SHG Cavity Locking Circuit Documentation

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The purpose of this paper is to document the SHG cavity locking circuit as well as talk a little about the theory of opperation of the circuit and some of the design choices. The ciruit was based primarily on two other circuits, one shown in Tyler Green's Thesis, the other the locking circuit used by the Saffman Quantum Computing group[1].

1 Background

Second Harmonic Generation (SHG) is a nonlinear optical process that takes two photons at one frequency and converts them to one photon at double the frequency, i.e. double the energy. This technique provides a way to build light sources at colors otherwise not available directly with convenient laser sources. This occurs by means of a crystal or material that has appreciable nonlinear susceptibility ($\chi^{(2)}$) where the response at 2ω depends on the electric field squared. Although the process is quite weak, because of the squared dependence increasing the intensity greatly increases the second harmonic light produced. A common route to boost the intensity in the nonlinear medium is to place the crystal in an optical cavity. We're placing our crystal in a ring cavity with a bowtie configuration. This cavity introduces a technical issue however, you need feedback to keep the cavity in resonance as you only have high circulating intensity when the cavity is in resonance. There are a variety of schemes used to lock cavities on resonance, including Pound-Drever-Hall and Hansch-Couillaud. We're going to use Hansch-Couillaud for our application. A couple of papers that were useful for the learning about this subject are the original paper by Hansch and Couillaud and a paper about a transmission-version of the technique by Vainio, Bernard, and Marmet[1, 2]. The description of the tecnique provided below is from these sources.

1.1 Hansch-Couillaud Locking

Hansch-Couillaud locking relies on changes in the polarization of light reflected (or tranmitted) from the cavity to produce an error signal to allow locking the cavity. The cavity requires an internal polarizer but in our application the nonlinear crystal serrendipitiously provides the polarization selection. A polarization analyzer consiting of a waveplate, beam cube and two photodiodes allows us to analyze the polarization of the reflected (or transmitted) light and a differential measurement pconverts this into our error signal shape.

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[1] See: lock-box.pdf available on the Hexagon Wiki and green_thesis.pdf available here: http://yavuzlab.physics.wisc.edu/pdfs/green_thesis.pdf

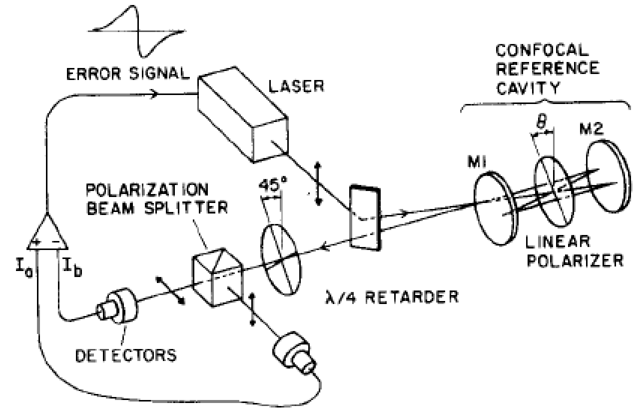

Fig. 2. Scheme for laser frequency stabilization.

Figure 1: Hansch-Couillaud Locking Scheme

Figure 1 from their paper shows the set-up. Polarized light from the laser is incident on the cavity. The cavity contains a polarization selection element, but it's transmission axis is rotated relative to the incident laser polarization. The incident laser light can be thought of as a component that will see the cavity as transmissive (when on resonance), i.e. the component with the same polarization, and a compenent that will see the cavity as very lossy and bounce off, the perpendicular component. The component that is transmitted will pick up a phase shift relative to the compoent that is initilly reflected, resulting in an eliptically polarized output. If the cavity is on resonance the phase shift would disappear. This provides the basis of the error signal. The eliptically polarized monitoring light is sent to a polarization analyzer which looks at the two polarization components, differential comparison of the components gives the error signal. The rest of this document will basically focus on the electronic amplifier alluded to as a triangle in the diagram as well as the associated electronics. This method has a couple advantages including that it evidentally offers a robust error signal with appreciable error signal size outside the immediate vicinity of the cavity resonance. The method also requires no external laser modulation as in Pound-Drever-Hall locking.

