Development of a GigE Phase Camera for LIGO: Progress Report I

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Certified by ……

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Abstract

The Laser Interferometer Gravitational-Wave Observatory (LIGO) has been obtaining science run data using three detectors, two at Hanford, WA and one at Livingston, LA. The goal is direct detection of gravitational waves (GWs) predicted by a solution of the field equation of Albert Einstein's General Theory of Relativity published in 1915. The technological advancement in terms of laser and quantum optics was one of the key components in the direct attempt of testing the hypothesis for GW. In this report for LIGO SURF 2010, I will describe the progress achieved between the time period of 15th June 2010 and 30th June 2010 in the development of a gigabit Ethernet (GigE) phase camera using CMOS and a frequency selectable auxiliary beam extracted from a laser. The goal of this camera is to 'see' the multiple complex signals imprinted on the laser light's amplitude and phase at different frequencies and provide feedback to an adaptive optics system to fine-tune the interferometer mirror surface of LIGO.

Research Problem

In LIGO, the laser is frequency-stabilized and the beam is made up of a carrier and phase modulated sidebands. Frequency stabilization refers to using a high finesse resonance cavity as a stable reference and a feedback control system to produce a stable narrow linewidth laser light which typically has low amplitude noise. But in LIGO, as light passes through the initial pre-mode cleaner and later on gets intensified in the resonance cavity at the two arms, the radio-frequency (RF) sidebands undergoes distortion in the beam profile. The phase front of the beam might have relative offset at the center compared to the sides. Thus measurement of the phase front can be a useful diagnostic for any change in the optics. For example it can map to any deformation that might occur inside the laser cavities or to any change in the index of refraction of the optics due to a change in temperature. Dr. Betzwieser has been working on building a phase camera, a high resolution wavefront sensor to measure spatial profile of the laser beam's frequency component, for some time using a RF photodiode. The limitation with the photodiode is that it can only measure and sample a single point at a time. In order to find the spatial profile at different portions of the beam, it was necessary to change the angle and positions of the incident beam on the photodiode to sample different parts of the beam. In this project, I intend to build a phase camera using CMOS sensor to do real time monitoring and measurement of the spatial profile of the beam.

Objectives for the two weeks period (06/15/2010 – 06/30/2010)

Before arriving at Caltech, I initially planned on using this two weeks time to set up the optics to start working with the camera, work with the existing code that was written by a previous SURF student Zach Cummings, and gather enough background information to allow myself to understand and implement the phase camera setup.

Progress in the past two weeks

I began my work on June 16th 2010 after the initial orientation. The initial setup (as in figure 1) of the phase camera as I found on the optics table required a trigger box. We decided to incorporate a multipurpose trigger box that should be able to drive the camera given a chosen signal from the frequency generator, as well as power the camera with a 12 V power supply. So we designed a circuit as shown in the figure 2. I soldered the circuit together in a Pomona Box and connected to the camera that was stationed at the optics table.

