LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
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2-micron, HIGH QE Photodetector for Quantum Metrology

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1 Introduction and Context

The Advanced LIGO detectors are the second generation of interferometers designed with increased sensitivity to GW strain. It almost provides a factor of 10 increase in strain sensitivity over a broad frequency band. The basis of the optical configuration of the Advanced LIGO interferometer is a Michelson interferometer with a Fabry-Perot resonant cavity in each arm. This builds up the phase shift produced by an arm length change. The challenge is to make the instrument sensitive enough to measure GW strain of very low magnitude. The key to enhance the sensitivity of these interferometers can be achieved by increasing the quantum efficiency of the photodiodes. We are looking forward to a third generation of interferometers, the LIGO Voyager.

The interferometer arm lengths need to be controlled with high precision. This will keep the light resonating in arm cavities. This problem involves five degrees of freedom namely, the arm cavity lengths, the differential and common mode lengths of the interferometer and the wavelength of the laser. The laser wavelength is controlled through the pre-stabilized laser. The positions of mirrors are adjusted using magnetic actuators that push or pull on fins attached to the optics. The control signals for the actuators are derived from photodetector sensors at pick-offs at the reflected and recycling cavity ports and by detectors at the dark port of interferometer. The laser source that is employed in this interferometric setup is diode-pumped, Nd: YAG master oscillator and power amplifier system. The laser can supply up to 180 W in a single frequency of 1064 nm. Laser stabilization helps in reducing frequency and optic noise in optic systems.

The Advanced LIGO interferometers are most sensitive instruments and to enhance their sensitivity we are planning to upgrade it to Voyager. Voyager will use a 2um laser instead of the present 1064nm laser. Shifting to 2um will involve new range of technologies like, photodetectors with quantum efficiencies of greater than 99 percent, which is very important for frequency independent squeezing. The main change will be to the mirrors, or test masses, that provide the signal from passing GWs. The new test mass will be of 200-kg and made of pure crystalline silicon with amorphous-silicon coatings. The absorption level of the silicon coatings will drop off dramatically near 2um. It will help us to operate at high power levels without worrying about thermal problems. It would boost the signal-to-noise ratio significantly.

2 Objectives

The prime goal of this project is to characterize the photodiodes at the wavelength of 2um, which will also be the wavelength of the laser to be deployed in Voyager. The characterization will include enhancement of the quantum efficiency by taking into consideration the dark current, dark noise, 1/f noise, junction capacitance, shunt resistance, series resistance, of various commercially available photodiodes. We will stabilize any temperature fluctuations observed in the photodiodes using the inbuilt thermoelectric cooler and an additional thermistor.

Furthermore, the output of the diodes will be used to measure laser fluctuations and also to actively stabilize the frequency and intensity of the laser using a closed feedback loop.

3 Experiment overview and approach

3.1 Components of the setup

We plan to use photo-diodes like HgCdTe, InGaAs with they being sensitive to the wavelength of the corresponding laser under use. These diodes have a built in Thermal Electric Cooler (TEC) which reduces thermal noise. OP27 can be used for the purpose of trans-impedance amplifier. A thermistor is to be used for the temperature measurement and control. In the end the output of TIA can be fed to the computer to perform any signal processing using python.

