Mode Matching a Nd: YAG laser to Reference Cavity
AIGO – University of Western Australia, Dept. of Physics - Gingin, WA
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Charlotte Nix, Lucienne Merrill

1. Introduction
Mode matching is the precise spatial matching of the electric field distributions of laser beams and cavity modes or waveguide modes. The process of mode matching a laser depends upon several initial steps, including but not limited to resizing the beam waist and adjusting its phase characteristics. These steps are completed through a series of optics, lenses, mirrors, wave plates, modulators, isolators and beam splitters (polarized and not).

In our particular research assignment, it was required that we mode match a 1064 nm Nd:YAG laser to a reference cavity, in the aspiration that eventually we would be able to direct the laser beam down 80m to the east arm cavity of the AIGO interferometer. Though time restricted us from completing both steps, the first was achieved, and the laser was locked to the reference cavity. The process of locking the laser to the reference cavity, stabilizing the laser's intensity, was to be done by measuring the reflected intensity from the cavity, measuring its derivative and using the error signal to lock the laser. This technique follows the infamous Pound-Drever-Hall method for set-up, and the details of the set up can be found as follows.

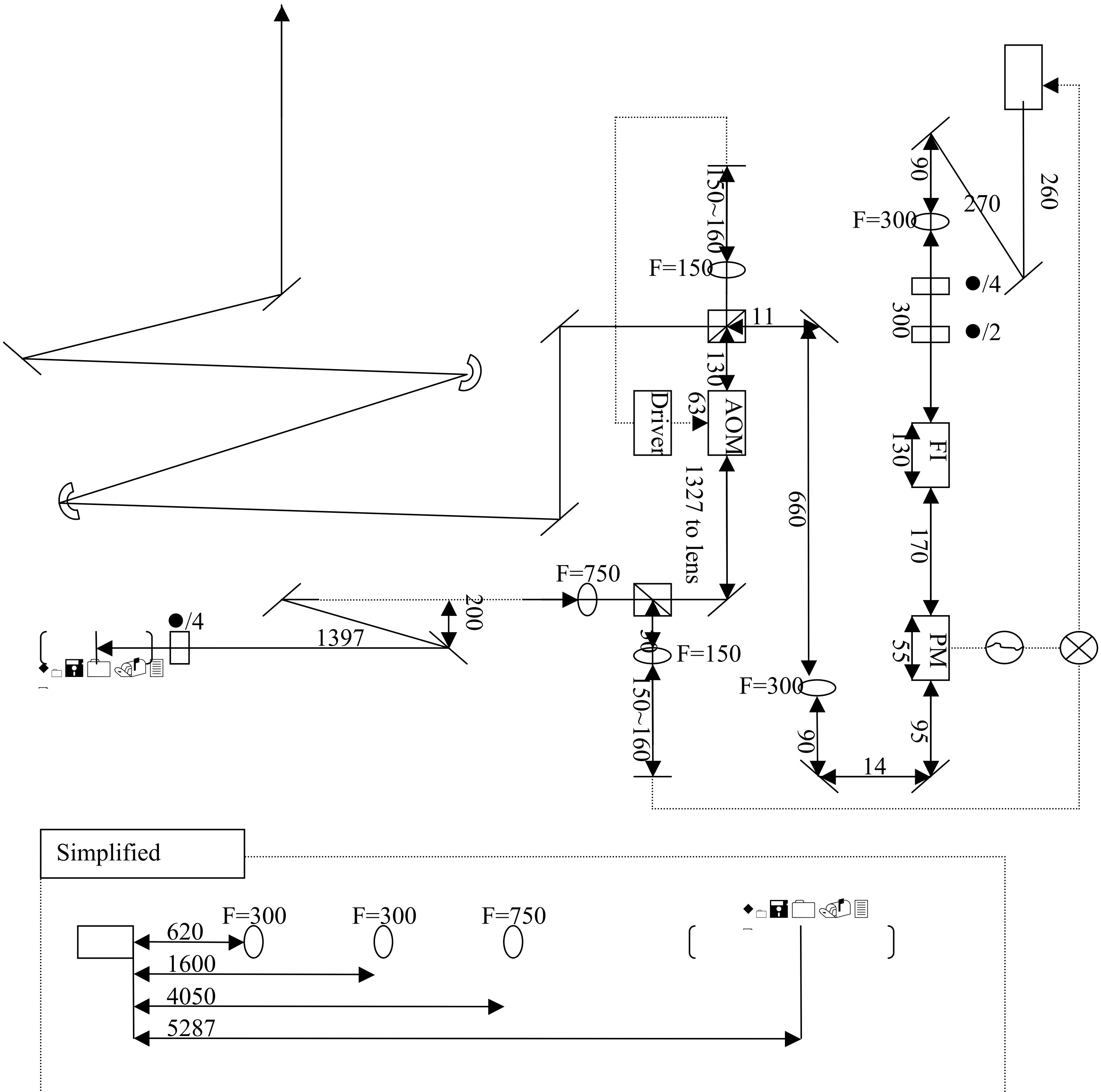
2. Method
As mentioned before, the set up that was modeled in mode matching a 1064 nm Nd: YAG laser was the Pound-Drever-Hall laser frequency stabilization technique. According to several papers it is an essential part of the technology of interferometer gravitational-wave detectors[1]. Our optical table arrangement was supervised and guided by Dr. Chunnong Zhao, with the help of several PhD students including Hai-Xing Miao and mechanical aide from the lab technician Steve Pople.

