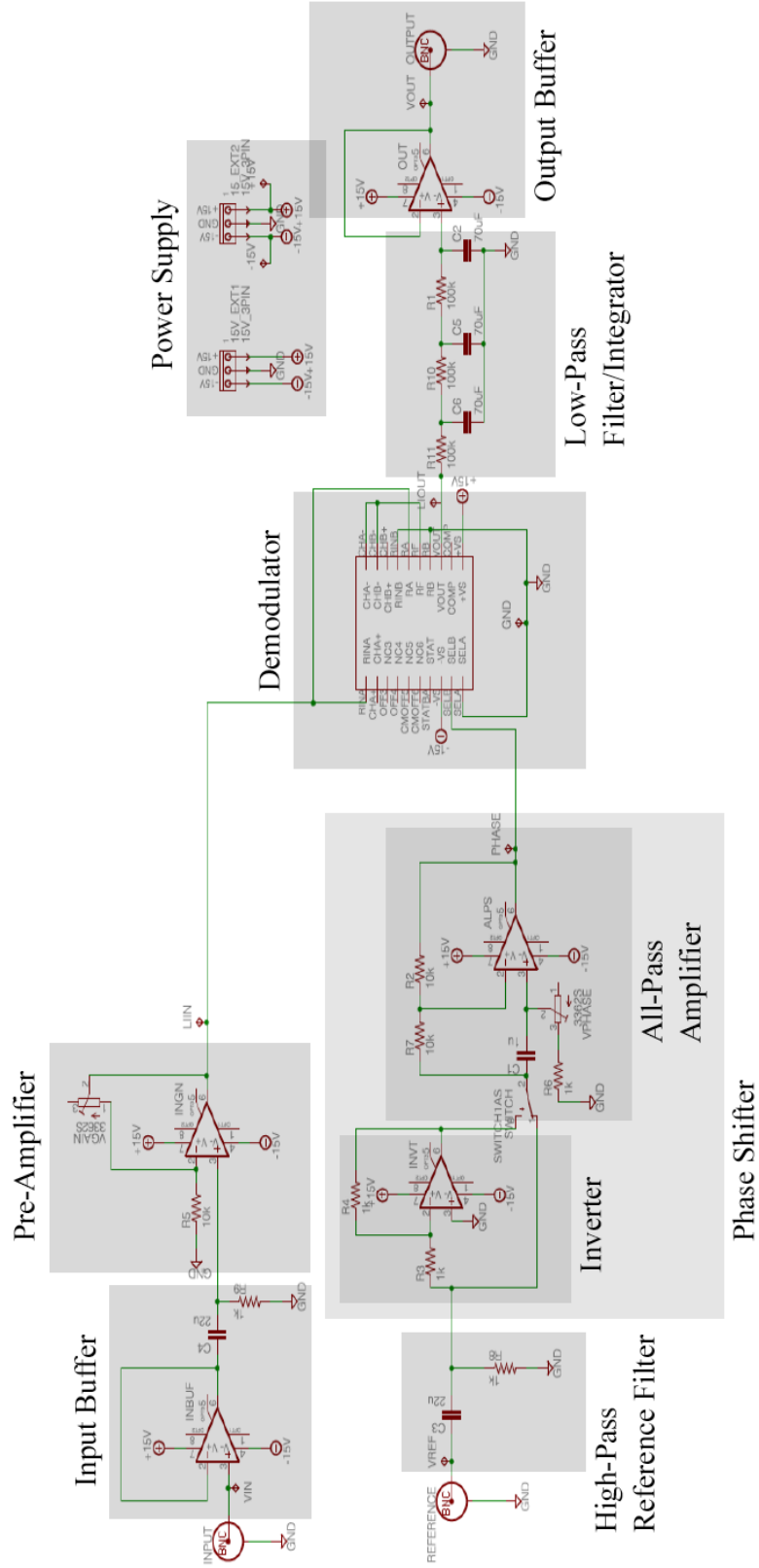


Figure 7: Lock-In Amplifier Schematic

### 3.5 Phase-shifting the Reference Signal <sup>[3]</sup>

The two-part design of this circuit allows for a phase shift from 0 to  $2\pi$  in the reference signal. The first  $0^\circ$  to  $180^\circ$  of the shift can be accomplished using an all-pass filter alone, but in order to realize the full range from 0 to  $2\pi$  the all-pass filter must be used together with an inverting amplifier. As shown in Figure 7, a switch allows for the reference signal to be fed into either the all-pass filter itself or the combination of the filter and inverting amplifier. When it is fed into the latter configuration, the effects of the amplifier and filter are additive, but due to the oscillatory nature of the reference signal, adding a shift of  $0^\circ$  to  $180^\circ$  on top of a  $180^\circ$  shift is equivalent to subtracting the same producing possible phase shifts ranging from 0 to  $2\pi$ .