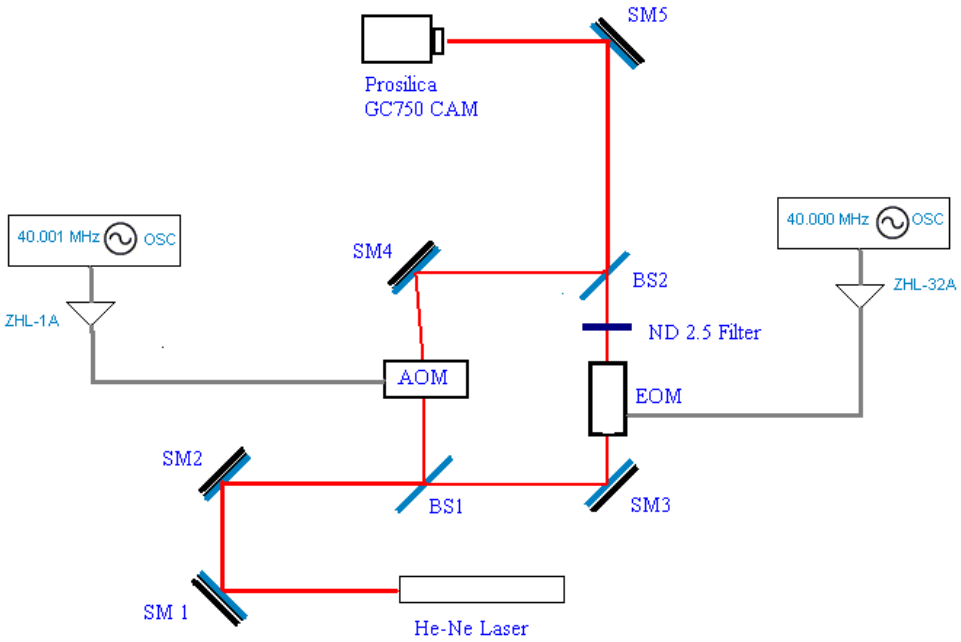

Figure 1: Optical layout of the initial setup

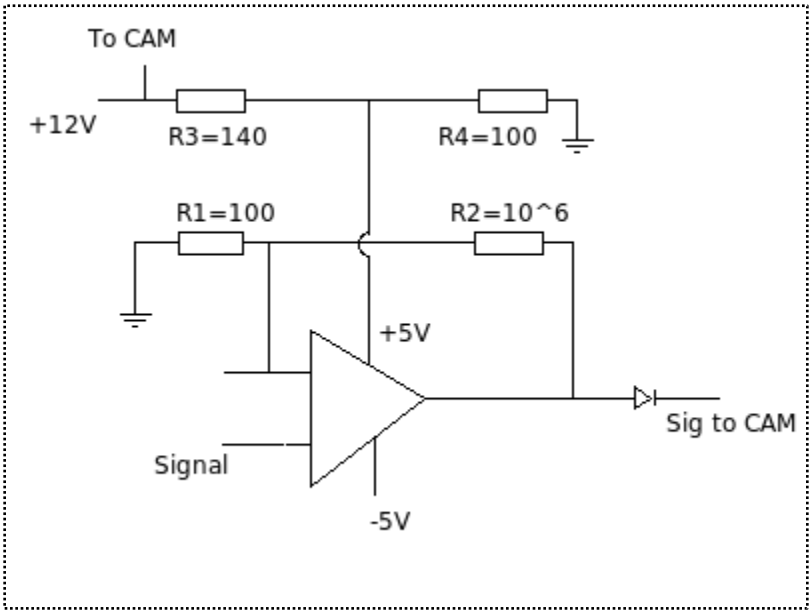

Figure 2: Trigger and power circuit for the camera

The camera trigger circuit takes a sinusoid input from the signal generator and produce a half square wave to trigger the camera. The key component in this operation is the op-amp which receives a sinusoid signal from the signal generator in its non-inverting input. As the op-amp attempts to zero the voltage difference between its inputs, it becomes saturated and produces an non-inverting signal. This signal is then passed through a passive diode to eliminate the negative voltage as the camera only takes positive voltage as its signal.

