LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Automated Laser Stabilization and Mode Matching for Triangular Cavity.

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There are many sources of noise and loss within the interferometers of LIGO. One source is quantum shot noise, which is mitigated by injected vacuum squeezing. However, even this is subject to readout losses within interferometer optics. In order to overcome this, it is proposed to pre-amplify the amplitude quadrature of the field containing the GW signal. This will be done with a Phase Sensitive Optomechanical Amplifier (PSOMA). The PSOMA contains two triangular ring cavities that serve as the power build up in the amplification. It is crucial that these cavities are stabily locked to the lowest order mode with the best solution of mode matching. My projects this summer directly contribute the quality and accuracy of mode matching and resonance build up within these triangular cavities.

Part I

Automated Laser Stabilization

1 Introduction

In any optical cavity, resonance is maintained using a combination of feedback control systems (FCS). The laser of our triangular cavity is acuated using Pound Drever Hall locking (PDH). This FCS modulates the laser frequency into higher and lower sidebands, which are sent into a mixer along with the carrier frequency resonating within the cavity. This mixer combines its inputs, and the output is sent into a low pass filter producing an error signal that can be approximated as linear around resonance. When the carrier frequency is above or below resonance conditions, the servo amplifier will respond to this linear error signal, and actuate on the laser frequency. The second FCS used is a temperature control servo (slow servo) which controls the temperature of the laser very precisely. The laser frequency is heavily dependent on temperature, which is why the temperature must be kept stable. Both of these FCS's are currenlty being done in the tabletop experimental PSOMA cavity in the Caltech lab to practice resonance.

2 Current Problem

The tabletop cavity is susceptible to becoming unlocked. This occurs when the laser frequency moves beyond the linear region of the error signal. Once that happens, one must turn off the servo amp that actuates the PDH lock. A reading of transmitted to reflected light will tell how the cavity is resonating. One then sweeps through different settings such as a temperature, input offset, and gain, to be able to create conditions where the cavity is near resonance and can easily find it again. This is a manual process that becomes tedious and requires time. The PDH lock is repeatedly turned on and off and on again until the cavity becomes locked. The set point of the temperature, gain, and input offset are then adjusted so that resonance can be maintained. The goal over the course of the summer is to implement and system that automates the process in which the cavity acquires lock.

3 Project Plan

Locking the laser cavity is done with a Moku:box, which is a FCS that comes with an iPad interface. As of right now, it can carry out the locking process described in the previous section. However, we want to design a system that can feed back a state that is beyond PDH range so that the Moku can lock automatically. Here's what the summer's weeks will look like:

- **Week 1:** Control Project: Become familiar with PDH locking and temperature control servo systems.
- **Weeks 2 - 4:** Control Project: Learn digital systems, outline sequence, and script process.
- **Weeks 5 - 7:** Control Project: Debug outlined sequence and determine channels to read/write into.
- **Weeks 8 - 10:** Control Project: Work on physical model of the control system, loop shaping .

4 Current Progress

In these first three to four weeks, I have spent a lot of time in the lab becoming familiar with not only the general set up, but with how the locking process works. I worked alongside Aaron Markowitz in setting up an LB1005 servo amp instead of the Moku to lock the cavity. This is where I gained a much better understanding of how locking is acquired, and conditions needed for lock to happen.

One of the major issues early on however, was figuring out what mode the cavity is being locked too. Usually, this can be easily determined with a beam profiling camera, that shows the shape of the beam on a large screen. However, even though resonance was being achieved, the beam was not being shown on the profile. It turned out that power on the order of microvolts was being transmitted through the cavity, meaning that it was locked, but to a condition of poor resonance. Solving this problem required adjusting the stiring mirrors of the cavity, to angle the light so that stronger power build up was achived. Once this was done, we were able to see the beam profile on the camera. It was then determined that we were locked to the 0 0 mode, which is what we wanted.

Over the next coming weeks, I will start deriving the transfer functions of the control system along with creating an outline of how the loop will work.

Part II

Mode Matching Solutions

5 Introduction

Before the laser enters the resonant cavity, it is properly mode matched with two lenses. In our cavity, these lenses are convex, and shape the beam so that it enters the cavity in such a way that it can achieve resonance with its given parameters (radius of curvature and cavity length). This mode matching allows us to have a controlled q parameter of the beam. However, upon physical construction, the modes we see are not the modes we modeled.

6 Proposed Problems

There are some hypotheses as to why this may be the case. One solution may be the use of the thin lens approximation. Considering the relative size of the beam and lens being used, the thickness of the lens may not be negligable. Using ABCD matrix calculations through these optical components can help us seek differences in the q parameter when a thin lens is used versus a thick lens.

Another issue that may be contributing to this discrepency are lens aberrations. Lens aberrations are when the light is not focused all in one point after propegation through a lens. This may be due to the curvature of the lens not being completely accurate for image focusing. As a result, the image can become blurry, and there may be multple focusing points for different rays of light. This can be seen in Figure 1a, as there are multiple points along the propegation axis where the light comes into focus.