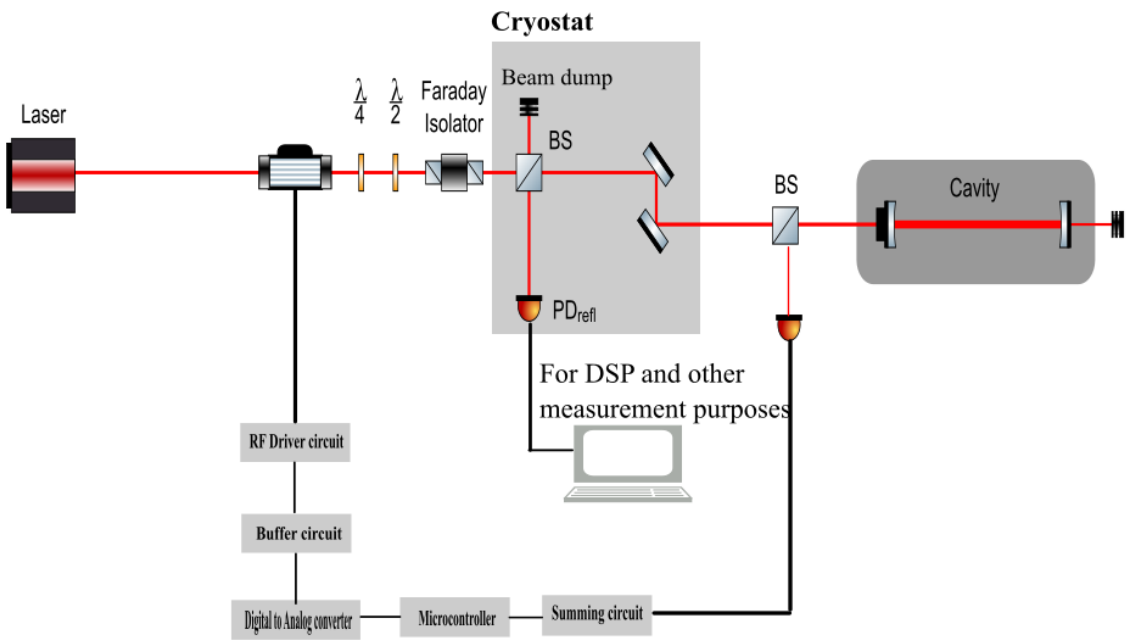


Figure 1: Experimental Setup

3.2 Quantum Efficiency of Photodiodes

The quantum efficiency N, of any photo-diode is defined as the fraction of incident photons that contribute to the photo-current.

$$Q.E. = \frac{R_{\lambda observed}}{R_{\lambda ideal}} = R_{\lambda}\frac{hc}{\lambda q} = 1240\frac{R_{\lambda}}{\lambda} \tag{1}$$

$$R_{\lambda} = \frac{I}{P} \tag{2}$$

where $h = 6.63 * 10^{-34}$ J-s, is the Planck constant, $c = 3 * 10^{8}$ m/s, is the speed of light, $q = 1.6*10^{-19}$ C, is the electron charge, R_λ is the responsivity (ratio of incident photocurrent I, to the incident light power P at a given wavelength) in A/W and λ is the wavelength of light in nm.

LIGO requirements call for a net quantum efficiency of 80% from the beam splitter to the detection electronics.