It's also worth noting that Vainio and colleaugues build on this original idea with much more detail for basically our exact application. In their set-up they utilize the transmitted light from the cavity to form their error signal, which has the advantage of the cavity acting as a filter. One issue they also discuss in detail that we encounter is that the error signal is not as simple as that depicted by Hasch and Couillaud, but has more structure. This is mainly due to the fact that in the frequency doubling application, the nonliear crystal is birefringent. As a result, the cavity resonances for different linear polarizations are at slightly different frequencies. This spreads the single resonance into two. Also, in general different polarizations experience different losses, e.g. absorption/conversion by the nonliear crystal is highly polarization dependant, as well as different initial amplitudes. This results in the error signal not having the same size for both dispersion features. They also mention how coupling into higher-order cavity modes will contribute to additional cavity resonances and more complex error signal. See their paper for details. We observe some of this behavior in our set-up.

1.2 Physical Set-up

A brief discussion of the set-up is in order to understand some of the limitations/challenges with the electronics. The cavity is set up as a ring cavity, talk to Nick Brewer for the details. This cavity configuration is desirable compared to a linear cavity as it allows for one-way oscillation so that the majority of our frequency-doubled light can exit in one direction from the cavity.

The main issue concerning the physical set-up relevant to the electronics is the mechanical resonance frequency of the piezoelectric transducer+mount+mirror system that is used to feedback and control the cavity length. Nick measured the piezo+mount+mirror system resonance frequency to be approximately 420Hz. See his work for details. The quick explanation of how this measurement is mades is as follows. The laser is scanned with a ramp on the laser piezo. This will produce cavity transmission peaks similar to scanning the cavity, except now it is the laser frequency that is being scanned. Next, the cavity is modulated with a small signal on the cavity piezo. The frequency of the modulation signal is started at very low frequency and swept to higher frequency until the cavity resonates, this is seen as a change to large excursions, lots of peaks being present. Thi onset of this behavior is the cavity resonance frequency.

Why this is relevant to the electronics design is that we need to make sure that we are not feeding back to the piezo near it's resonance frequency. In circuit terms we want the gain to roll off much lower than 420Hz in order to avoid making the cavity resonate. We also want a healthy phase margin at the piezo+mirror system resonance frequency.

2 Circuit Overview

With a qualitative overview of Hansch-Couillaud locking and our set-up, and a quick discussion of mechanically-imposed bandwidth considerations, the remainder of this document discusses the details of the electronics. This purpose of this circuit was to provide the locking feedback, via Hansch-Couillaud locking, for the SHG cavity to double 1055nm light to get 527.5. There are 4 main sections of the circuit: a ramp generating section, an photodiode input section, a slow feedback section that goes to the SHG cavity piezo, and a fast feedback section that goes to the laser current modulation.