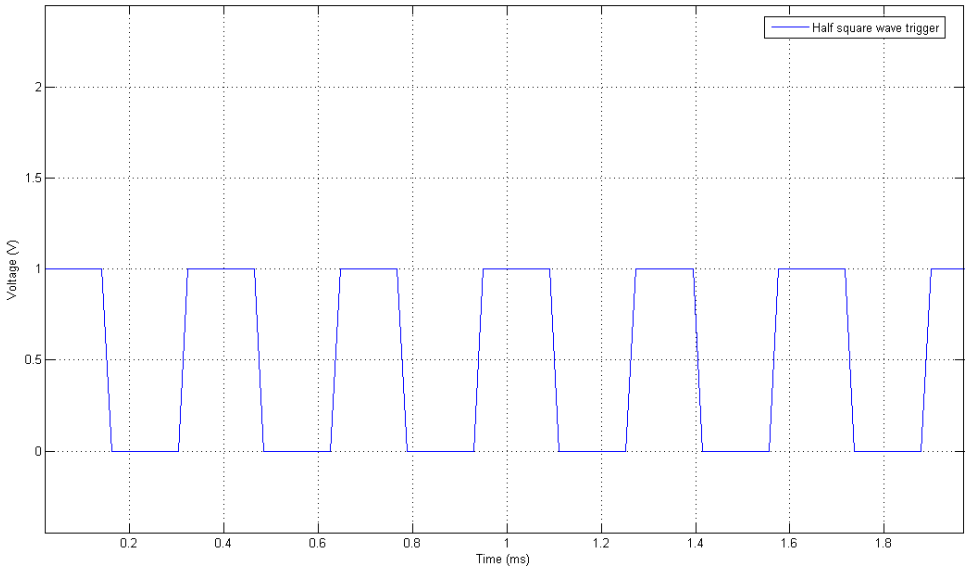

Figure 3: Trigger circuit output

Once the trigger circuit is in place, we took a series of pictures using the camera code that we previously had. The exposure time was taken at 30 μs.

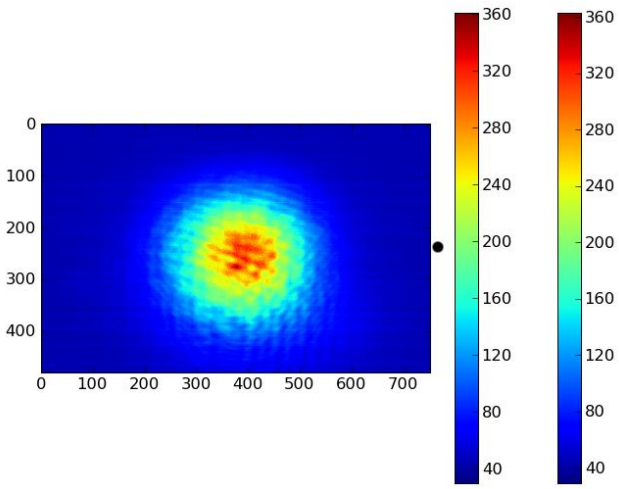

Figure 4: A snapshot of the beam coming after SM5 from Figure 1

As I am done with the trigger circuit, my next task was to understand in details about the optics that is in the setup. I intended to analytically calculate the power that is going in the camera. So I decided to trace back to the basic optics.

In our setup, we used an Acousto-Optic Modulator (AOM) to shift the frequency of the light so as to have a reference beam. An AOM consists of a piezo-electric transducer (PZT) attached to a crystal whose refractive index changes when an acoustic wave propagates through it.