First, the Nd: YAG laser we were working with at the AIGO site was an infrared laser beam, operating at a current of 1.700A and a voltage of 2.701V. The laser is a model from Innolight GmbH. In order to get better frequency stabilization from the laser than what was provided "out of the box"; there were several pieces of optical equipment through which we had to pass the laser beam, before we were to send it through to the reference cavity. In effect, we followed the basic layout for locking a cavity to a laser found in Black's paper. The equipment used will be explained in detail, but the layout for our particular scheme can be found in Figure 1, as a reference to the descriptions.

Figure 1.

[1] Black, Eric D. " An Introduction to Pound-Drever-Hall laser frequency stabilization"

Figure 1. The straight black line indicates the path of the laser beam.

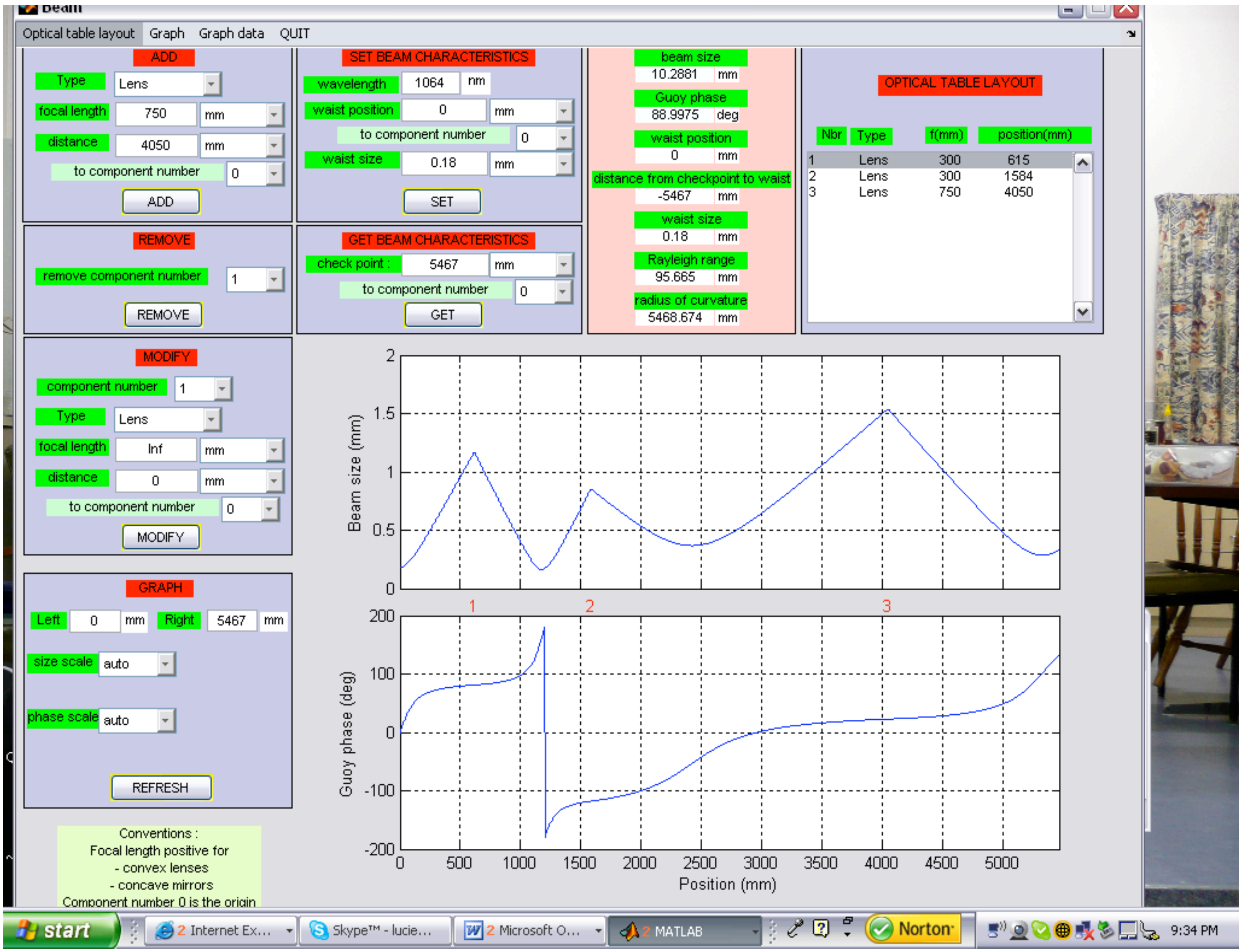


The foremost part of the arrangement is, of course, the laser that which is used for the experiment. As already mentioned, the laser is a 1064 nm Nd: YAG laser, operating at ~3.5W. The laser beam is emitted from a black box, 160 mm x 100 mm x 100 mm, where the beam is emitted at ~75 mm from the base of the laser's box. The height of the beam is a crucial part of the set up, all of the optics that had to be set up to help stabilize the laser beam had to be set up at a height of ~75 mm, so that the beam could pass through them at their centers.

The next part of the optical arrangement included two steering mirrors, used to control the direction of the laser beam before having to send it through any optical instruments of importance. The first of the two mirrors was placed 260 mm away from the laser's box, and the second was placed 265 mm from the first. It must be mentioned that our optical arrangement had to be configured such that it would fit, and align properly on a 12 m x 30 m table. The possible arrangements given a selection of mirrors, lens and several other optical pieces items were therefore limited.

