Frequency Locking Circuits


Stephen Rupper


A senior thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Bachelor of Science


Scott Bergeson, Advisor


Department of Physics and Astronomy

Brigham Young University

April 2014

ABSTRACT

Frequency Locking Circuits

Stephen Rupper
Department of Physics and Astronomy
Bachelor of Science

We report the design and fabrication of a simple integral-gain feedback circuit. This circuit is used in our laboratory to control the frequency of single-frequency lasers. A short tutorial on feedback control is given. The $80 control circuit will be used to replace more expensive commercial systems currently in use in our lab.

ACKNOWLEDGMENTS

# Contents

# List of Figures

# Chapter 1

# Introduction

## 1.1 Overview

Since the laser was invented, it has continued to grow in use and ability. More and more industries are incorporating this tool into their everyday routines. Lasers are now used for removing cavities, correcting eyesight, measuring distances, and generating images. With all of these applications, there has been a need to find ways of changing and stabilizing laser properties. For example, when ionizing an atom in our lab, we must use a very specific wavelength or the atom will not be ionized. If the frequency of a laser drifts, then the data gathered for spectroscopy will not be accurate. In our lab, we use many different types of lasers for varying purposes. Because many of these lasers need to have a stable output frequency, we have invested in multiple frequency locking devices. Laser frequency locking devices are based upon the principles of feedback controlled systems. These control units are basically electronic signal integrators and are relatively simple in principle but take time to build. Commercial units are available, but they are in the $2000 dollar price range. The purpose of this project is to create a simple locking circuit that can be adapted to work with any of the lasers in our lab.

## 1.2  Injection Locking

One example of how feedback control is used in our lab is injection locking. Injecting locking takes place when coupling is introduced between two oscillators. If the frequencies of the two oscillators are similar enough for the given coupling, the first oscillator will lock to or adopt the frequency of the second oscillator. An example of this would be two pendulum clocks mounted on the same wall. After a little while, the pendulums will synchronize and oscillate together. An example of this principle can be seen on Youtube (www.youtube.com/watch?v=kqFc4wriBvE).

In our laser system, the optical cavity acts as the oscillator of the laser. When the output of the first oscillator, or seed laser, is directed into the optical cavity of the second laser, injection locking can occur. It is important to make sure that the frequency of the stable seed laser is within the linewidth of the second laser. By doing this, the seed laser encourages the first laser to lase in a single mode and at it's own frequency. This can be accomplished using feedback control [1].

## 1.3  Feedback Control

Control systems date to as far back as 300 BC when the Greeks first made water clocks to keep track of time [2]. Since then, great strides have been made in the field of control systems and now feedback control systems. An example of a feedback controlled system is the cruise control in a car [3]. For this example, we will look at both an open-loop and a closed-loop system. A regular and functional block diagram for an open-loop system can be found in Fig. 1.1. We can see that for this system, the desired speed is our input, the engine is our actuator, the road grade is our disturbance, and our actual speed is the output. If we then look at the functional block diagram in Fig. 1.1 B), these parts of the block diagram correspond to $r$, $u$, $w$, and $y$. This diagram also shows that the output of the system, $y$, depends only on the desired speed $r$ and on the road grade $w$. As an example, let's assume that at 55 mph, a change in the road grade of 1% corresponds to a 5 mph

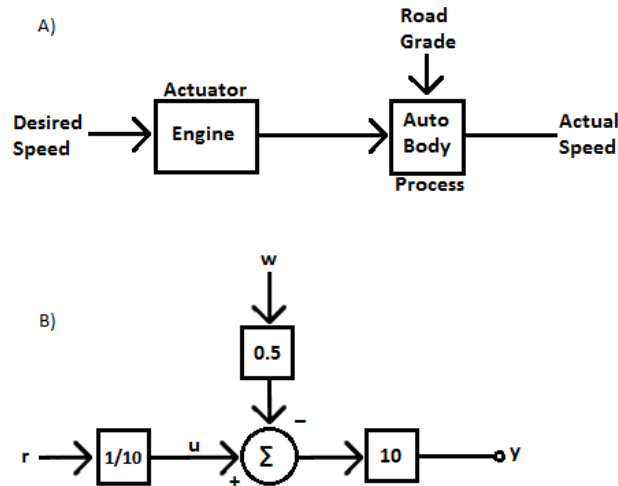change in the speed of the car. We can then solve for the actual speed, *y*,