2.1 Ramp

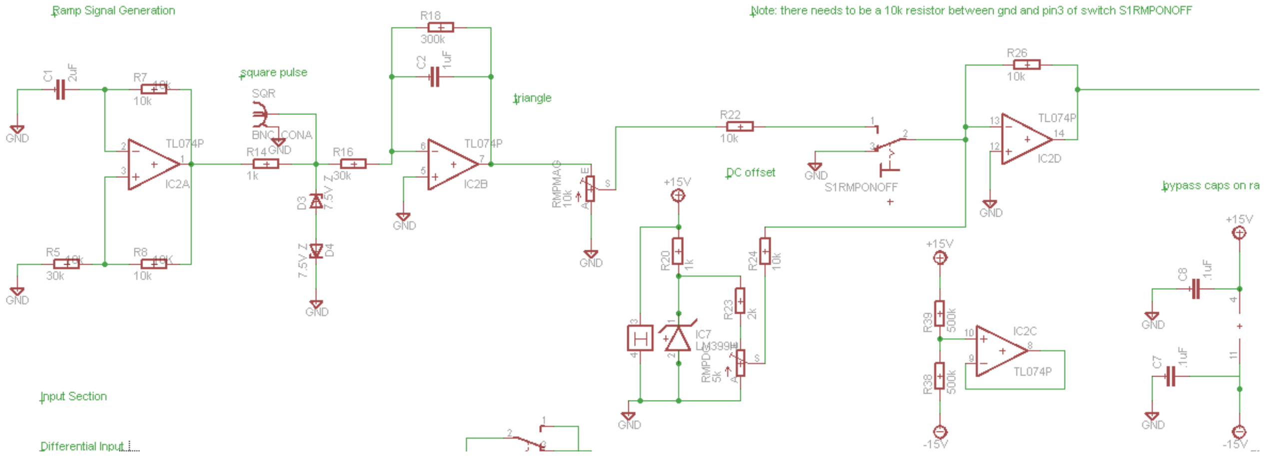

Figure 2: Ramp Section

Our lock boxes usually have an external ramp at a very low frequency, around 10Hz. This is so that you can ramp the piezo and see your saturated absorption peaks and in our case see SHG cavity transmission peaks. Since the ramp frequency doesn't need to change and it's relatively easy to make a triangle wave, i thought i would incorporate the ramp into the lock-box circuit, eliminating another external connection. Also the external function generators often don't work super well or have DC drift. The ramp is made from 2 op-amp stages. The first is a relaxation oscillator which creates a square wave. This square wave is clipped with 2 shunt diodes to flatten the output. Note: this square wave also has a pick-off as this is a convenient trigger for the oscilloscope. Next the square wave is integrated to create a triangle wave. There is a potentiometer that controls the size of the square wave. Next a LM399-based positive DC voltage reference is added to the triangle wave. The reference is positive because the piezo driver should only be supplied with positive voltage. This DC reference is controlled by a potentiometer as well. The the DC offset control and ramp size control gives you the two knobs you need to zero in on a cavity peak and facilitate finding a good piezo voltage at which to turn on the lock. Note, when the lock is switched on, the ramp is grounded (S1RMPONOFF), but the DC contribution is still added to the feedback voltage.

There are more sophisticated ways to generate a triangle that would probably give a more linear/perhaps more stable result, but this seemed to work so i ran with it. Also, since the voltage range is small that you're scanning over, the nonlinearity of the ramp is not much of a problem. Note: there is one unused op-amp in the package. It is held at about 0 input voltage and wired with feedback so that it does not charge up or rail or cause any issues.