One thing to note is that the higher up the beam comes through the lens, the larger the distance is between its focusing point, s'_h, and the paraxial focal point f'. This trend can be seen with equation:

$$\frac{n}{s} + \frac{n'}{s'_h} = \frac{n'-n}{r} + \left[\frac{h^2 n^2 r}{2f'n'}\left(\frac{1}{s}+\frac{1}{r}\right)^2\left(\frac{1}{r}+\frac{n'-n}{ns}\right)\right] \tag{1}$$

We see that as h increases, we get a larger right hand side of the equation, meaning that s'_h gets smaller on the left side to compensate, making the lens aberration greater. This tells us that if the laser beam is wide enough upon entering the lens, then lens aberrations may cause higher order modes in the cavity that do not align to the resonance conditions we originally plan for.

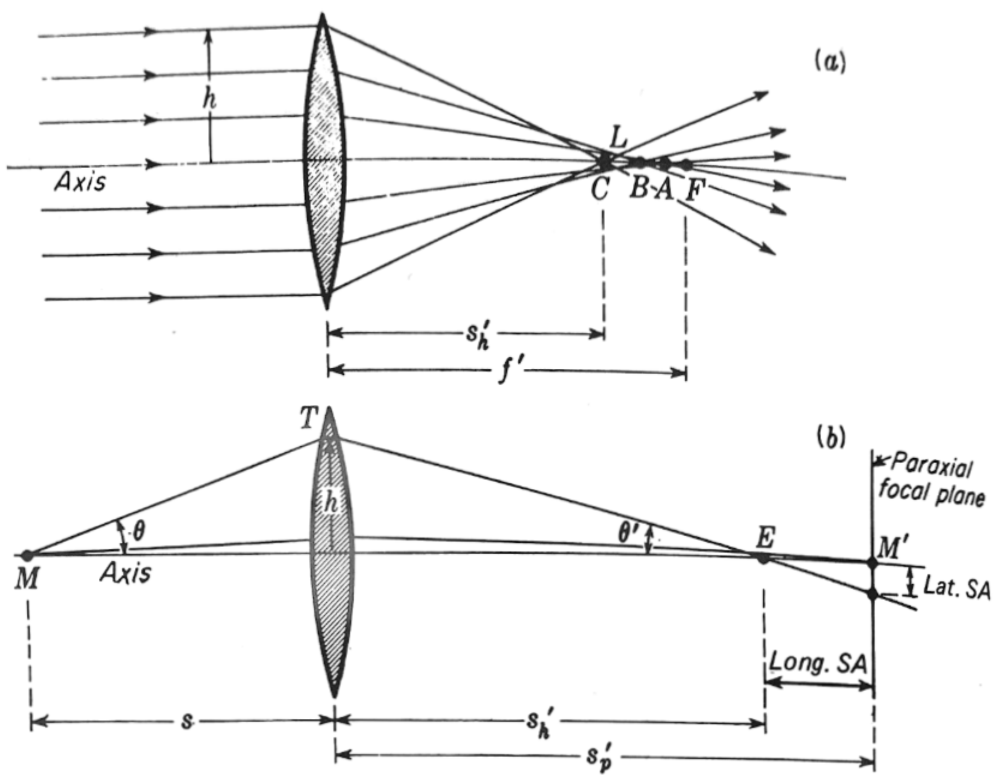

Figure 1: (a) Diagram of how lens aberrations occur, and how they can be perceived. (b) Notice here the Longitudinal Spherical Aberrations (Long. SA) and Latitudinal Spherical Aberrations (Lat. SA), which come in to play in the beam being misaligned within the cavity.

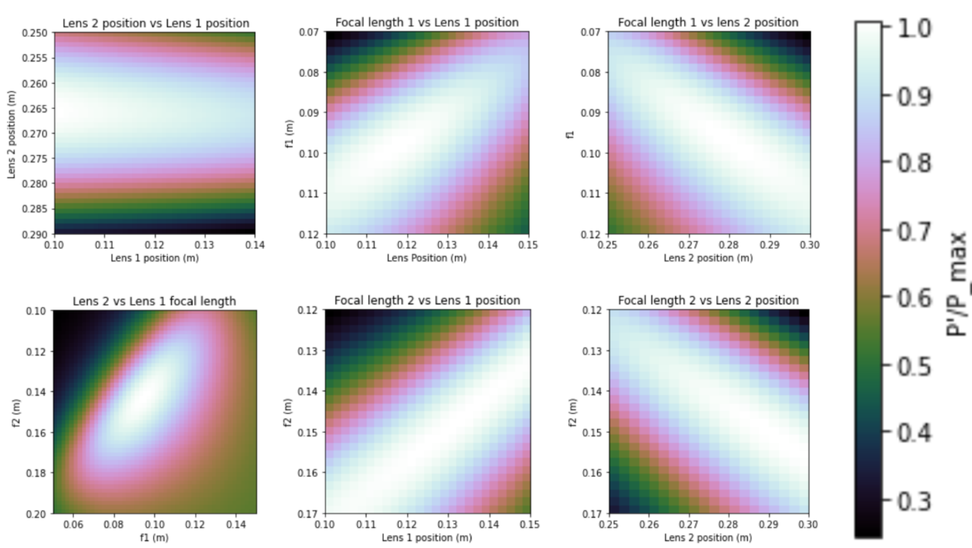

Figure 2: Heat maps of varying two lens mode matching parameters. We measure the power transmitted per maximum power allowed. The max power means we achieve highest resonance.

