LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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Temperature control of silicon mirrors in locked cavities at 123 K
Progress report 2

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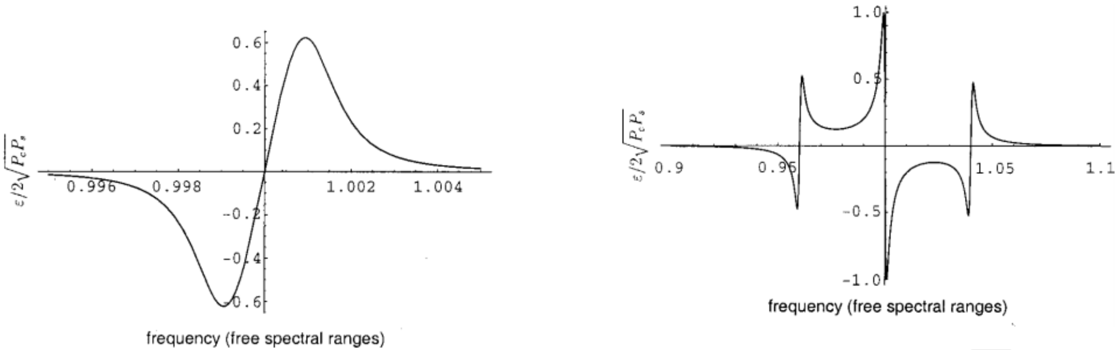
1 Introduction

LIGO (**L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory) was designed to detect gravitational waves, per Albert Einstein's theory of general relativity. It uses a modified Michelson interferometer to detect changes in the length of its four-kilometer-long arms, of the order of $10^{-21}m$. It needs to be this sensitive in order to capture the very faint strains on the order of 10^{-24} coming from distant astrophysical phenomena such as coalescence of black hole in binaries.

One idea for enhancing LIGO sensitivity is a *cryogenic* setup whereby the mirror test masses used in the interferometer and part of their suspensions are held under low temperatures (123 K). This design targets thermal noise, related to Brownian fluctuations on mirror coatings. As this noise increases with temperature (given by the frequency-domain thermal noise term $S(f) \propto k_B T$), it is best reduced by working at cryogenic temperatures. One of the issues related to LIGO sensitivity is related to length fluctuations in the interferometer cavities. To investigate that, it proves useful to work with a small (4 inches long) optical cavity made of silicon.

Noise in the laser leads to frequency fluctuations in the laser beam to be locked to an optical cavity. It is crucial to be able to maintain lasers on resonance with the cavity, and for that a means to sense and control frequency fluctuations is needed. The Pound-Drever-Hall (PDH) locking technique uses phase modulation and the reflected laser beam to monitor the resonance situation with the cavity. This can be used as an error signal for how far off resonance the system is.

The basic method behind the PDH technique is to generate sidebands in the beam going towards the cavity using a modulation frequency Ω. As these are frequency sidebands $\omega \pm \Omega$ (away from resonance at the laser frequency ω), they get reflected along with part of the carrier beam. This reflected signal is where the error signal mentioned above comes from. Depending on whether the modulation speed Ω is big or small, this error signal $\epsilon(\omega)$ will have two different forms, both of which happen to be antisymmetric around resonance points. Example plots of these forms are represented on the next page :



The Pound–Drever–Hall error signal, $\epsilon/2\sqrt{P_cP_s}$ vs $\omega/\Delta\nu_{\text{fsr}}$, when the modulation frequency is low. The modulation frequency is about half a linewidth: about 10^{-3} of a free spectral range, with a cavity finesse of 500.

The Pound–Drever–Hall error signal, $\epsilon/2\sqrt{P_cP_s}$ vs $\omega/\Delta\nu_{\text{fsr}}$, when the modulation frequency is high. Here, the modulation frequency is about 20 linewidths: roughly 4% of a free spectral range, with a cavity finesse of 500.