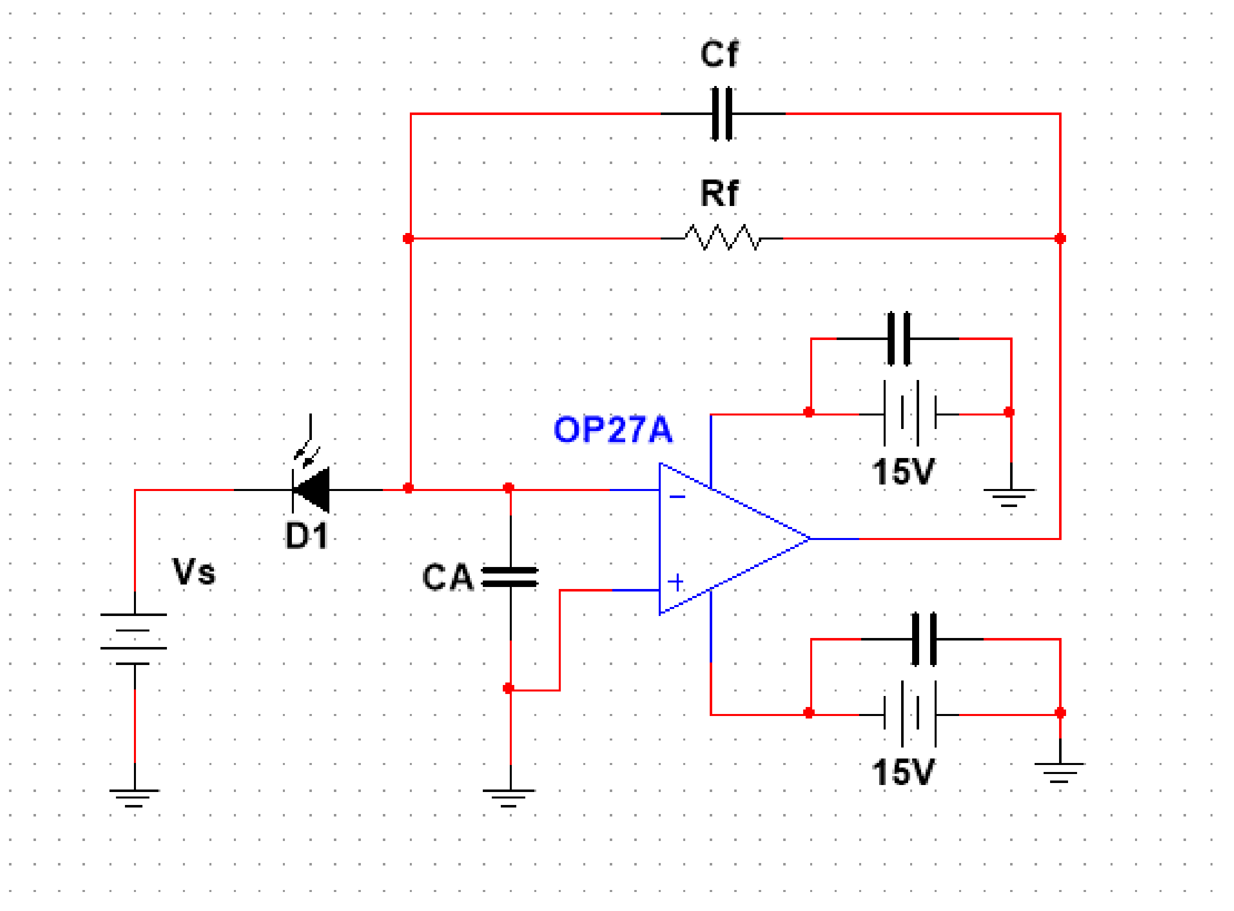


Figure 2: Circuit setup of Photodiode and TIA

A trans-impedance amplifier circuit can be used to measure the output current of the photo-diode. The corresponding photo-diode can be reverse biased and additionally connected to an op-amp with a resistor in feedback loop. This results in smaller photo-diode capacitance but an increase in dark current, temperature drift and noise. In order to keep minimum errors, the bias voltage must be very clean; meaning low noise and good temperature stability. The output voltage will be directly proportional to the input current applied at the inverting terminal of the op-amp. Spike transitions can be observed, however, if the feedback resistor is switched to other values in order to change the gain during signal acquisition. The photo-diode will be kept inside the cryostat and the rest of the electronics will be outside to avoid any out-gassing that may occur. We will use probes in order to measure the current from the photo-diode and send them to the TIA.

3.3 Laser Stabilization

The summing current of the diode can be obtained by connecting them in parallel. We can measure the output current by using a low noise operational amplifier. A closed loop feedback system can be used to stabilize the frequency of the laser under test.

We can use an AOM (Acoustic optical modulator) to stabilize the intensity of laser beam. We can use an AOM and use an RF driver in order to drive it. The RF driver accepts two DC voltages as input. One controls the intensity and the other the frequency of modulation. A microcontroller can be used for compensating any fluctuations by reading the signal from the photodiode and sending the output voltage to the intensity control input on the RF driver. The PID algorithm programmed on the microcontroller can constantly perform voltage corrections as needed.

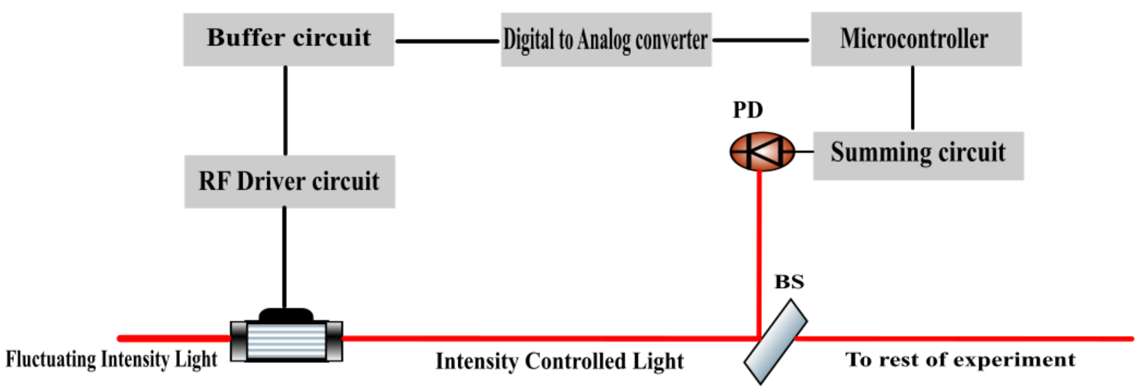


Figure 3: Circuit setup for laser stabilization

3.4 Noise Measurement

The noise floor for this system is determined by noise features of the photodiodes, quantum noise and thermal noise.