The first amplifier is an op amp in the inverting configuration shown in Figure 7, which does an optional phase shift of the reference by  $\pi$ . Equation 13 gives the gain for an op amp in an inverting configuration:

$$G = -\frac{R_f}{R_{in}} \quad \text{Equation 13}$$

The second amplifier in this construction is an op amp all-pass filter. The analog implementation of this circuit, shown in Figure 7, is able to induce amplitude to phase quadrature, i.e., a  $90^\circ$  or  $\pi/2$  phase shift, at the corner frequency  $\omega$  (radians/s), given by Equation 14:

$$\omega_{corner} = \frac{1}{RC} \quad \text{Equation 14}$$

An RC filter inducing a frequency dependant delay accomplishes this phase shift. The capacitor behaves as a short circuit at high frequencies, thereby creating a voltage buffer with no phase shift and  $G=1$ . At DC and low frequencies, the capacitor behaves as an open circuit creating an inverting amplifier, as shown in Figure 7, with  $G = -1$ . As mentioned previously, at the corner

frequency given by Equation 14 the all-pass filter produces a  $90^\circ$  phase shift between the input and output signals.

In order to produce a variable phase-shift, the corner frequency given by Equation 14 must also be varied. To accomplish this a potentiometer with a variable resistance ranging from 0 k $\Omega$  to 100 k $\Omega$  in series with a 1 k $\Omega$  resistor was used. The 1 k $\Omega$  resistor is necessary to provide a minimum 1k $\Omega$  input impedance at high frequencies. Otherwise, at low frequencies the circuit would appear as a zero impedance load and not be able to draw any current from the previous circuit.

### **3.6 The Output Buffer <sup>[3]</sup>**

The output from the demodulator is then fed into a combination of three low-pass RC filters and an op amp non-inverting buffer, as shown in Figure 7. This filters out all AC components as described in section 3.1. Equation 14 given above also determines the cutoff frequency in radians per second, i.e., the frequency above which no signal is passed. An op-amp non-inverting buffer with unity gain follows the low-pass filters, which compensate for the attenuation of the filters. The signal exiting this buffer is the output signal that will be sent into the feedback loop.