Figure 1: Here the error signal for both slow (left) and fast (right) modulations. It is normalized in units of $2\sqrt{P_cP_s}$ with P_c and P_s the powers in the carrier and in each sideband respectively. [1]

The important takeaway from both of these graphs is that the PDH technique provides us with a way to track *signed* deviations from resonance. Operationally, this should result from the experimental design I started setting up from Week 5 to Week 7 (Figure 2).

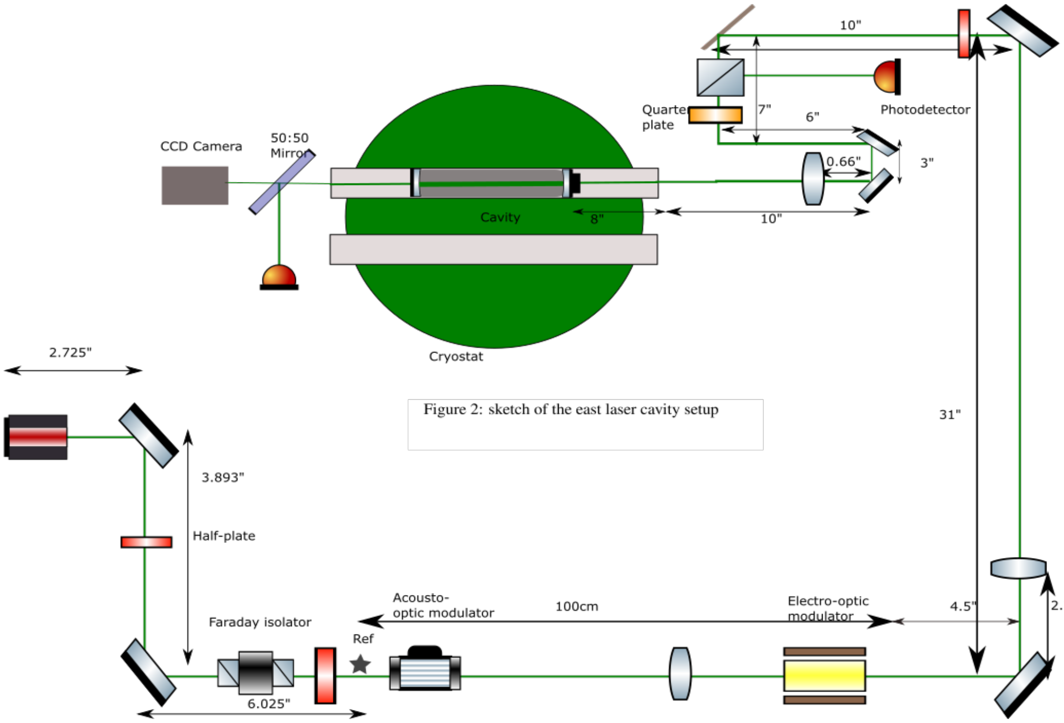
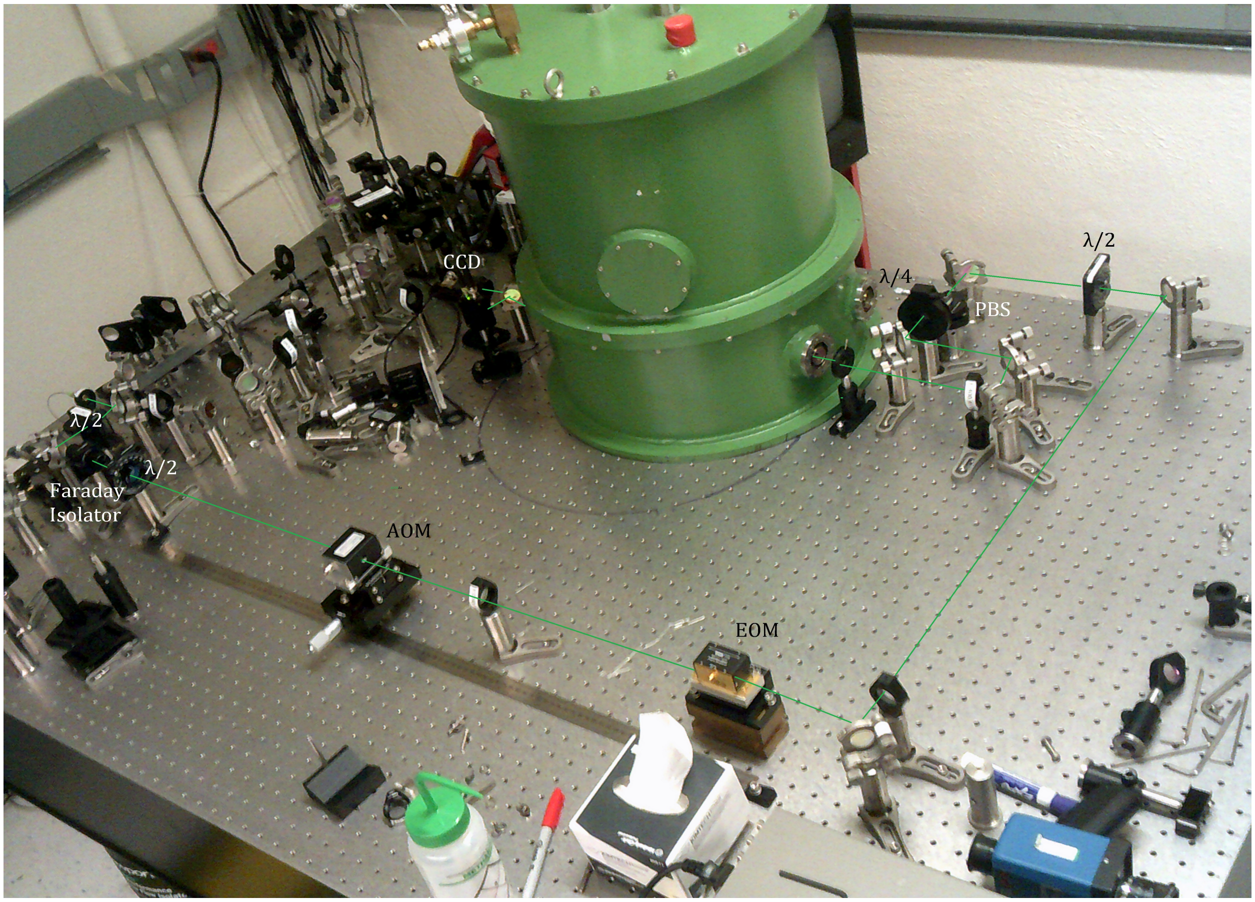