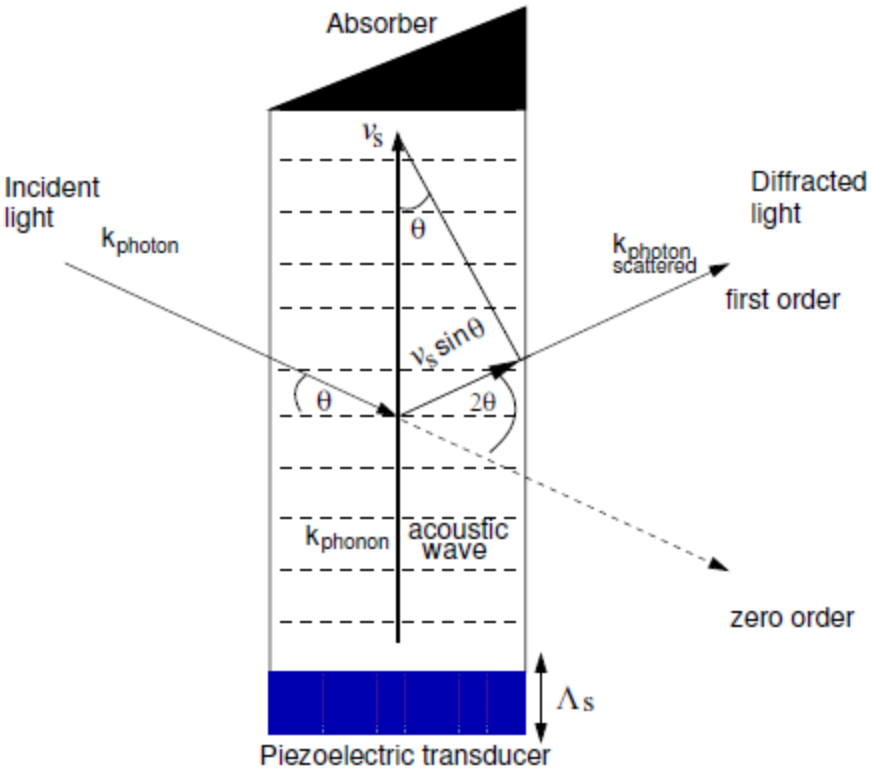

Figure 5: Schematics of how AOM works [2]

As the PZT is driven using an RF generator, the acoustic wave travels through the crystal with a frequency f_s and velocity v_s .Thus the incident light is Doppler shifted w.r.t the lab reference frame.

So the diffracted light have frequency, f_d , where

$$f_d = f_{incident} \left(1 + \frac{v_s \sin(\theta)}{c}\right) \quad (1)$$

If we consider the spacing between the lattice of the crystal as diffraction grating then,

$$\sin(\theta) = \frac{m \cdot \lambda_{incident}}{d} \quad (2)$$

where d is the grating constant (lattice spacing) and $m = +1, +2, +3...$ is the diffraction order. We can write the speed of the sound in the crystal in terms of its wavelength, Λ_s , and its frequency, f_s .

$$v_s = \Lambda_s \cdot f_s \quad (3)$$

Since $\Lambda_s = d$, then combining equations (2) and (3) gives us,

$$v_s \sin(\theta) = f_s \cdot m \cdot \lambda_{incide\ nt} \quad (4)$$

Thus substituting equation(4) to (1) gives us,

$$f_d = f_{incident} \left(1 + \frac{f_s \cdot m \cdot \lambda_{incident}}{c}\right) \quad (5)$$

$$\text{Or,} \quad f_d = f_{incide\ nt} + m \cdot f_s \quad (6)$$

AOM's function can also be explained in terms of the particle nature of light. Sound waves can be thought of as made up of phonons with energy, E_s . If the incident photon has energy, $E_{incident,}$ then according to law of conservation of energy, the diffracted beam will have energy, E_d , where

$$E_d = E_{incident} + m * E_s \quad (7)$$

So, the diffracted beam will have a frequency,

$$f_d = f_{incident} + m * f_s \quad (8)$$

This is how an AOM shifts the frequency of the incident laser beam.

The Electro-Optic Modulator (EOM) in our setup is used to add RF sideband to the part of the laser beam incident on it. An EOM contains a synthetic electro optic medium, in our case a Potassium Titanyl Phosphate (KTP) crystal, whose refractive index is proportional to the electric field applied on it. As an electric field is applied to it, the light spends longer time inside the electro-optic crystal. Thus a phase change occurs to the overall beam. Initially the electric field of the laser beam is $E_o e^{iwt}$ and as it passes through the crystal it becomes,

$$E_{inc} = E_o e^{i(wt + \beta \sin \Omega t)}$$

$$\approx E_o [J_o(\beta) e^{iwt} + J_1(\beta) e^{i(w+\Omega)t} - J_1(\beta) e^{i(w-\Omega)t}]$$

For clarity let w be w_c as in frequency of the carrier and $\Omega = w_{sb}$ as in frequency of the sideband added. Thus E_{inc} becomes,

$$E_{inc} \approx E_o [J_o(\beta) e^{iw_c t} + J_1(\beta) e^{i(w_c + w_{sb})t} - J_1(\beta) e^{i(w_c - w_{sb})t}]$$

As shown in figure 1, when the two beams merge together at BS2 (Beam Splitter 2), the overall electric field becomes,

$$E = E_o \left[J_o(\beta) e^{iw_c t} + J_1(\beta) e^{i(w_c + w_{sb})t} - J_1(\beta) e^{i(w_c - w_{sb})t} + A_r e^{i(w_c + w_r)t} \right]$$

where E_oA_r is the E-field term of the frequency shifted beam of the AOM, and w_r is the frequency by which the overall carrier is shifted.