Several sources are responsible for the photodiode noise, mainly, shot noise, thermal noise (Johnson noise), flicker noise ($1/f$ noise) and generation-recombination (G-R) noise. Material properties of the various electronic components used, will contribute to the thermal noise of the system.

The photodiode is represented as an equivalent resistor, Rd in parallel with a capacitor, Cd in series with resistance Rs. The total noise of the diode will be the sum of all its components.

The fluctuations in the flux of the electron and hole currents that carry the electrical current, result in the shot noise. The shot noise current for a reverse biased photodiode is,

$$\overline{(i_{shot})^2} = 2qI_d\Delta f \tag{3}$$

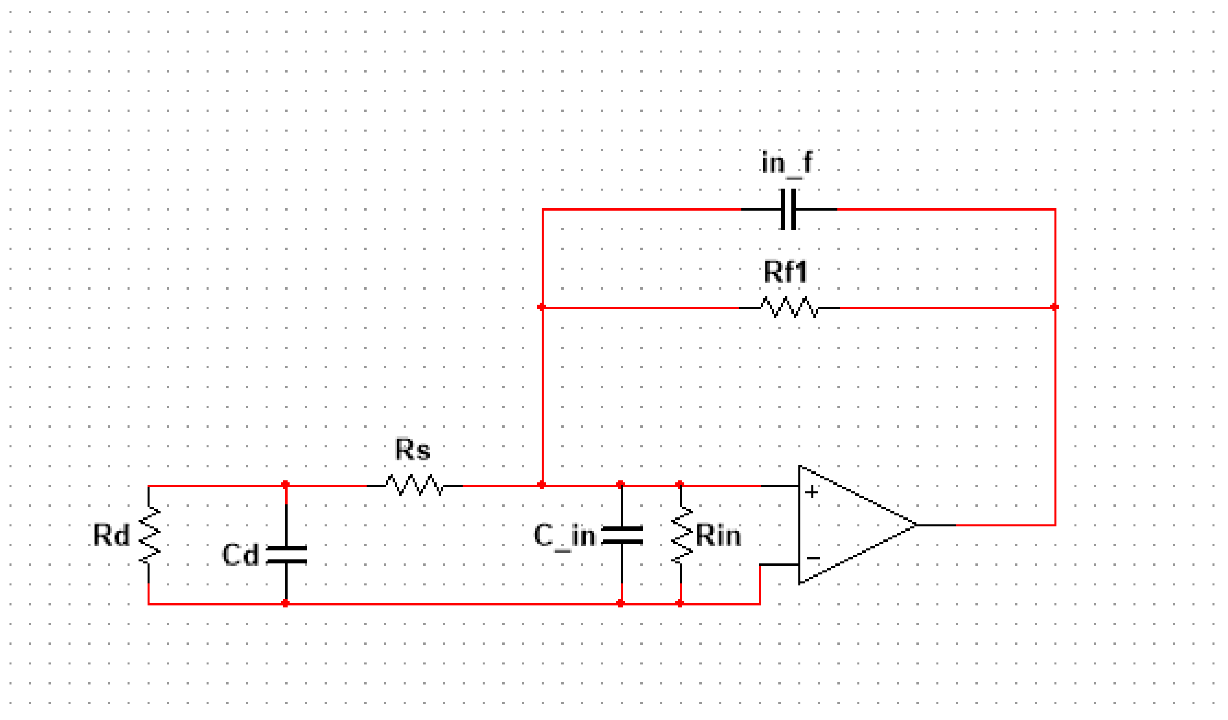


Figure 4: The Equivalent noise circuit for a photodiode

Where, q is the electron charge, I_d is the photodiode current, and Δf is the noise equivalent bandwidth (NEB).

The noise at low frequency may be contributed from two sources. One is the flicker noise that dominates at low frequencies. It is one of the main limiting factors in detection sensitivity. The current spectral density of the flicker noise can be evaluated using the semi-empirical expression:

$$S_{i,1/f} = \frac{I_{dark}^{\beta} k}{f^{\gamma}} \tag{4}$$

Where, I_{dark} is the diode-dark current, k and γ are the coefficients of the photodiode that depend on fabrication process like quality and technology, β value is an empirical constant that depends on the doping, and f is the frequency.