Figure 2: sketch of the east laser cavity setup



2 Weekly Progress

Weeks 5 and 6 Based on previous pre-cavity experimental setups, I started mounting the basic elements I would need:

- **Half-wave plates:** Used all across the setup, in order to prepare the beam into desired linear polarization states (for instance before a Faraday isolator, or before a polarizing beam splitter).

- **Quarter-wave plate:** Put after the polarizing beam splitter. it allows it to intercept reflecting modes from the cavity,

- **Faraday isolator:** Blocks reflected beam from returning back to the laser, by rotating the polarization by 45°

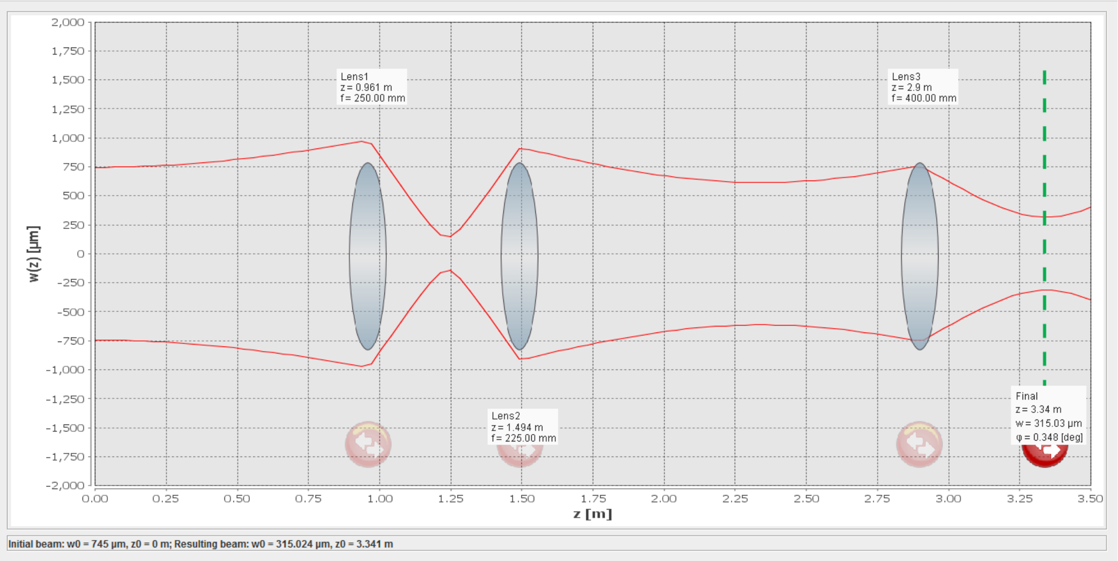
- **Acousto-optic modulator (AOM):** Provides amplitude modulation and frequency shift.

- **Electro-optic modulator (EOM):** Provides phase modulation, and is crucial to implementing the PDH technique.

•**Polarizing beam splitter:** Redirects part of the reflected beam in a transverse direction. This can be picked up by a photodetector to monitor the reflected mode.

• **CCD Camera:** Put in transmission, it allows to observe the transmitted mode(s).

Given a certain rough topology of the setup (with a final length of 334 cm), and the known target waist at the start of the cavity (315μm), I calculated lens solutions using a Java applet called JAMMT (”Just Another Mode-Matching Tool”):



Initial beam: w0 = 745 µm, z0 = 0 m; Resulting beam: w0 = 315.024 µm, z0 = 3.341 m

This can be verified by recursively using:

$$w_{n+1} = \frac{f_n w_n}{\sqrt{(f_n - d_{n+1,n})^2 + \frac{\pi^2 w_n^4}{\lambda^2}}}$$

$$t_{n+1} = \frac{\lambda f_n (f_n - 2d_{n+1,n}) + \sqrt{\lambda^2 f_n^4 - 4w_{n+1}^4 (f_n - d_{n+1,n})^2 \pi^2}}{2\lambda (f_n - d_{n+1,n})}$$

with w_n the waist at the lens n at position z_n and focal length f_n, t_n the distance between the lens n and the location of the waist w_n, and $d_{n,n-1} = z_n - z_{n-1} - t_{n-1}$ is the distance between the lens n and the waist w_{n-1} location behind it.

Week 7: After setting up the pre-cavity elements, we started suspending the cavity pair inside the cryostat. After opening up the cryostat and suspending the pair,we made sure that we could get a correct output mode by aligning the beam to the cavity. An optical cavity composed of multiple modes, also called Hermite-Gaussian modes m,n due to the mathematical solutions being generated by a product of a Gaussian and Hermitian polynomials of order m and n. We are usually interested in the 00 mode as it has the cross-section of a normal Gaussian (circle), but we also obtained some higher-order modes, which can be mathematically represented in Figure 3:

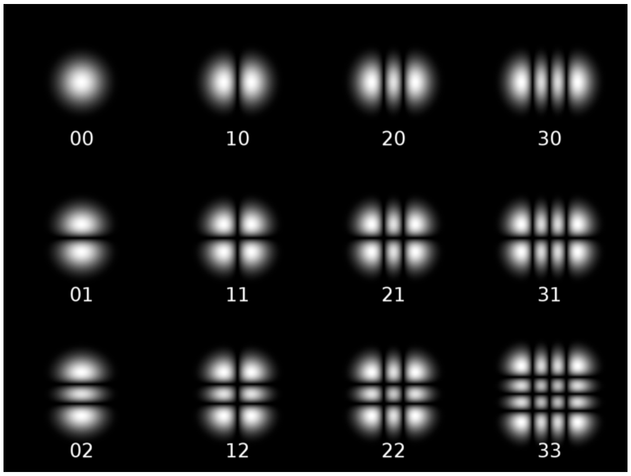
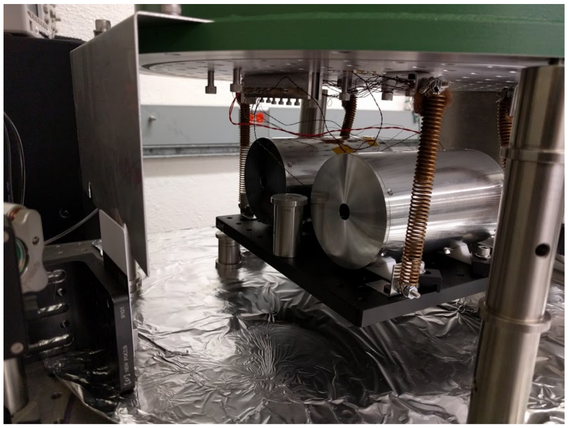
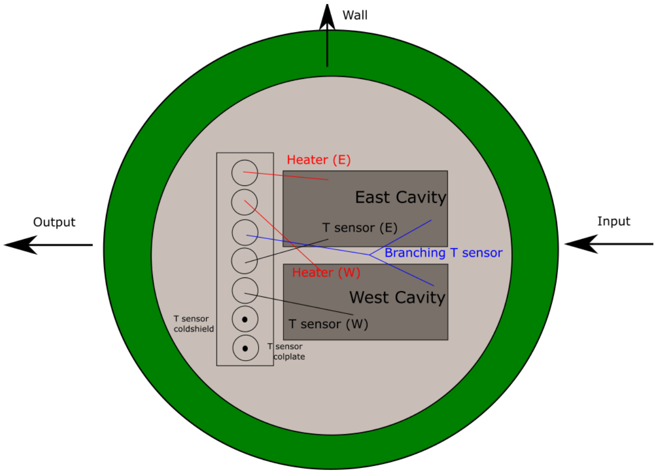


Figure 3: Twelve Hermite-Gaussian low-order modes ($m, n \leq 3$) [2]

Some of the higher-order modes that we obtained (which had the estimated forms of $20,0$ and $7,0$) were seen as we were scrolling through frequency space with the means of two actuators: temperature and current. The temperature actuator has a large range and a low bandwidth, while the current actuator has a smaller range but a higher bandwidth. Whenever we landed on a resonance mode, we would dither the current in order to make it more noticeable. To detect other modes across frequency space, we dithered the temperature instead. Across time, the laser temperature (and hence frequency) can drift away, and so we have to make sure we can maintain the 00 mode by constantly updating the driving parameters. After securing that mode, we connected some temperature sensors and heaters to the cavities and closed the cryostat (photos below).





3 Conclusion

At this stage, the cavities are suspended securely inside the cryostat. We will be able to check if there is any adjustment to the cryostat position/rotation to do in case we lose the 00 mode in transmission. After that, we will start driving the modulators in the setup in preparation for the frequency stabilization.

I should also be working towards the last -and additional- step to our project: the temperature dithering. As mentioned in my earlier progress report, I will be using an incident laser beam to affect the temperature of the cavity mirrors. An evaluation of the relation between the supplied laser power and the resulting dT around the target temperature (zero-crossing point) of $123K$ will be necessary as well.

References

[1] E. D. Black, "An introduction to Pound-Drever-Hall laser frequency stabilization," American Journal of Physics 69, 79-87 (2001).

[2] http://www.optique-ingenieur.org/en/courses/OPI_ang_M01_C03/co/Contenu_13.html