In the frequency domain the carrier, sidebands and the reference beam would look like the one in figure 6.

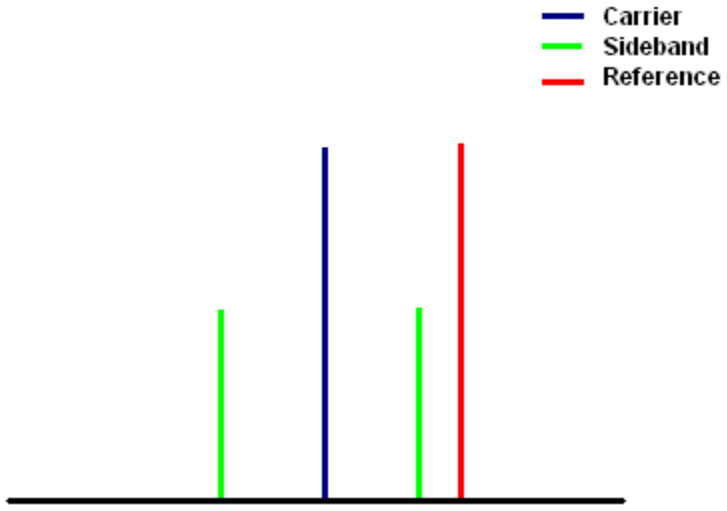

Figure 6: Frequency domain picture at BS2

The carrier and reference when combined together would produce a beat signal with a frequency equivalent to the offset of the reference beam. As I rigorously calculated the power I separated the power of the beat signal from the carrier.

The overall power is given by,

$$P = E^* \cdot E$$

So plugging in expression for E and simplifying,

$$P = P_o[{J_0}^2 + 2{J_1}^2 + {A_r}^2 + 2J_0A_r\cos(w_r)t - 2{J_1}^2\cos(2w_{sb})t + 2J_1A_r\cos(w_r - w_{sb})t - 2J_1A_r\cos(w_r + w_{sb})t] \quad (9)$$

As we are interested in how much power the camera can handle over an exposure time, τ, I calculated the integration of the power over a time segment dt.

$$\int_0^\tau P\,dt = P_o[{J_0}^2\tau + 2{J_1}^2\tau + {A_r}^2\tau + \frac{2J_0A_r\sin(w_r)\tau}{w_r} - \frac{{J_1}^2\sin(2w_{sb})\tau}{w_{sb}} + \frac{2J_1A_r\sin(w_r - w_{sb})\tau}{w_r - w_{sb}} - \frac{2J_1A_r\cos(w_r + w_{sb})\tau}{w_r + w_{sb}}]$$

The first three terms in this expression are called the DC component. To suit our case in which the difference between the frequency of the reference beam and the frequency of the sideband is very small compared to either of them, I allowed $\tau \to 1/(w_r - w_{sb})$.

Thus the integrated power becomes

$$P\tau = P_o\left[{J_0}^2\tau + 2{J_1}^2\tau + {A_r}^2\tau + \frac{2J_1A_r \sin(w_r - w_{sb})\tau}{w_r - w_{sb}}\right] \quad (10)$$

The fourth term, let us say the oscillatory term, is what we want our camera to see. So I simulated the ratio of the oscillatory part over the DC w.r.t the camera exposure time, for which I get the camera sensitivity. In between, using a photodiode, we measured the beat signal and found it to be at 1:300 of the DC level which gave us an idea of the visibility of the oscillatory term over all the DC noise.