Another noise component that is contributed by low frequency is the generation recombination (G-R) noise. The fluctuations in the carrier flux due to generation, recombination, and trapping of carriers in semiconductors are manifested as noise due to variation in the number of free carriers. The spectral response of G-R noise is almost uniform up to a frequency which is determined by the lifetime of the carriers in the photodetectors.

Photodiode dark noise arises due to dark current which varies directly with temperature in photoconductive mode. A differentiating circuit can be employed whose output will be the voltage that reflects the difference of the currents. The corresponding noise can then be measured.

The photodiode noise can be approximated by the following expression, which takes into account the 1/f noise, shot noise and thermal noise,

$$\overline{i_{Pd}^2} = \overline{i_{1/f}^2} + \overline{i_{shot}^2} + \overline{i_{pd\_th}^2} \tag{5}$$

On the other hand, variable laser power will contribute to the quantum noise. Technical noises any arise due to laser frequency and flicker noise from TIA.

3.5 Temperature Stabilization of Photodiodes

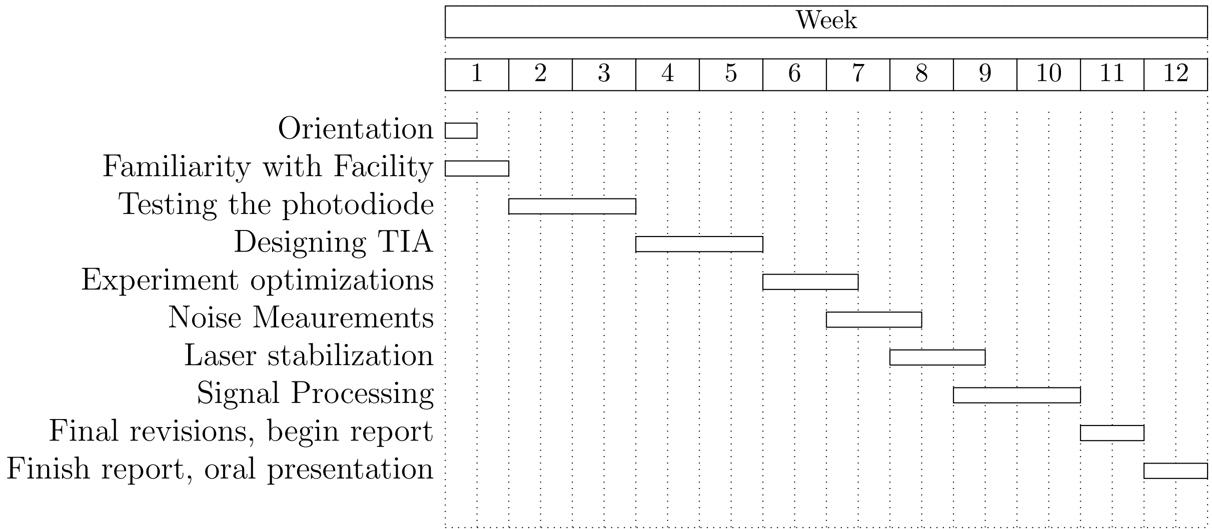
A thermistor can be used to measure the temperature fluctuations in the photo-diode. The output of the thermistor can be fed to the inbuilt Thermo-electric cooler in photodiodes, which can in turn perform the temperature stabilization. If the detector is cooled, it is also practical to cool the amplifier.

3.6 Signal Processing

The output obtained from the trans-impedance amplifier can be fed to a micro-controller. The corresponding noise in the output can be removed using python for signal processing. The respective micro-controller can be programmed in such a way to calculate error due to variations in output and perform the respective calculations using a PID algorithm.

4 Project Timeline

In this twelve-week program the first and last week will be reserved primarily for orientation and project reports, respectively. Following the first week which will involve being familiar with the equipment, we will start with testing the photodiode for the various noise that is contributed by its components. The next week can be spent in designing the transimpedance amplifier. The following week can then be utilized in optimizing the setup. We can then move to performing laser stabilization using the photodiode output. The Signal Processing can be put for the last, when we complete the optimization of the setup.



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