**Figure 1.1** A) Block diagram for a simple open-loop cruise control system. B) functional block diagram for a simple open-loop cruise control system

$$y = 10(u - 0.5w)$$

$$y = 10\left(\frac{r}{10} - 0.5w\right)$$

If we plug in our values, we get

$$y = 10\left(\frac{55}{10} - 0.5(1)\right)$$

$$y = 55 - 5$$

$$y = 50$$

We can see that for a 1% change in the road grade, the speed of our car will decrease by 5 mph. At 55 mph, this is a 9.1 % change in car speed which is quite substantial. However, we can use a closed-loop system to improve this result.

For a closed-loop feedback control system, the block diagram is different than in Fig. 1.1. Looking at the component block diagram of this system, Fig. 1.2, We can see that, the throttle is our control variable, the engine is our actuator, the road grade is our disturbance, and the speedometer is our sensor. In this example, we can choose our desired speed and then compare it to the output of the speedometer. This comparison takes place at the controller and it's output (which is directed into the engine) is our error signal. The error signal tells the engine to either increase or decrease the throttle in order to force the output speed at the speedometer to match our desired speed.
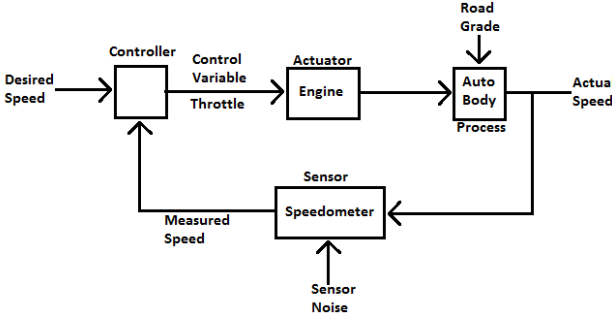
**Figure 1.2** Block diagram for a simple cruise control system.
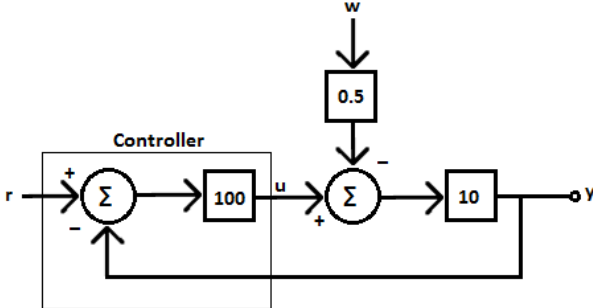
**Figure 1.3** Functional Block diagram for the simple cruise control system.

If we again assume that, at 55 mph, a change in the road grade of 1% corresponds to a 5 mph change in the speed of the car, then we can create the functional block diagram in Fig. 1.3. Looking at this diagram, we can assign variable names to specific parts of the process. The variable r is the

input, u is comprised of what takes place inside the box, and w is our disturbance. For this example

we have set the gain to be 100. When solving for our closed-loop output $y_{cl}$, we find that;

$$y_{cl} = 10(u - .5w)$$

Where

$$u = 100(r - y_{cl})$$

This then gives

$$y_{cl} = 1000r - 1000y_{cl} - 5w$$

$$1001y_{cl} = 1000r - 5w$$

$$y_{cl} = 0.999r - .005w$$

Plugging in values for $r = 55$ mph and $w = 1\%$, we see that;

$$y_{cl} = (0.999)(55) - (0.005)(1) = 54.95$$

Using this feedback system, our output is only changed by 0.05 mph. With out the feedback

portion of our system, the speed would have been changed by 5 mph. Looking at this example, it

is easy to see how important close-loop feedback systems are. Because they are so useful, we can

look around us and see their application everywhere.

