LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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SURF LIGO Summer 2016 project
Progress report 1

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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) . One of the issues related to LIGO sensitivity is related to length fluctuations in the interferometer cavities. To investigate that that, it proves useful to work with a small (4 inches long) optical cavity made of silicon.

For instance, 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. According to the Pound-Drever-Hall (PDH) locking technique, an opto-electronic system can be devised along the beam between its emission from a collimator to the point at which it enters the optical cavity. This 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.

Another effect of thermal fluctuations happens at the level of the cavity is on the thermo-elastic level: thermal expansion. After setting up the opto-electronic system and matching the laser beam to the cavity, it will become essential to monitor and maintain the cryogenic silicon's temperature at the zero-crossing point for the thermal expansion coefficient. This refers to the temperature value at which there is neither a positive coefficient (thermal *expansion*) nor negative coefficient (thermal *contraction*).

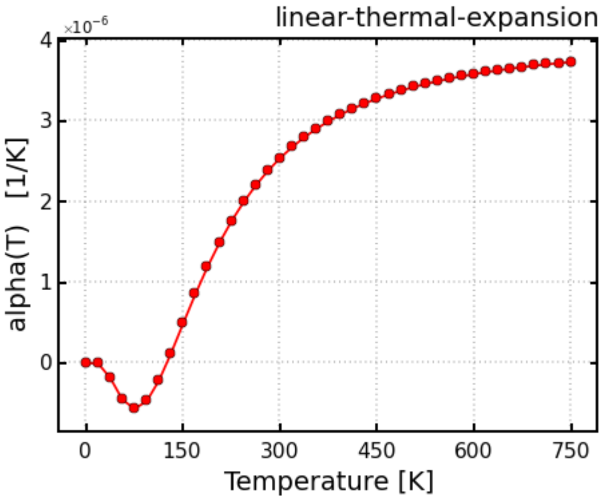

Figure 1: linear coefficient of thermal expansion $\alpha(T)$ as a function of temperature for silicon. (Notice the second zero at around 123 K) [2]

2 Weekly Progress

Weeks 1 and 2: For these first two weeks I was learning about the materials needed for my first task: determining fundamental parameters for the laser beam. It is a Gaussian beam, with a waist w_0 and a Rayleigh length z_R (after which the cross-sectional area doubles). The spot width of the laser varies across longitudinal distance z (along its axis) in the following way:

$$w(z) = w_0\sqrt{1+(\frac{z}{z_R})^2}$$

To obtain enough data points for a function fit of this form $w(z)$, I took ten $(z, w(z))$ measurements with the help of this setup:

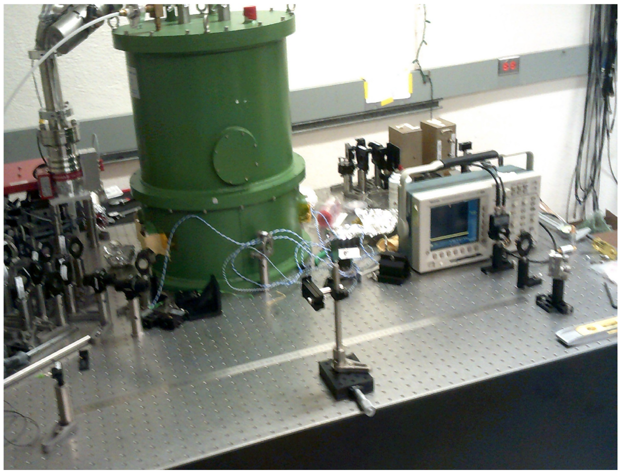

Photo of the setup for measuring the laser beam profile:

[A razor edge between the collimator and a photodetector. The mirror at the corner and the lens were for directing the beam into the photodetector aperture.]

To obtain an individual cross-section data point $(z, w(z))$ at a distance z away from the collimator, I used a razor edge -placed at z-to progressively obstruct the laser beam. At each stade of the obstruction, I measured the displayed voltage on the oscilloscope behind the photodetector. With voltage being an indication of the transmitted laser power, given a razor edge dip of x_0 into the laser cross-section, the voltage $V(x_0)$ should take the form of:

$$V(x_0) \propto power\ at\ (x_0) \propto \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{x_0} E^2 dxdy \propto \int_{y=-\infty}^{+\infty} \int_{x=-\infty}^{x_0} e^{-\frac{2(x^2+y^2)}{w(z)^2}} dxdy$$

which yields: $V(x_0) \propto V_0(1- \text{erf}(\frac{\sqrt{2}}{w(z)} x_0))$. By fitting a sigmoid curve of the general form $A + B$ $\text{erf}(C(x_0 - D))$, $w(z)$ can be obtained from $\frac{\sqrt{2}}{w(z)} = C$ (Figure 2). With this form, four degrees of freedom determine the following graphical aspects: A is a vertical offset, B controls the vertical width of the sigmoid, C is a slope parameter and D accounts for a reference point in the razor edge dip. I obtained data sets for two laser collimator orientations: horizontal and vertical.