After arranging the mirrors, and steering the beam in a straight direction down the table (see Figure 1 as a reference to the "straight direction"), a 300 mm focal length lens was aligned and fixed such that the beam would be centered through the lens, and that the focal point of the beam would be positioned through the Faraday isolator, so that the waist size going through the isolator would be no bigger than 3 mm. The waist size of the beam through the Faraday Isolator was calculated, using several different lenses, via a program on MAT lab 7.0, given to us by Dr. Zhao. The MAT lab program that we were given is entitled "Alexei's Code" and is used to calculate beam waist sizes and guoy phases for a series of lens and mirrors (according to ones needs for the experiment) as the beam travels certain distances. The MAT lab program associated with our experiment can be seen in Figure 2. Although it seemed easy enough to send the beam straight through the Faraday Isolator from the lens, the beam propagating through the isolator had to have its phase shifted by two wave plates, a λ/4 and λ/2 wave plate in that order.

Figure 2. Alexei's Code – MAT lab



The Faraday Isolator that we incorporated into our setup was the Optics for Research Isolator, Model IO-5-1064-VHP. The Isolator that we were using approximately 130 mm x 50 mm, where its input hole was raised to the height of the beam, 75 mm. An isolator transmits light in one direction only. An isolator consists of a Faraday rotator, two polarizers and a body to house the parts. The Faraday rotator consists of a magneto-optic material contained in a magnetic field. The plane of polarized light rotates while transmitting through glass (or other material) that is contained in a magnetic field. The direction of rotation is dependent on the direction of the magnetic field, and not on the direction of light propagation (non-reciprocal). Laser light, whether or not polarized, enters the Input Polarizer and becomes linearly polarized, say in the vertical plane (0°). It then enters the Faraday rotator rod, designed to rotate the plane of polarization (POP) by