One point to consider, however, is the value that we chose for the gain. It may seem like we

arbitrarily chose the value of 100 to be our gain but this in not entirely true. This choice came after

consideration of the system. If we look at Fig. 1.3 again, we can see that our gain multiplies just

the error signal. Since our goal is to control the speed of the car, we can do this by having the error

signal play a large role in our system. If we plug G in for the value of our gain we can see how to

add more weight to our error signal;

$$y_{cl} = 10(u - .5w)$$

$$y_{cl} = 10Gr - 10Gy_{cl} - 5w$$

$$(1 + 10G)y_{cl} = 10Gr - 5w$$

$$y_{cl} = \frac{10Gr}{1 + 10G} - \frac{5w}{1 + 10G}$$

$$y_{cl} \approx r - \frac{w}{2G}$$

For large values of $G$, the actual speed, $y_{cl}$, is essentially equal to the desired speed, $r$. This shows us the importance of our gain value. If we have a low value for the gain, our output is controlled by the disturbance. However, if we choose a large value for the gain, we can shift the control to our input value and easily choose the car's speed. Knowing these principles, we can apply them to our locking circuit and create a reliable way to control the laser's frequency.

## 1.4   Phase Error

Right now, it may seem as if we can choose any large value for our gain and our system will always work. This is not true. If we let our gain approach infinity, then our system output will begin to oscillate.

In Engineering, designers use Bode plots to figure out where their system will work well and where it will not. When the phase changes by $\pi$ radians, then negative feedback becomes positive feedback. Instead of designing a nicely controlled system, the output will swing wildly and uncontrollably between extremes.

Bode plots are comprised of a magnitude plot and a phase plot depicting by how much the phase will be shifted with a change in frequency. Careful analysis of these plots will allow an engineer to build a more stable feedback system.

In our case we are using a simple integrator as a feedback element. In practice, we make the gain as large as possible without causing the system to oscillate.

# Chapter 2

# Design

## 2.1 Finding our Error Signal

Since our goal is to control the frequency of a laser, and not the output of a cruise control system, we need to create a new block diagram. Figure 2.1 shows the block diagram for our system. In this diagram, $x$ consist of the controls for the laser, the laser we are locking becomes $G$, $y_0$ is the desired laser frequency, and H is our locking circuit. To find our error signal, we need to look at what happens when we mix $y$ and $y_0$.
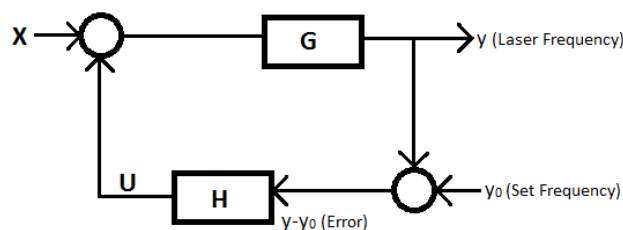


**Figure 2.1** Block diagram for locking a laser in the lab.

In our lab, we use an RF interferometer to convert $y - y_0$ into a DC phase signal [4].

$$y = \frac{e^{i\theta_1} - e^{-i\theta_1}}{2i}$$

$$y_0 = \frac{e^{i\theta_2} - e^{-i\theta_2}}{2i}$$

$$(y)(y_0) = \frac{1}{4i^2} \left[ e^{i(\theta_1 + \theta_2)} - e^{i(\theta_1 - \theta_2)} - e^{-i(\theta_1 - \theta_2)} + e^{-i(\theta_1 + \theta_2)} \right]$$

$$(y)(y_0) = \frac{1}{2} \left[ \frac{e^{i(\theta_1 + \theta_2)} + e^{-i(\theta_1 + \theta_2)}}{2i} - \frac{e^{i(\theta_1 - \theta_2)} + e^{-i(\theta_1 - \theta_2)}}{2i} \right]$$

$$(y)(y_0) = \frac{1}{2} \left[ (\cos(\theta_1 + \theta_2) - \cos(\theta_1 - \theta_2) \right]$$