I used a MATLAB script for least-squares nonlinear functions to fit the intensity plot model to the data sets for each $(z, w(z))$. While error functions always have two horizontal asymptotes, my selected number of datapoints per plot consistently yielded a fitting function without getting to the part with the tail to the right. That asymptote is determined by the dark voltage offset, when no laser light gets transmitted into the photodetector. Across my measurements, the oscilloscope displayed a dark voltage value of $-250mV$.

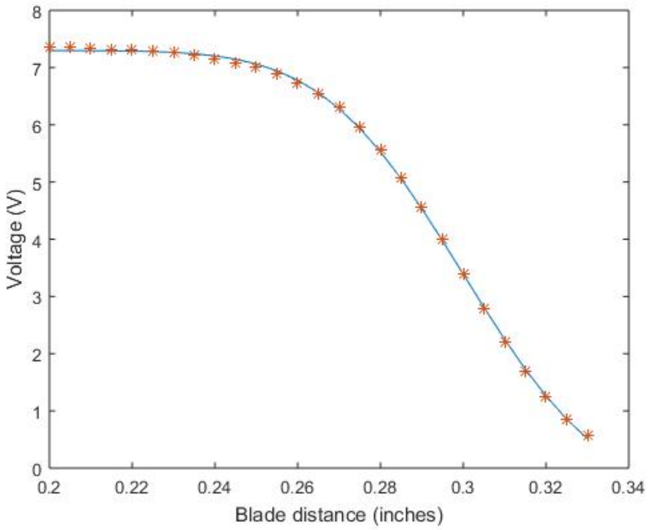

Figure 2: Beam profile (horizontal collimation, blade at z= 715 mm)

$C = 26.6$ in^{-1} and thus $w(z) = 0.135$ cm in this instance

Doing that for multiple $(z, w(z))$ measurements yields two hyperbolae (Figure 3) describing the widening of each Gaussian beam. Given the two different (w_0, z_R) parameter pairs (suggesting a slight asymmetry), in order to pursue further computations based on one transversally symmetric beam, effective values for w_0 and z_R will be kept at a geometric ($w_0 = \sqrt{w_{0,X} w_{0,Y}} = 745$ μm) and arithmetic ($z_R = \frac{z_{R,X}+z_{R,Y}}{2} = 0.507$ m) means respectively.

	Horizontal	Vertical
w_0 (μm)	805	690
z_R (m)	0.503	0.512

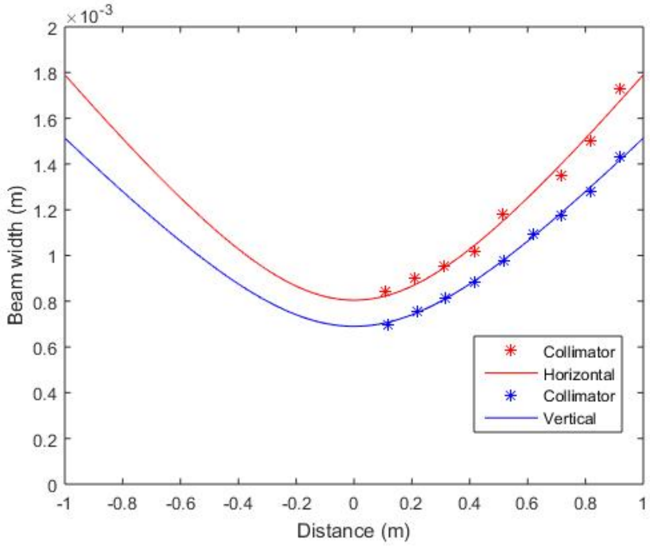

Figure 3: Beam width vs. distance for the two laser collimations

Week 3: After obtaining beam profiles for the laser I have been using, I started setting up the system of optical and electronic elements between the laser collimator and the presumptive location of the cavity (the cavity will be inserted after the equipment table is correctly prepared).