45°. It then exits through the Output Polarizer whose axis is at 45°. The light leaves the Isolator, and reflections occur. This reflected light constitutes feedback. This feedback re-enters the Isolator, back through the Output Polarizer where it is repolarized at 45°. It then passes back through the rotator rod and is further rotated by another 45°, making a total of 90° with respect to the Input Polarizer (0°). It is seen that the light is extinguished here. Thus, the laser is isolated from its own reflections. [2]

After sending the beam through the Faraday Isolator, it was necessary to change the polarization of the beam again, using a λ/2 wave plate, before sending it into the Phase Modulator. The beam size didn't need to be refocused with a lens to pass through the Phase Modulator; its waist size was already corrected enough with the 300 mm lens and its path through the Faraday Isolator.

The Phase Modulator that was used as a part of our optical arrangement was the New Focus: Smart Optics for Research, 10 MHz, and Model 4003 IR Resonant Phase Modulator. The modulator was The New Focus phase modulators consist of an electro-optic crystal of length l with electrodes separated by the crystal thickness d. The electric field is applied along a crystal axis and transverse to the direction of optical propagation. Modulation is induced onto the laser beam by aligning the polarization of the input beam with the crystal axis along which the electric field is applied. An electronic signal is then directly modulated onto the laser beam through the electro-optic effect resonant phase modulators; the crystal is combined with an inductor to form a resonant tank circuit. On resonance, the circuit looks like a resistor whose value depends on the inductor's losses. A transformer is used to match this resistance to the 50-W driving impedance. The crystal in this resonant circuit results in a voltage across the crystal electrodes that can be more than ten times the input voltage across the SMA connector. This leads to reduced half-wave voltages and larger modulation depths when compared to the broadband modulators.[3]

After the beam passed through the phase modulator, it was necessary for us to steer the beam back up the table, as we were reaching the end of our limit for table space in the vertical direction (see Figure 1 for reference). The mirrors were spaced ~140 mm apart, and the beam was sent back up the table, to another lens with a focal length of 300 mm. The lens is spaced approximately 86 mm from the fourth mirror fixed on the table. The 300 mm was used to focus the beam through another λ/2 wave plate, a fifth mirror for directional purposes and a beam splitter. The beam splitter that was introduced into this portion of the optical arrangement is very important, because it split the beam into its two distinct paths. One path of the beam leads to the 80 m cavity of the east arm AIGO interferometer and the other path passes through more optics and eventually reaching the reference cavity.

Our primary goal after this first beam splitter was to direct the beam into the reference cavity that was made for our set up. After the beam splitter, the laser beam was passed

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[2] http://laser2000.de/fileadmin/Produktdaten/SK_WEB/Datenblaetter_OFR/OFR%20Isolators%20-%20IO-xx.pdf

[3] http://www.newfocus.com/products/documents/manuals/400X_Manual_RevD.pdf

through an Acoustic Modulator. The Acoustic Modulator was positioned onto a rotating base, and hooked up to a driver which was powered with a 24 Volt power supply (2.6 Amps). The driver was attached to a 2 and 3 dB attenuators with are attached to an oscillator, powered by a 12 Volt power supply.

The Acoustic Modulator is created by Intra-Action Corporation, Acousto-optics, AOM Model 40R. The oscillator connected to the AOM is a voltage controlled oscillator; model ZOS-50, operating at 25-50 MHz. An Acoustic Modulator uses the acousto-optic effect to diffract and shift the frequency of light using sound waves. The amount of light diffracted by the sound waves depends on the intensity of the sound, which means that the intensity of the sound can be used to modulate the intensity of the light in the diffracted beam. We had to adjust the AOM in several directions, rotating it back and forth to try and find different modes of light resulting from the diffraction of the beam. The best order we could find was mode 1, and we were able to adjust the AOM so that we got the most intense laser beam in the diffracted beam leaving the AOM.