Now letting

$$\theta_1 = wt + \phi_1$$

$$\theta_2 = wt + \phi_2$$

We get

$$y * y_0 = \frac{1}{2} \cos(2wt + \phi_1 + \phi_2) - \frac{1}{2} \cos(\phi_1 - \phi_2)$$

This gives us an error signal of $\frac{1}{2} \cos(\phi_1 - \phi_2)$ which will be the input to the locking circuit. The out put of the circuit will be sent into the controller and adjust $y$ (the laser frequency) to swing it closer to $y_0$ (the set frequency).

## 2.2   Circuit Diagram

The circuit diagram changed multiple times during the course of the project. Initially we wanted to build an inverting and non-inverting locking circuit on the same board. We changed this in order to simplify the circuit. When making this change, we also added a DC-DC convertor to power the Op-Amps. After this first change in the schematic, we later removed one of the initial resistors and added two capacitors to the DC-DC converter outputs. Figures 2.2-2.4 show the changes that were made to the circuit diagram.
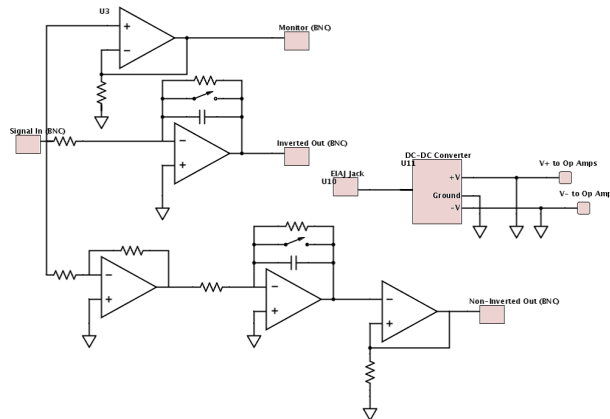
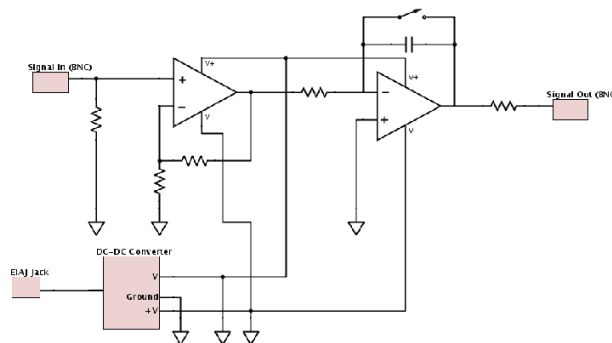**Figure 2.2** Both an inverting and a non-inverting amplifier are present.



**Figure 2.3** Non-inverting amplifier and buffer have been removed.

## 2.3   Prototyping The Boards

When it came time to design the boards in a prototyping software, we chose to use PCB123. While this software already contains many components in it's database, it lacked almost all of the components that we planed on using. Because of this, I needed to build the footprint and layout for the AD823AN op amp, A26-ASA00BB18-L DC-DC converter, 611-ET01-002 switch, ED6464-ND and ED3013-ND IC sockets, ARF1998-ND BNC connectors, CP-102A-ND EIAJ port, and the SA105E104MRA capacitors. After all of these were completed, I was able to begin designing the boards. Once I had finished designing the boards all that was left to do was to wire the connections
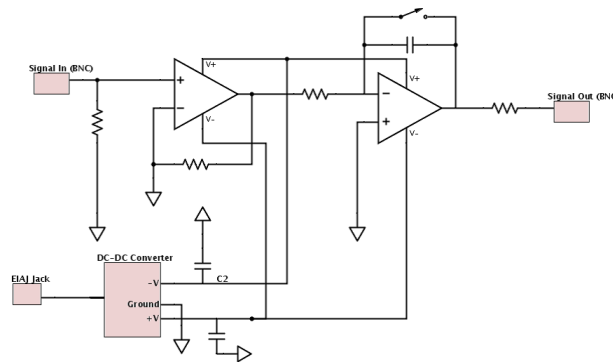
**Figure 2.4** One resistor has been removed and two capacitor have been added. This is the circuit that was used.

and place the order.