One first thing to determine was the target laser beam waist. Constrained by the cavity length ($L = 4$ in) and radii of curvature (flat mirror and a $R = 50$ cm mirror), the target waist ends up equal to $w = 315\mu$m (using $R(L) = L(1 + (\frac{\pi w}{\lambda L})^2)$)

At this point I have laid out a preliminary sketch of the elements to be introduced along the beam path, based on the previous pre-cavity setup but adapted to the cryotable instead of the previous table the instruments were on (Figure 4). I expect to finish distance estimates and construct the setup by the end of Week 4. These will require adapting the placement of setup elements to the constraints of lens optics (position and focal length decisions) for minimizing the laser spot width whenever needed along the path, like any of the apertures of the modulators, or ultimately getting the desired laser waist by the end of the path (onto the cavity).

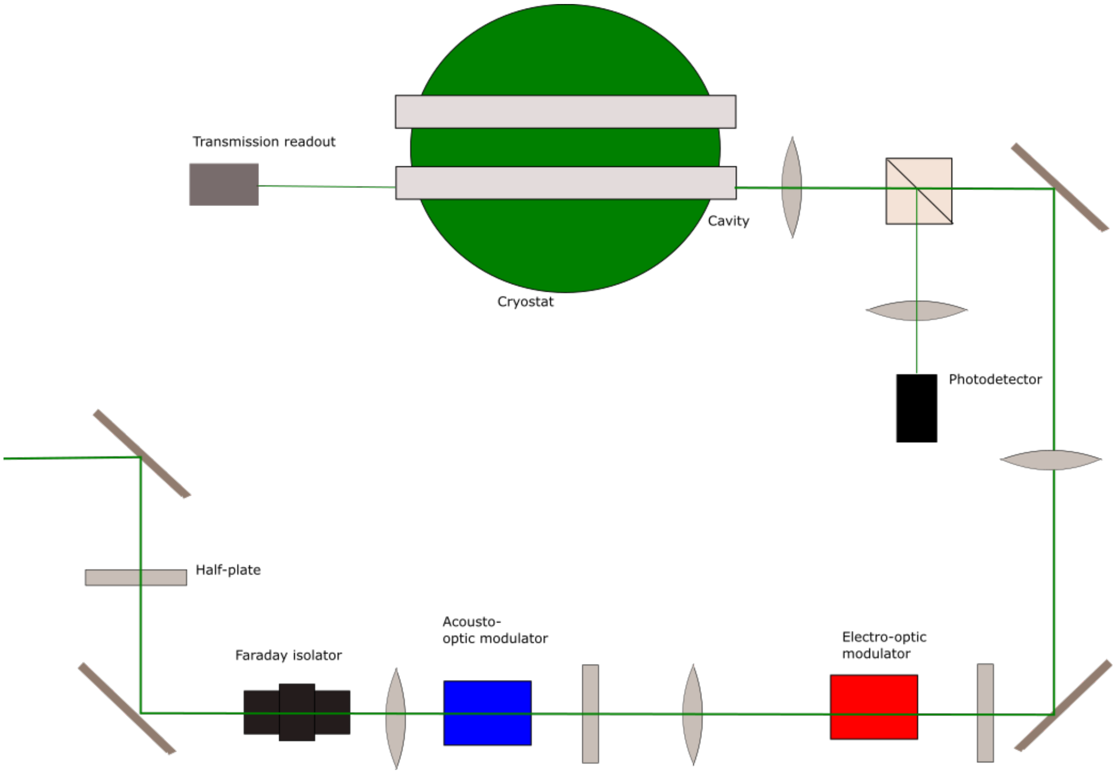

Figure 4: Preliminary drawing of pre-cavity table setup

3 Conclusion

I will be working on accurately determined the required distances and make any adjustment for additional/superfluous instruments I might have chosen for this preliminary design. After that I should verify the modematching of the laser to the cavity, and then align and lock the cavity. In parallel I will have to think a bit about the temperature control part of my project. For that I will be working at the level of the zero-crossing value of silicon 123 K. By slowly varying (dithering) the temperature, with the help of an intensity modulated laser incident on the cavity, I should accurately measure the offset from zero in either direction.

References

[1] A. Weinstein, SURF LIGO introductory lecture (2016).

[2] Linear coefficient of thermal expansion. Digital image. Exciting-code.org. N.p., n.d. Web. 6 July 2016. <http://exciting-code.org/beryllium-phonon-and-thermal-properties-si>

[3] H. Kogelnik and T. Li, ”Laser beams and resonators,” Appl. Opt. 5, 1550-1567 (1966).

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