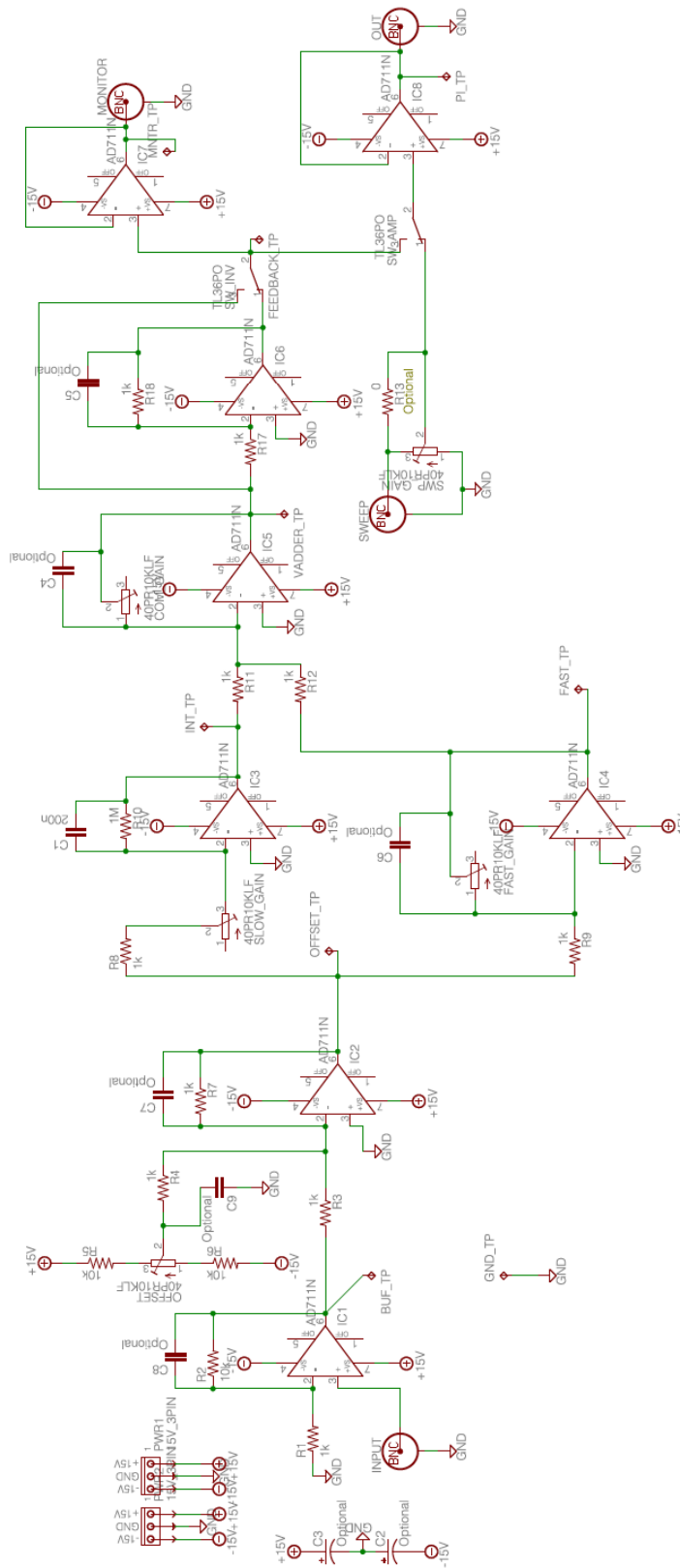


Figure 8: PI Precision Amplifier Schematic

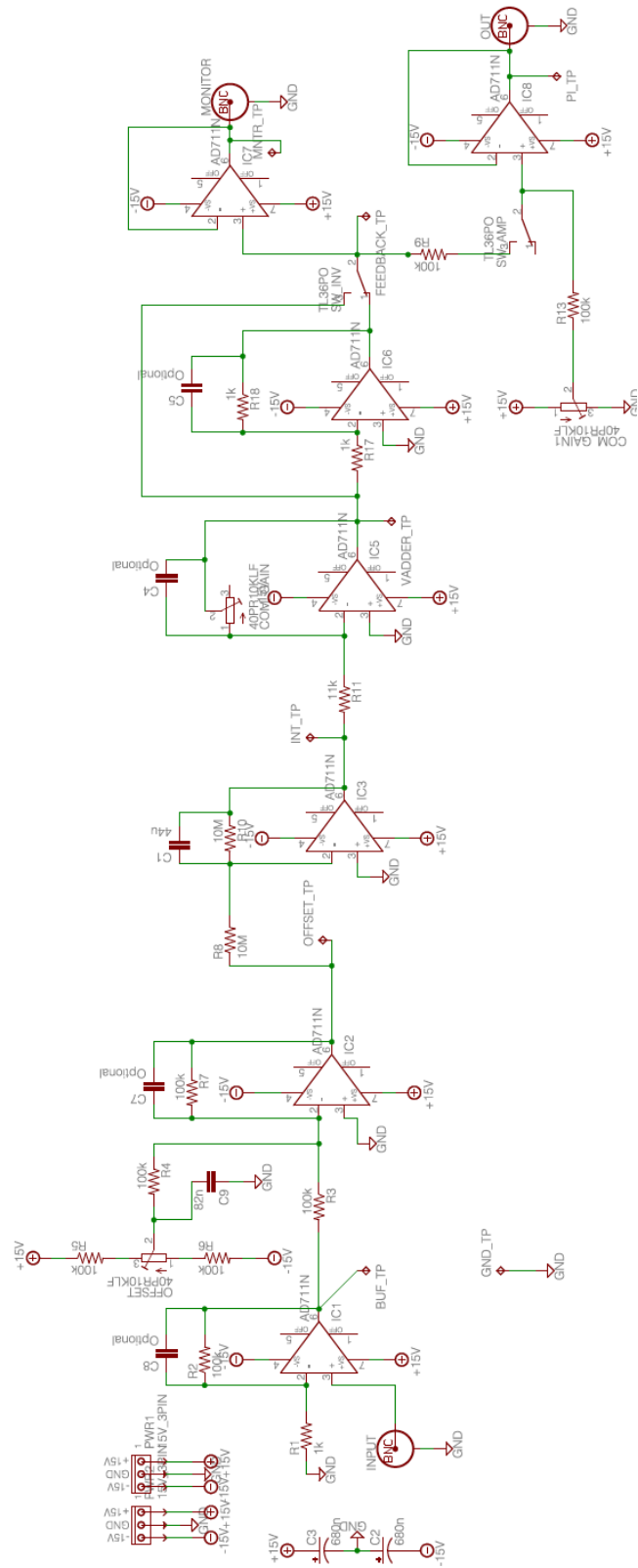


Figure 9: Integral Feedback Controller Schematic

### 3.7 PID Feedback Controller Schematic<sup>[2, 3]</sup>

In order to apply feedback control to the laser lock system, the PID amplifier shown in Figure 8 was designed using many of the same analog elements used in the Lock-In Amplifier circuit from Figure 7. Figure 8 is a multipurpose schematic that can be used in various applications. In practice, this design was modified to suit the purposes of the Laser Lock. Only the integral gain portion of this circuit was used to implement the feedback; this provided ideal performance in terms of both response time and convergence to the desired state. The modified schematic implemented in the laser lock is shown in Figure 9.

The input signal is first sent into a non-inverting amplifier with a gain of 10, as given by Equation 12. The enlarged signal is then sent into an adder, an op-amp in the summing non-inverting configuration, where it is summed with the desired set point for the system to generate the error signal described above. The desired state is set using the OFFSET potentiometer and ranges for +15V to -15V DC. The error signal is then sent into an op-amp integrator, IC3 in Figure 11. This circuit is similar to a non-inverting amplifier, but instead of operating the feedback loop through a resistor the feedback operates through a capacitor. As a result, this circuit performs integration in that the output voltage is proportional to the time integral of the input voltage, i.e., the magnitude of the output voltage is determined by how long a voltage is present at the input as the current through the feedback loop either charges or discharges the capacitor.