After the boards and parts arrived, I quickly realized that I had made a few mistakes in some of the footprints and also on the boards themselves. The pins on the switch were rectangular and, when making the footprint, I had used the smaller of the two dimensions for the diameter of circular holes. Because of this, I had to surface mount solder the switches into place which made them less stable. The switch also ended up protruding slightly too far from the box and needed to have a larger hole drilled into the end caps. While this was not very important to the functional value of the circuit, it diminished the aesthetical appeal of the completed boxes.

The boxes that we ordered were not tall enough to fit BNC connectors. This was problematic because I had printed the boards to fit the length and width of the boxes exactly. Since we could no longer use the BNC connectors and we could not find a new box that fit the same dimension, I switched to SMA connectors and hard wire them to the boards. After completing these corrections, the boards fit nicely into the boxes and were ready to be tested.
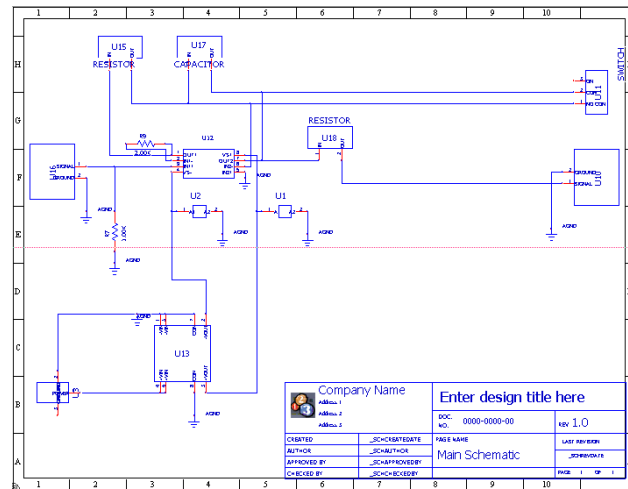
**Figure 2.5** A picture of the completed schematic in PCB123. The software file for this schematic is Locking circuit.123 and can be found on the byulaserlab google drive in the experiment folder.
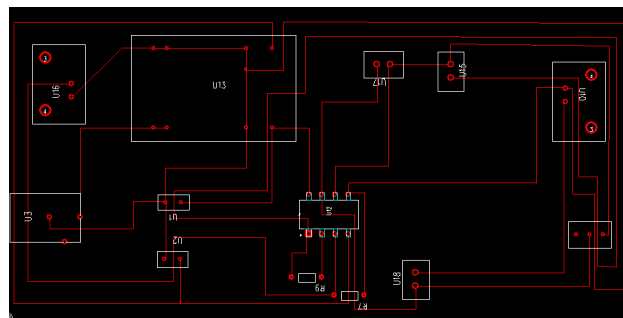


**Figure 2.6** Layout of board and wiring. The software file for this schematic is Locking circuit.123 and can be found on the byulaserlab google drive in the experiment folder.