7 Project Plan

Overall, the plan is to model a mode matching situation in which lens aberrations and thick lenses are taken in to account.

- **Week 1:** Read up on ABCD calculation, and mode matching.
- **Weeks 2 - 4:** Begin creating a mode matching tolerance map for different mode matching solutions Also create ABCD matrix calculation of thin lens propegation.
- **Weeks 5 - 7:** Work on ABCD calculation with thick lens, along with completing mode scan of cavity. Determine method of analyzing lens aberrations.
- **Weeks 8 - 10:** Compare differing solutions and parameters (concave and plano lens, mirror configurations). Model for antisymmetry.

8 Current Progress

So far in these three to four weeks, I've completed an ABCD matrix calculation of a thin lens, and it matches very closely to the model wanted to be attained. There were some difficulties in figuring out the parameters to be used, since we are starting off modeling as a fabry perot cavity instead of a ring cavity. However, after a few hours of looking through the measurements, we were able to make a good two mirror model of a three mirror cavity.

My next steps were to create a heatmap of varying mode matching parameters. As seen in Figure 2, there are several different heat maps with combinations of varying parameters. What's interesting is that the movement of lens 2 changes the resonance conditions much greater than the movement of lens 1. However, we see that changing the focal length of either lens has about the same affect on the cavity resonane.

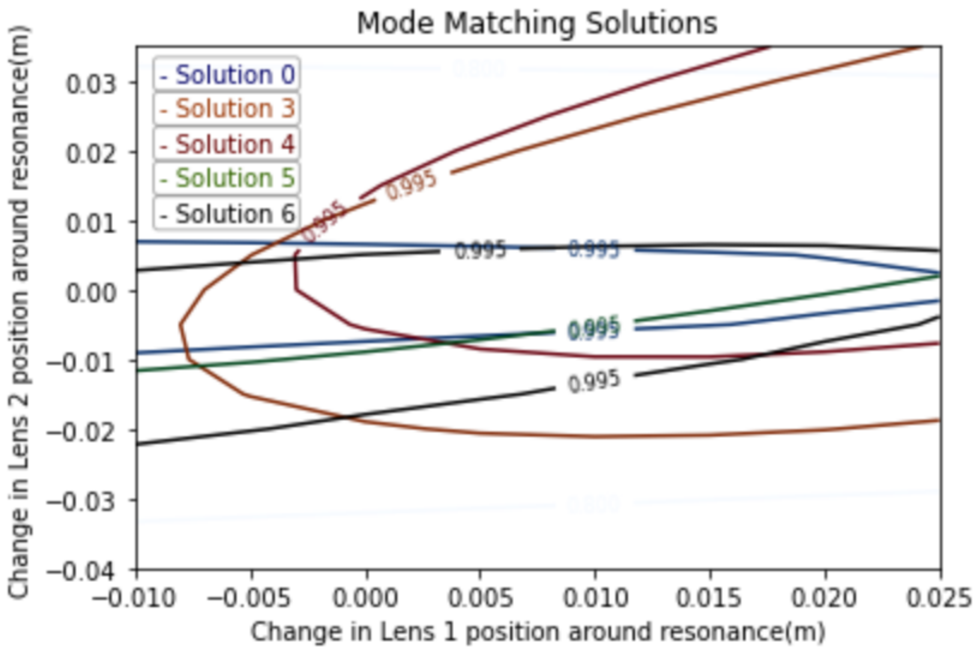

Figure 3: Contour maps of several configurations of mode matching. Each configuration has different parameters of length and The interior of each color curve represents the region in which the mode matching is 99.5 percent resonant. The x and y axes are changes in respective lens positioning according to resonant position, in which 0 would be the position of highest resonance. The areas are compared to see which has the greatest tolerance to change in motion.

These types of heat maps are usefull to us because it allows us to see if there are any configurations that bring about higher resonances that are not being configured in the lab.

I've also created a layered contour map of different mode matching solutions and their tolerance to movement. As we can see in Figure 3, there are different areas of resonance for different configurations of lenses. This contour can give us insight into which configuration can give us the maximum power with the most amount of room for error.

In the weeks to come, I will begin using a thick lens ABCD calculation, along with thinking of how to analyze lens aberrations. I will also begin modeling for a three mirror cavity instead of a two mirror cavity. Later in the week, we will complete a mode scan of the cavity to be able to pin point where our parameters lie.

The thick lens calculations will involve not only using the radius of curvature of the first lens surface, but using the thickness of the lens as its own distance, and then the end radius of curvature. If we see significant differences in the thin lens and thick lens calculations, then it may be something to heavily consider.

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