Following the integrator, the signal is passed through another non-inverting amplifier with variable gain in order to boost the signal. It can then be passed through an optional inverter to phase shift the signal by  $\pi$ . The final element in the circuit is a voltage divider controlled by a switch. It provides a DC offset voltage ranging from 0V to +15V, which serves to quickly bring



the system close to a desired state before feedback is applied. The output of the feedback is then sent to the laser itself where it will stabilize its frequency.

#### 4 Functional Realization of the Laser Lock System

Section 3.1 described the mathematics and theory behind the function of lock-in amplifiers. In practice, however, the ways to achieve this are limited by the functions of the analog devices employed in the circuits. Thus, although Section 3.1 is theoretically true and mathematically useful in explaining how lock-in amplifiers should function, it is not usually how they are realized. Our version of a lock-in amplifier from Figure 7 does not behave exactly as described in Section 3.1, although it achieves the same basic function: an output signal proportional to the amplitude,  $\Delta A$ , of the input signal. As discussed in Section 2, this amplitude is the value of interest because it is proportional to the derivative of the resonance signal, allowing us to determine an error using the feedback controller.

Figure 10A shows a typical set of inputs into the lock-in amplifier we designed. The top signal is generated by the photodetector described in Section 2, and is of the form given by Equation 15.

$$S(t) = A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \quad \text{Equation 15}$$

The bottom signal, meanwhile, is the square wave reference signal from the function generator shown in Figure 5. Equation 16 gives its mathematical form.

$$R(t) = \text{sign}(\sin(\omega_{ref} t)) \quad \text{Equation 16}$$

The AD630 chip, which we used to achieve the lock-in functionality, contains within itself a voltage controlled gain switch. Equation 17 gives the output produced by the chip.

$$\begin{aligned} S_{out} &= S(t)R(t) \\ S_{out} &= A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \text{sign}(\sin(\omega_{ref} t)) \end{aligned} \quad \text{Equation 17}$$

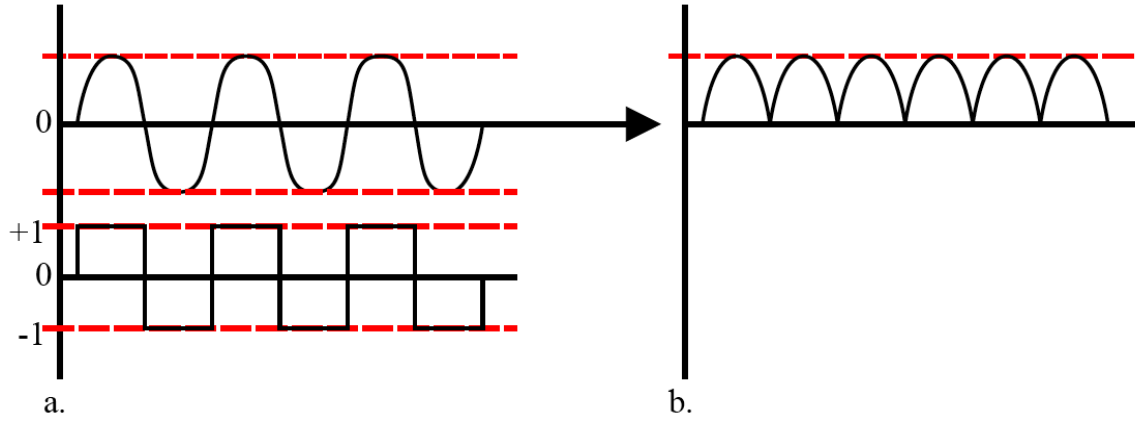


Figure 10: Input and Output of the lock-in amplifier.

The input signal ( $V_{ref}$ ) which is shown at the bottom of Figure 10A, is sent into the AD630's internal comparator.<sup>[1]</sup> A comparator is an analog electronic element similar to an op amp that is capable of comparing two voltages or currents and switching its output to indicate which is larger. This comparator switches the internal gain from +1 to -1 according to its high or low state at the frequency of the square wave shown at the bottom of Figure 10A, producing the signal shown in Figure 10B and given by Equation 17 at the output of the AD630. The three low-pass filters at the output of the AD630 behave as an integrator like the one described in Section 3.7. They remove any residual modulation of the signal and generate an output proportional to the AC amplitude of the input signal at the dither frequency. Equation 18 shows the mathematical effect of the combination of the AD630 and the three low-pass RC filters.

$$V_{OUT} = \int_0^{\tau} A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \text{sign}(\sin(\omega_{ref} t)) dt \quad \text{Equation 18}$$

Because a Fourier series of simple sine waves can approximate any oscillating function, Equation 18 can be rewritten as Equation 19, where the sign function from Equation 15 is converted to a simple sine function.

$$V_{OUT} = \int_0^{\tau} A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \sum_{i=1}^{\infty} A_i \sin(i\omega_{ref} t) dt \quad \text{Equation 19}$$

Taking only the first term of the sum in Equation 19 gives Equation 20.

$$V_{OUT} = \int_0^{\tau} A_{sig} \sin(\omega_{sig} t + \theta_{sig}) \sin(\omega_{ref} t) dt \quad \text{Equation 20}$$

Equation 20 now looks like the multiplication of two sine waves, as discussed in Section 3.1.