# Chapter 3

# Testing

## 3.1   What Did Not Work

When I tested the circuits, I immediately saw a problem. When checking the EIAJ port, I found that the voltage was not what I expected to see. I measured a floating voltage of one volt when the port was soldered onto the board and a value of 12.2 volts when the port was off the board. First, I checked to make sure the wall wart and port were working correctly by changing them out for new ones. When this failed to solve the problem, I check to see if there were any unintentional connections being made that were not part of the schematic. None of this helped me discover the problem and I had to look elsewhere. Upon reviewing the data sheets again, I found that I had misunderstood the layout for the DC-DC convertor and that the diagram I used was a top view and not a bottom view. To fix this, I removed the convertors from the boards, cut the traces on the boards, remounted the convertors, and then used wire to correct the bad connections. Once this was done, I began testing the circuits again and found that all the voltages were correct. I then connected the circuit to a signal generator and tested it by sending in a 1 volt signal. This resulted in a $-12$ volt output which is what I expected to see. Since this worked, I then applied a 1 volt
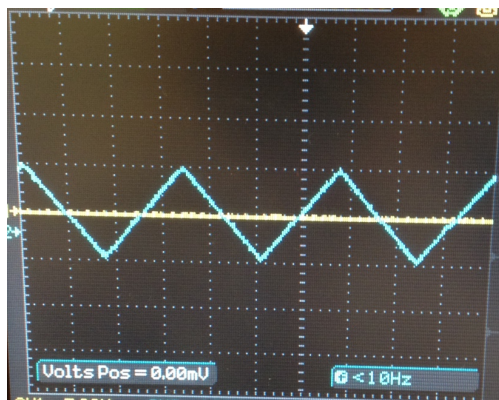
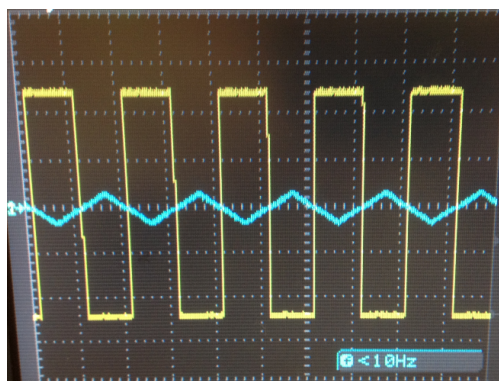**Figure 3.1** Input (blue) and output (yellow) before the switch was flipped



**Figure 3.2** Input (blue) and output (yellow) after the switch was flipped

triangle wave and saw an output of a $\pm 12$ volt square wave. The circuit passed these test perfectly and inverted the signal just as we desired.

## 3.2 Locking A Laser

Once I felt confident that the circuit was working properly, I used it to try locking a laser in our lab. After testing a few different combinations of capacitors and resistors, I was able to consistently lock the lasers frequency with the circuit. The lock circuit was used to offset-lock one mode of a frequency comb to a Rb-stabilized diode laser. This showed that the circuit was indeed working

as desired and that we would be able to adapt it to other lasers by using different combinations of resistors and capacitors.

# Chapter 4

# Conclusion

## 4.1  Corrections

After verifying that the circuit design worked, I needed to make corrections to the PCB123 file to make sure new boards were not printed off with the mistakes that I had corrected still present. The first change that I made was to move the location of the switch further back. This allowed for the completed box to be more aesthetically pleasing. I also moved the EIAJ port closer to the edge of the board so that it made a better connection with the wall wort. After these two adjustments, I enlarged the pin holes for the switch, changed the BNC connections to SMA, and corrected the pin layout for and rewired the DC-DC convertor. These last three changes were all the corrections I made when soldering the components onto the boards and when testing the circuits.

## 4.2  Results

We have shown that it is possible to build a simple circuit that will reliably lock a lasers' frequency. This is significant because similar circuits that are available for purchase cost on average $2000 dollars. We estimate the cost of each of these circuits to be roughly $80 dollars, or 4% the retail

price.

# Bibliography

[1] B. Cummings, Hicken, "Demonstration of a 1-W injection-locked continuous-wave titanium: sapphire laser," Applied Optics **36,** 7583–7587 (2002).

[2] F. Lewis, *Applied Optimal Control and Estimation* (Prentice-Hall, 1992).

[3] G. F. Franklin, in *Feedback Control of Dynamic Systems*, 5th ed., J. D. Powell, ed., (Pearson Prentice Hall, 2006).

[4] D. A. Thrasher, M. Burbidge, M. N. Conde, and S. D. Bergeson, "Comments on "Intensity noise of an injection-locked Ti:sapphire laser: analysis of the phase-noise-to-amplitude-noise conversion"," J. Opt. Soc. Am. B **28,** 1553–1555 (2011).