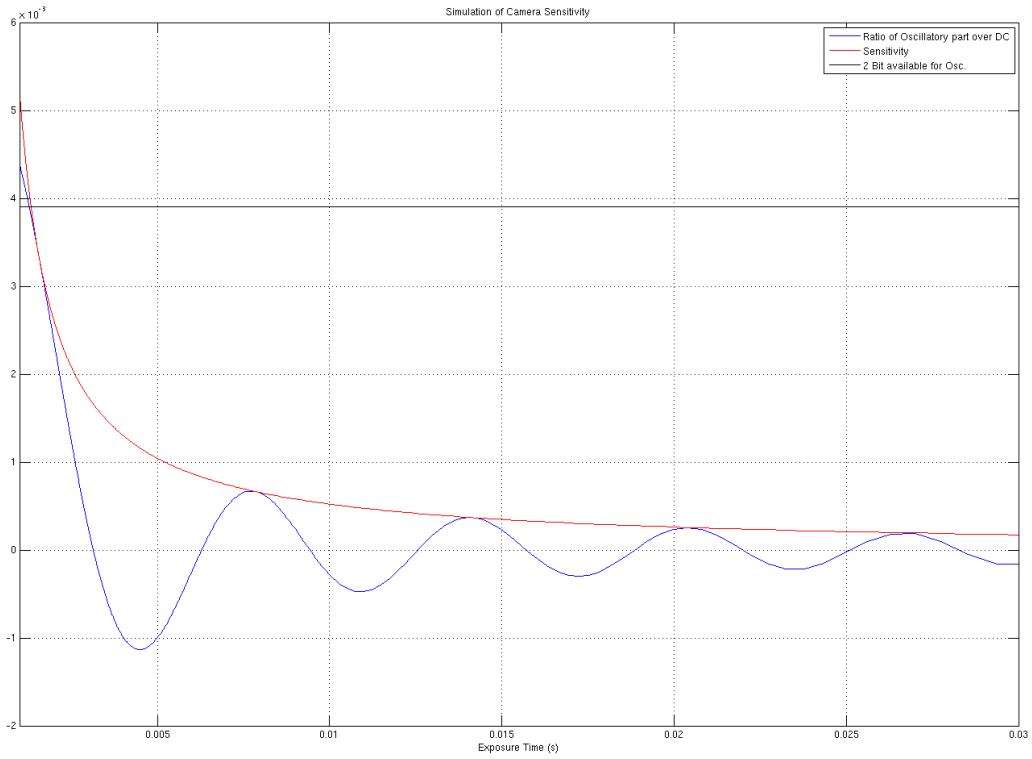

Figure 7: Camera sensitivity at the current power level

After the analytical calculation, I realigned the He-Ne setup that is currently sitting at the optics table since we changed the SM1 (Steering Mirror 1: ref Figure 1) with a silvered mirror more suited for the wavelength emitted by He-Ne laser. As of writing this report, I am on the way fixing the alignment and taking pictures with the current power level.

Project Goal for the month of July

I plan to finish the following tasks for the month of July.

1. Produce different beat signal and confirm that the camera works with the He-Ne laser setup.
2. Find a work around to the Quantum efficiency (QE) issues for the Prosilica GC750 camera currently being used. This camera has a QE of 50% at 633 nm (He-Ne laser wavelength) and less than 5% at 1064 nm (infra-red laser). This is a pressing issue once the initial He-Ne setup is confirmed to work. Besides, the CMOS chip of the camera has a built-in infra-red filter which would make detection of beat signal difficult.
3. Move to the 1064 nm laser (infra-red) setup with a confocal cavity to eliminate DC noise as much as possible
4. Test two methods proposed by my mentor for detecting the beat:
   i)Quad partition of beat signal.
   ii) Fourier transform method
5. Read about fringe analysis and phase lock techniques and applying them in the building process of the phase camera.
6. Write a code to merge the triggering of the camera and the image processing to streamline the process.

Reference

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