According to Fourier's theorem, Equation 17 will equal zero unless  $\omega_{sig}$  equals  $\omega_{ref}$ . When they are equal however, the output will be a DC signal proportional to  $A_{sig}$ , which is the only quantity we need to determine for our circuit to function properly.

## 5 Characterization of the Laser Lock

Figure 11 shows the laser lock system in action, using the second harmonic generation experiment described in Section 2. Channel 1, labeled Sensor in Figure 11, measures the output voltage of the system, in this case the level of laser light hitting a crystalline disk with multiple resonant modes. Channel 4, labeled Error in Figure 11, monitors the error signal generated by the feedback controller, and Channel 3, labeled Feedback, monitors the output of the feedback that is being sent back into the laser in order to keep its frequency stable. Channel 2 is the same as Channel 3, except for a large DC offset discussed in Section 3.7.

Figure 11A shows how activating the lock stabilizes the system's output to the minimum of the resonance (Sensor). It shows that the frequency of the laser's light is being held constant by the lock-in amplifier and feedback loop. As expected, it is a stable DC signal whose magnitude corresponds to the minimum of the resonance peak. This stabilization occurred within 20 seconds of switching the lock on. Figures 11B and 11C show that the lock continues to hold the experimental output stable because there is very little deviation in the Sensor signal. There are small fluctuations in the Error signal corresponding to changes in the laser's frequency, and, as expected, a steady buildup in the Feedback output to compensate for these deviations. Although ideally the Error signal would fluctuate about zero, we see that it is offset by about 1

volt. This occurs because there is a small additional signal from the op-amp used in the adder in Figure 9 that is summed along with the experimental output and the set point signals. This signal is subsequently amplified causing the Error signal to be offset from zero.