2.2 Photodiode Input Section

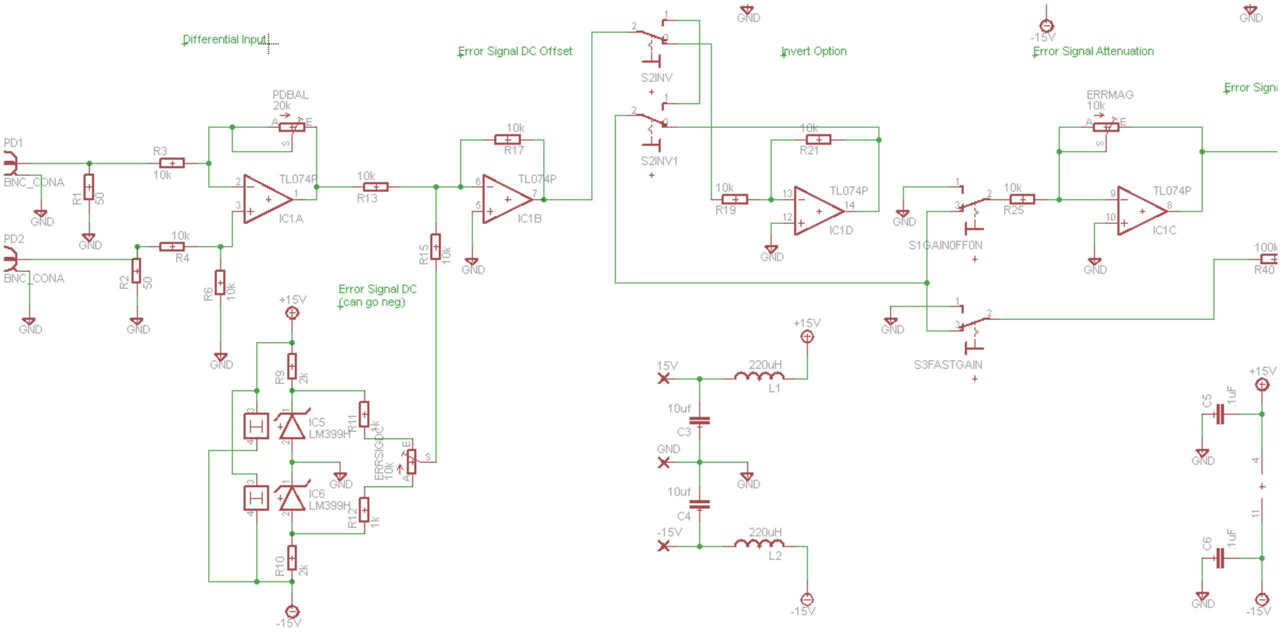

Figure 3: Photodiode Input Section

This input section is very similar to the differential input section found in Saffman Group's lock-box circuit[2]. Initially we experimented with using a purpose-built differential amplifier chip for our input stage. However we found that we needed a little more flexibility in the circuit. That chip did not allow us to easily adjust the DC offset or relative size of the two inputs, so we changed to this configuration. The first stage is an op-amp set up as a differential amplifier. A potentiometer is in the feedback path to adjust the size of one of the inputs relative to the other, i.e. to balance the signal size from the 2 photodiodes. In principle, if one was much bigger than the other you could also compensate by adjusting the photodiode gain. As of now we're operating them with equal gain, but we could potentially change that if we end up with very unbalanced intensity in different polarizations.

One outstanding issue is that the circuit has impedance matching 50ohm resistors on the photodiode inputs. In practice, i found that the circuit worked without including these resistors, and including them will shrink the input signal significantly. For now they are left out of the constructed lock-box, hopefully this impedance mis-match won't pose any issues; if this becomes a problem, we can modify accordingly.

After the differential section, a DC voltage reference similar to the one used in the ramp section is added, although this reference can be negative. This reference is controlled by a potentiometer. This DC offset pot and the balancing pot allow us to clean up the error signal. Next the resulting (hopefully symmetrical and centered around zero) error signal is run through an optional inverting stage controlled by switch 2. After the inverting stage, the error signal is sent into slow and fast feedback branches. The slow feedback branch is grounded by switch 1 when the ramp is on (S1GAINOFFON). After the switch it is sent to an attenuation stage that controls the size of the error signal sent to the remainder of the slow feedback branch. Note: i think the switch could be more logically located after the attenuation stage but is located before it as that was where it was placed in the working prototype. The fast feedback branch is is turned on and off with switch 3.

Note: there are a few accessories visible in this diagram as well. There are filtering caps and inductors on the supply rails, this is a tie-over from Saffman Group's circuit. Although as of right now, 100uH inductors are in the circuit; wasn't sure how much current the circuit was going to draw so I used a smaller inductors that could handle more current. As of right now the circuit draws at most about 300-400mA right at turn-on; i think this is the LM399 reference diode heaters heating up. There are also filtering capacitors visible on the op-amp package rails.

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[2] See: lock-box.pdf available on the Hexagon Wiki