After the Acoustic modulator, the beam is split into two due to the first order mode shape, so it was necessary to block the least intense beam being emitted from the acoustic modulator. After isolating just one of the beams from the AOM, we needed to use another mirror to direct the beam horizontally down the table. The beam was then passed through another λ/2 wave plate, to readjust the phase of the beam for the polarized beam splitter, required to split the beam direction in two directions. The beam passed through the polarized beam splitter down towards the reference cavity, and a reflected beam (reflected from the reference cavity) passes back through the beam splitter, sent orthogonal to its propagation onto a photodetector, which eventually allowed us to mode match and lock the laser to the reference cavity.

Before sending the beam into the reference cavity, it was necessary to calculate the appropriate waist size of the beam, so that it would pass through and reflect off the cavity wall such that none of the beams intensity was lost.

$$R(z) = z\left[1 + \left(\frac{z_R^{\ 2}}{z^2}\right)\right]$$

$$1m = 100mm\left[1 + \left(\frac{z_R^{\ 2}}{100mm^2}\right)\right]$$

$$z_R = 0.3m = \frac{\pi\omega_0^{\ 2}}{\lambda}$$

$$\omega_0 = 0.319mm$$

The beam propagating from the beam splitter is sent through a series of two irises (needed for the directing the reflected beam back to a photodetector). After the irises, a 750 mm lens was placed at 4,050 mm from the laser. The reference cavity required a beam waist size of approximately 0.32mm, and a raised height of the beam itself. At the placement of the 750 mm lens, we were able to create a beam waist of 0.32856 inside of the reference cavity. After changing the size of the beam waist with the 750 mm lens, it was necessary to raise the beam height. We used a raised mirror, and two steering mirrors to lead the beam into the cavity. Right before the beam entered the cavity, it was necessary to add a λ/4 wave plate, to change the phase of the beam again before it entered the cavity.

Once we had the beam centered and leading into the reference cavity, it was now time to deal with the reflected signal propagating back out of the cavity. This was the most difficult, and time consuming part of the process. The idea was simple, the method was hard. It required a lot of fine tuning, adjusting and readjusting the steering mirrors in front of the reference cavity to find the reflected beam and steer it back along the same path that the original beam propagated from. Once we found the beam, and directed it along the right line of the original beam, we worked on centering the beam from the beam splitter onto the photodetector, so that we could read the signal returning from the reference cavity and begin the mode matching process.

The photodetector picks up the reflected beam from the reference cavity; the output of this signal is compared with the local oscillator's signal via a mixer. According to Black's paper, a mixer is a device whose output is the product of its inputs, so the output will contain signals at low frequency and twice the modulation frequency. The low frequency signal is what will tell us the derivative of the reflected intensity from the reference cavity, and this derivative will be used to lock the laser. In our particular set up, we used a low-pass filter on the output of the mixer, isolating the low frequency signal, sent it to an amplifier and back into the tuning port of the laser, giving us the ability to lock the laser to the cavity.

Before we could isolate and stabilize the laser to the cavity, we had to mode match the cavity to the zero order mode, in order to measure and utilize the frequency sidebands of the zero order mode, where the output was read from the photodetector onto an oscilloscope, to find the finesse of the cavity. We were told that the reference cavity should have finesse of approximately 6000, but in order to see that our set up and mode was correct, we had to measure the finesse on our own, using known sidebands, and our experimental bandwidth data. The side bands were introduced and controlled by the phase modulator, set at 10 MHz from the function generator. This was used to calculate the Δ ν full-width, half-max, Δ ν Sep, and ultimately the finesse of the reference cavity. The calculations are as follows:

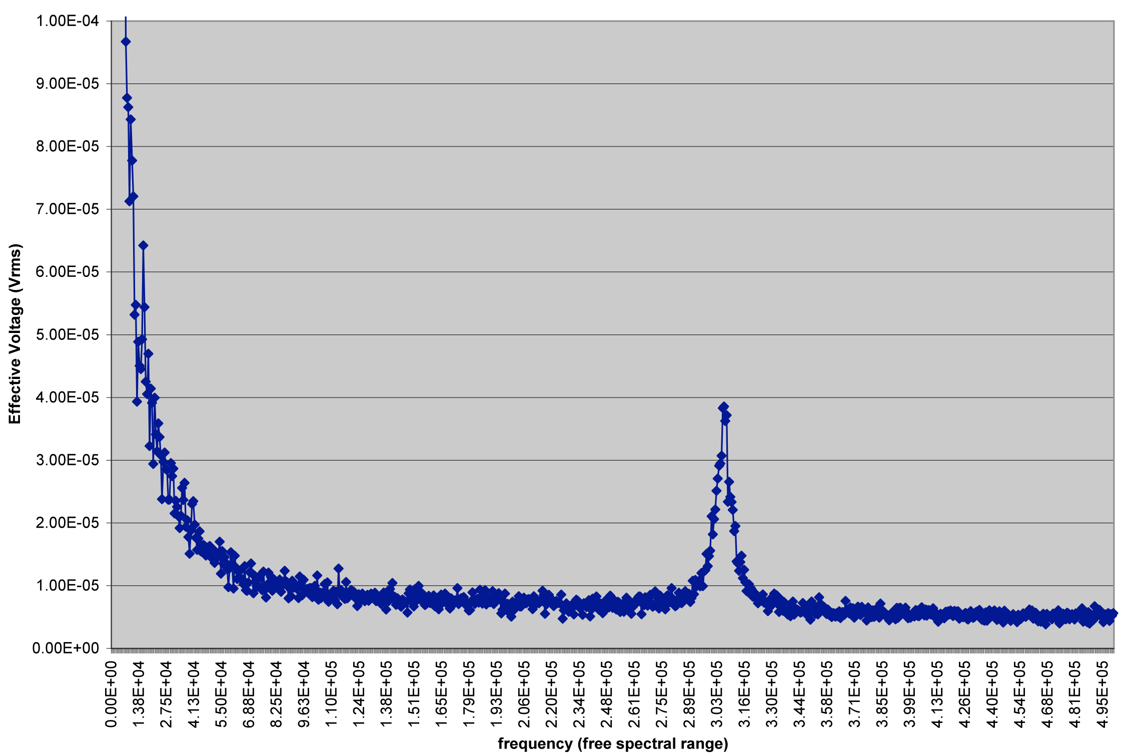
$$\Delta\nu_{FWHM} = \frac{10MHz \bullet 65.8Hz}{5376.3Hz} = 1.22\times10^{5}\,Hz$$

$$\Delta\nu_{FSR} = \frac{c}{2L} = \frac{c}{400mm} = 7.5\times10^{8}\,Hz$$

$$Finesse = \frac{\Delta\nu_{FSR}}{\Delta\nu_{FWHM}} = 6129$$

Our measured finesse for the reference cavity is 6129, as shown above. Once we knew that our finesse measurement was accurate, in comparison with the given finesse, we were able to find the frequency of the incident light, the free spectral range. We read this frequency from the Vector Signal Analyzer, which was attached to the output coming from the mixer and the local oscillator. Ideally the cavity and laser's frequency should be resonant about zero, but there is always some sort of residual motion present, which create frequencies which need to be readjusted. The residual motion can be read in the error signal, which is measured on the Vector Signal Analyzer. Using this error signal we are able to measure the control loop gain of the laser and feed this signal back into the PZT of the laser, which therein allows us to lock the laser to resonance.

Figure 3. Effective Voltage v. Frequency of the incident light.



When we calculate the laser frequency change in comparison to the amount of error signal being read, the results show that there is 1 Volt of error signal read for every 425.2 kHz of residual laser frequency noise that shift out of resonance.

1 Volt = 1 MHz

$$43.8mV \Leftrightarrow 43.8KHz$$

$$\frac{43.8KHz}{103mV} = 425.2\,{KHz}/{V}$$

At the peak of the frequency noise trace data, around 100 kHz, the noise level was 250.94 x 10^{-9} Vrms. In order to calculate the residual noise that shifts out of resonance

4. Conclusion

The error signal that we calculated from the measurements being read across the oscilloscope is pumped back into the PZT of the laser, where it is locked to the reference cavity and held on resonance for as long as the laser needs to be in use.

After locking the laser to the cavity it is possible for the laser to be mode matched and locked into the 80 m cavity of the east arm of the AIGO interferometer. Despite the fact that we were unable to lock the laser to our final goal, the 80 m cavity, locking it to the reference cavity was hard enough, and we are very proud of our accomplishment.