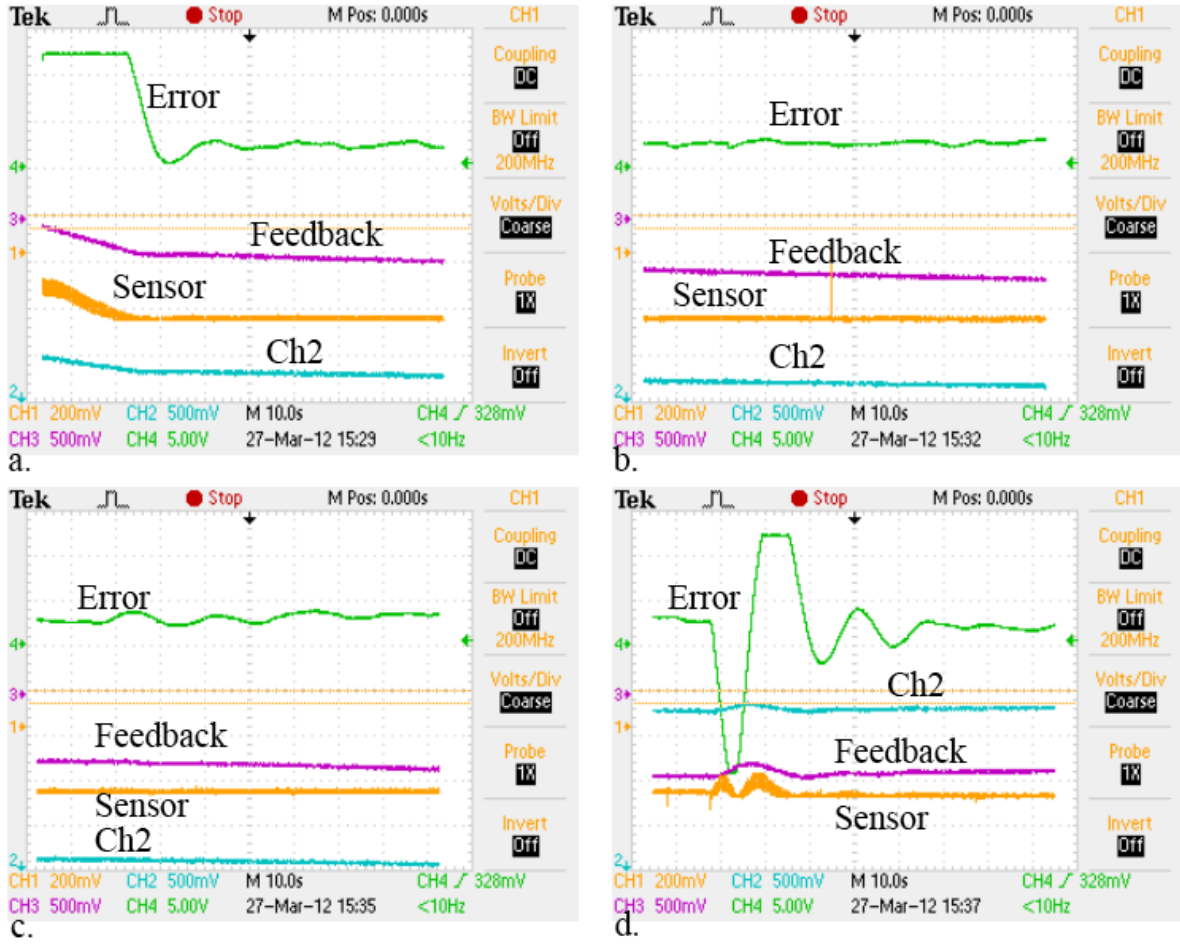


Figure 11: Experimental system with the laser lock on.

In Figure 11D, we tested the effectiveness of the lock by blowing on the disk and rapidly changing its temperature. Small changes in temperature have a great effect on the frequencies of the resonant modes within the disk, but the lock was able to quickly re-stabilize the system despite the change in external conditions, as would be expected. Blowing on the disk also produced a large change in the Error signal.

Figure 12 shows the same system after the lock is disabled. Figure 12A, shows what happens immediately after the lock is disabled. The system jumps off resonance almost immediately and the Error signal drops to zero because the feedback has been deactivated. Figures 12B and 12C meanwhile show the output signal (Sensor) when the laser's frequency has been manually tuned to the approximate minimum of the resonance. Relative to the same output signal with the lock activated, it is approximately ten times as noisy and also suffers from greater fluctuations and drifts. The output signal is also less resistant to changes in experimental conditions, and it is much harder to manually stabilize the system at the resonance minimum.

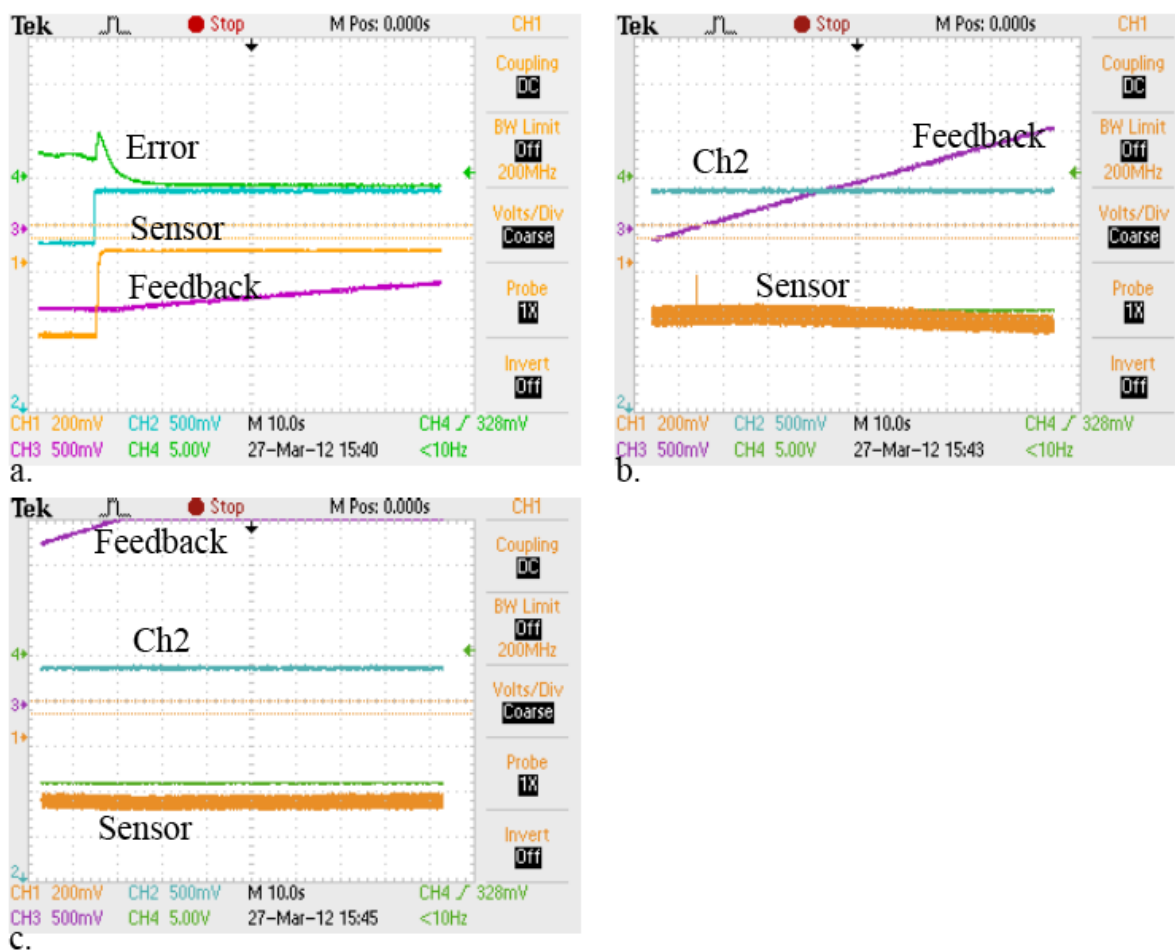


Figure 12: Experimental system with the laser lock off.