2.3 Slow Feedback

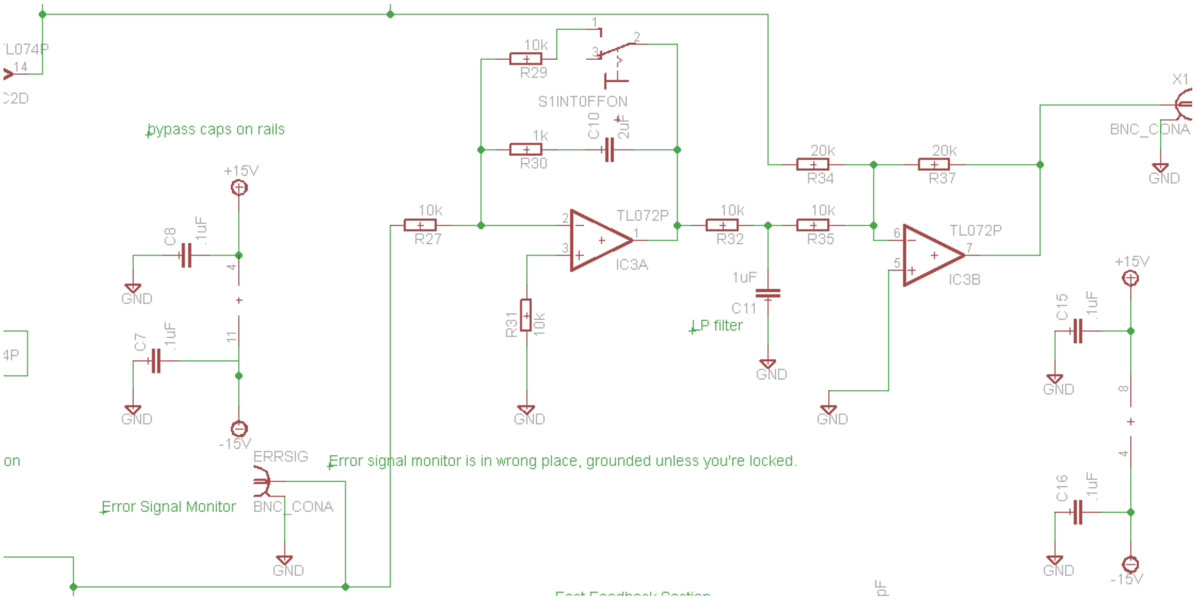

Figure 4: Slow (Piezo Voltage) Feedback Section

The feedback section is the heart of the lock-box. The error signal is run into an integrator stage (IC3A). In the actual implementation we used an OP200 op amp as it has better offset voltage and currents as that is better for an integrator stage. Also, when the error signal is off and the ramp on, the integrator is bypassed through a 10k resistor. This keeps the stage from railing when not feeding back the error signal. Switch 1 is a 3-pole switch and controls the integrator (S1INTOFFON) turn-off as well ramp on-off and feedback on-off.

The integrator stage has very high DC gain as we want for the piezo feedback but is also followed by a passive filter; this is to further suppress gain at low (i.e. piezo resonance frequency), but not DC, frequencies. Adjusting the cap C11 will control this roll-off. Also adjusting resistor R30 and C10 will modify the integrator feedback performance. These parameters were adjusted to give the best performance. After the integrator stage is a stage that adds the feedback signal to the DC contribution of the Ramp signal. This sum goes to the cavity piezo driver.

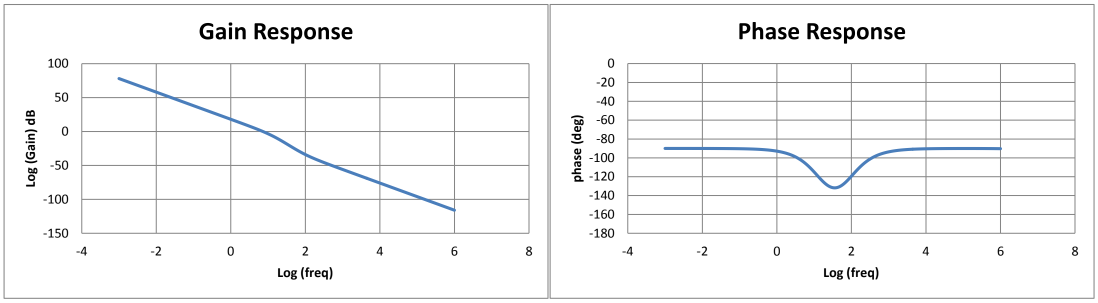

Figure 5: Slow Feedback Simulated Performance

Fig 5 shows the simulated piezo stage (last two amplifier stages) performance from Multisim. As you can see the roll-off is at very low frequency. Despite the gain being about -30dB down at 100Hz, we still see piezo oscillations on top of the transmitted cavity signal, the piezo still seems to resonate somewhat. This seems to be a limitation to circuit performance. Note also that the phase margin is still about 45deg at very low freq and is better everywhere else. Turning on the fast feedback suppresses the piezo resonating but the circuit performance could be better. We are planning to place the SHG cavity in a box to isolate it some from the room and disturbances as well as change the piezo cavity mirror to a different configuration that is much lighter and so should have a much higher mechanical resonance frequency. This should help with the piezo resonating and hopefully with overall feedback circuit performance. Integrator gain could also be increased if the piezo mechanical resonance frequency is pushed to higher frequency.