Figure 13 shows the effects of the laser lock being on and off in a longer time frame: 50 seconds per division vs. 10 seconds per division. As expected, Figure 13A shows that the lock holds stably for 10 minutes and has been shown to operate well for over an hour. It also shows the high level of activity of the lock because of the frequency of changes in the Error signal. When the lock is switched off in Figure 13B we see that the system's output begins to drift off resonance after approximately 5 minutes, as shown by the gradual movement of the Sensor signal towards its zero point.

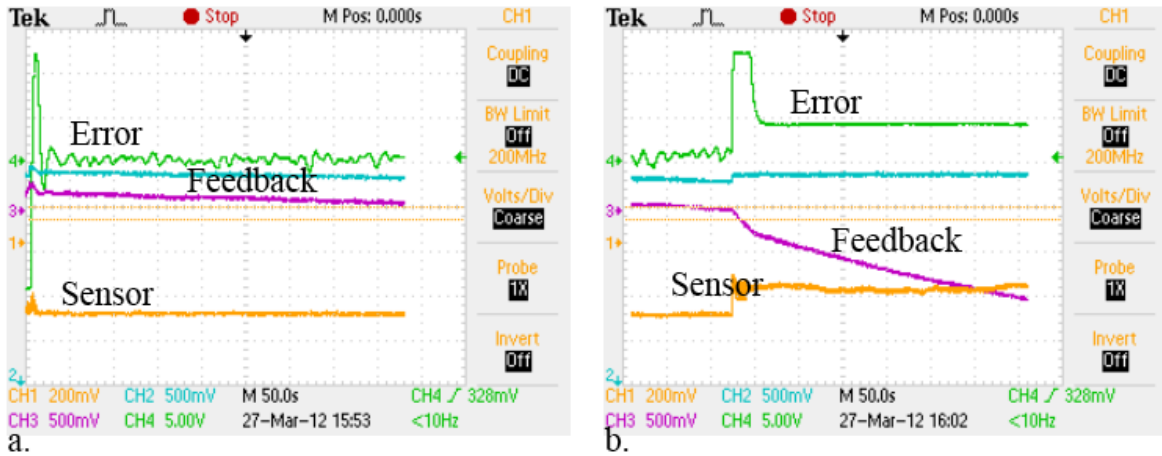


Figure 13: Experimental system in the long frame with the lock on (A) and off (B).

## 6 Conclusion

In conclusion, the laser lock system was shown to function as expected and it achieves the desired result of stably tuning a laser's frequency to the desired set point. It was shown to be able to acquire a stable lock onto the peak of a resonance within 20 seconds of being switched on and hold at this point for over an hour, which is considerably more efficient than manually tuning and retuning the laser. From Figures 11 and 12 we can also see that the laser lock system functions as expected according to the theory in Section 3.

Figure 14 shows the lock-in amplifier built according to the schematic in Figure 7 that is actually used in the experimental setup described above. Likewise, Figure 15 shows the Integral

Feedback Controller constructed based on the schematic from Figure 9. This controller was built using the printed circuit board shown in Figure 16, which was designed from the schematic in Figure 8. This board was designed to be adaptable. It can be modified to fit a variety of needs and applications as either a feedback mechanism or a tunable precision amplifier.

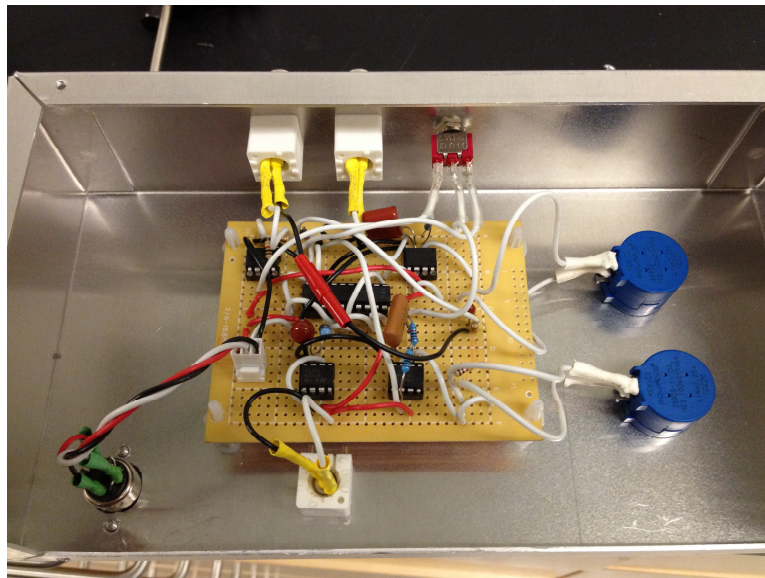


Figure 14: Prototype Lock-In Amplifier



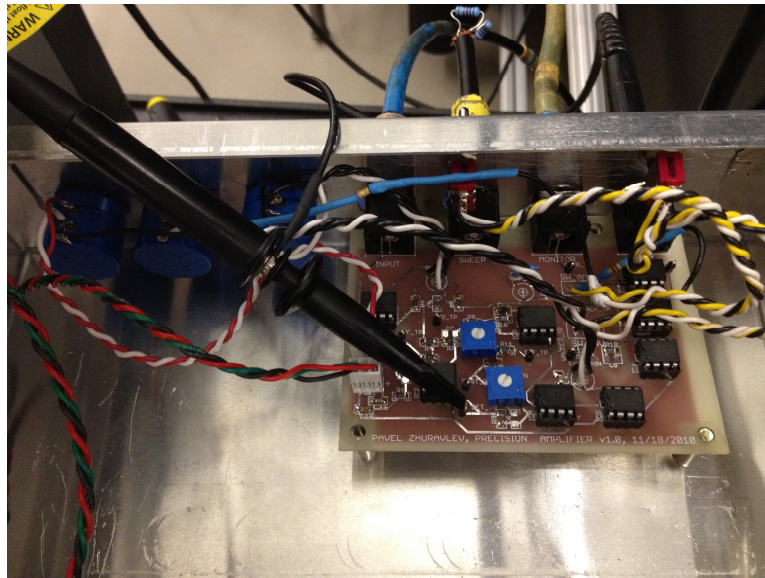


Figure 15: Integral Feedback Controller

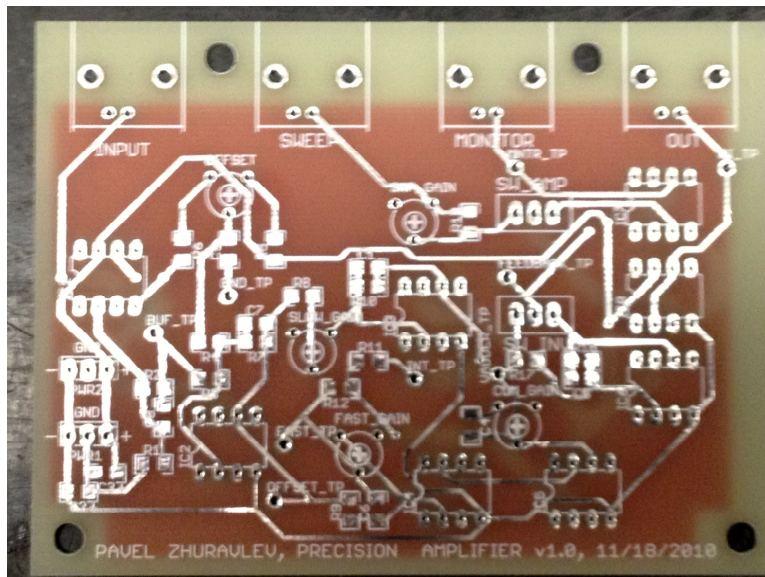


Figure 16: PID Feedback Printed Circuit Board



## 7 References

1. Analog Devices, Inc. “AD630 Datasheet (Revision E)”. (2004).  
<[http://www.analog.com/static/importedfiles/data\\_sheets/AD630.pdf](http://www.analog.com/static/importedfiles/data_sheets/AD630.pdf)>.
2. S. Aubin, E. Mikhailov, J. Nelson. “Chapter 11: Feedback and PID Control Theory”. William and Mary Analog Electronics (Physics 252) Lab Manual (2012).  
<[http://physics.wm.edu/~evmik/classes/2011\\_spring\\_Physics\\_252\\_Analog\\_Electronics/lab\\_manuals/LabManual\\_Chpt11.pdf](http://physics.wm.edu/~evmik/classes/2011_spring_Physics_252_Analog_Electronics/lab_manuals/LabManual_Chpt11.pdf)>.
3. P. Horowitz, W. Hill. *The Art of Electronics* (2<sup>nd</sup> ed.). Cambridge University Press, New York (1989).
4. S. Salvatori, M. Girolami. “Compact, four-quadrant lock-in amplifier generates two analog outputs”. EDN [Internet]. 54(24): 45-6 (2009).
5. S. Sengupta, J. Farnham, J. Whitten. “A simple low-cost lock-in amplifier for the laboratory”. Journal of Chemical Education. 82(9): 1399-401 (2005).
6. M. Simons. “Efficient Generation of Quantum Light Using Whispering Gallery Mode Resonators”. (2012).
7. Stanford Research Systems, Inc. “About Lock-In Amplifiers”.  
<<http://www.thinksrs.com/downloads/PDFs/ApplicationNotes/AboutLIAs.pdf>>.