2.4 Fast Feedback

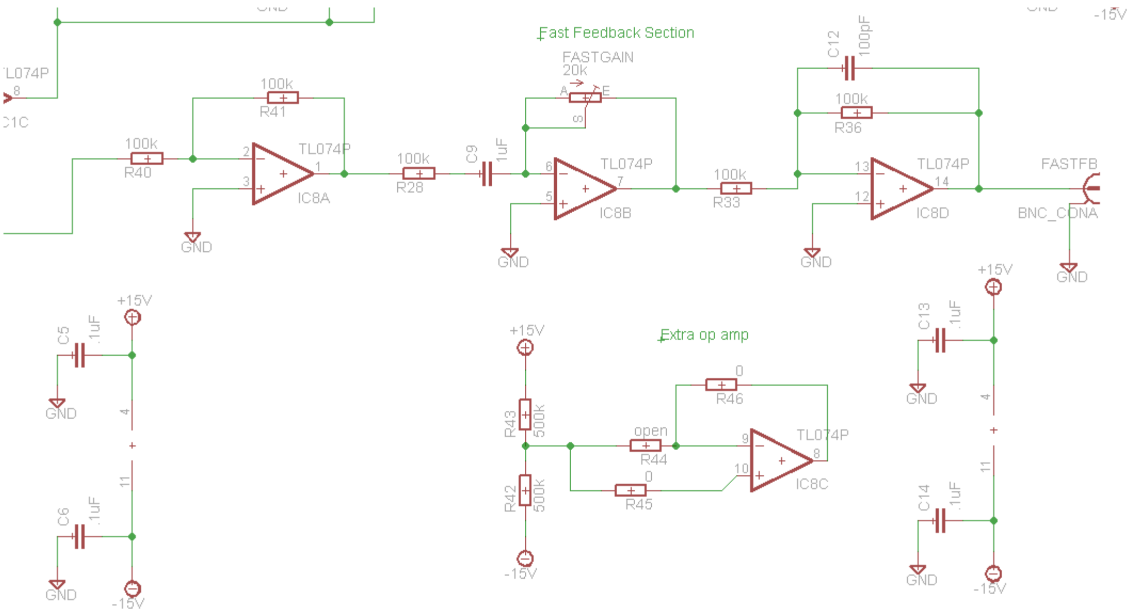

Figure 6: Fast (Laser Current) Feedback Section

The last section of the circuit is somewhat optional but I definitely wanted to include it, especially since we don't currently have a way to lock the laser diode. In the future we plan to lock the laser to a reference cavity, which would make this stage unnecessary. Until we start operating that way, fast feedback to the laser diode suppresses fast fluctuations on the laser by locking the laser to the SHG cavity (which fluctuates relatively slowly), at least at fast time scales. Incorporating it definitely enhanced feedback performance and can be clearly seen by turning it off and on.

The fast feedback stage is pretty straightforward. The first stage is an inverter, this makes it so the phase of fast feedback is the same as the phase of the slow feedback, both sections have 3 inverting stages. After the inverter there is a coupling cap that couples high frequencies to this feedback branch, DC is left to the piezo feedback. Next there is a gain (really attenuation) stage that controls the size of the fast feedback signal. Finally there is a gain stage with a bypass cap that rolls of the gain at very high frequency. The output of this goes to the laser current driver.

Note: there is an additional op-amp that is not used in this package. This one is also held at about GND with feedback but has connections for resistors. If we should want to add an additional op amp stage, the resistors can modified with connections to allow a little circuit flexibility.

3 Circuit Revisions/Issues

There were a few issues that popped up after the board was made that should be fixed/taken into account in future versions of this circuit or similar circuits.

1. Text shorting between rail and ground: interestingly, in the uppper right hand corner of the board, there was some text that said "Piezo Feedback" in the copper layer. For some reason the copper lettering was too long for the box, the cutout that surrounded it. As a result, a part of the letter overlapped between the +15V pin and the ground plane. This caused there to be a short, scraping that spot clean fixed the problem. We should keep this in mind, that improperly sized text if it's in the copper layer can cause problems.

2. Ground plane vias don't connect anything: I tried to follow good practice and sprinkle in some vias to connect the two ground planes together throughout the board, however I didn't name them 'GND' and as a result they are isolated from the ground net. Minor issue, but something to be aware of on future projects.

3. Error signal monitor is in the wrong place: This was a dumb mistake, i located the pick-off for the the error signal downstream from the feedback switch, switch 1, as a result in that location you would only see the error signal if the feedback is on, this isn't so useful for dialing in the shape of the error signal. I picked it off from other pins, but if there were to be future versions of this circuit, we should move the pick-off.

4. Missing resistor, i'm not sure if this was an issue or not, but i think it's a good idea to put a pull down resistor to ground on the switch that controls the ramp on-off. I added that as i saw some weird behavior as i was building up the circuit but i also had a switch backwards that i fixed later, so i'm not sure if it's a problem or not, but i do think it's good practice.

Appendix: Full Circuit Diagram

References

[1] T.W. Hansch and B. Couillaud. Laser frequency stabilization by polarization spectroscopy of a reflecting reference cavity. *Optics Communications*, 35(3):441 – 444, 1980.

[2] M. Vainio, J.E. Bernard, and L. Marmet. Cavity-enhanced optical frequency doubler based on transmission-mode hansch-couillaud locking. *Applied Physics B*, 104(4):897–908, 2011.