Measuring the quantum efficiency of a photo diode using radiation pressure

Scott Rager
Penn State University

Abstract

Quantification of the performance of instruments used in taking scientific data is important in determining the amount of error and reliability of the data taken using these instruments. The goal of this project is to measure the quantum efficiency of a photo diode, which describes how well the photo diode converts light photons into electric current. The common method of measuring quantum efficiency utilizes a power meter to measure a laser's power along with the photo diode. This paper describes the theory and implementation of an experiment that attempts to determine quantum efficiency using radiation pressure. This experiment is a novel approach that utilizes a Michelson interferometer and very light mirror with a mass of only 20 mg. If successful, this project will be able to determine the photo diode's quantum efficiency with an error of less than 1 %, a dramatic improvement over the common method of measurement using a power meter.

1. Introduction

Experimental scientists rely on a variety of instruments to record data from experiments. Without these instruments, developing and proving scientific theories would be impossible. With modern technology, the ability to develop instruments that exhibit better performance and accuracy has dramatically increased. With any real device, however, some sources of imperfections will always cause a source of error in any experimental data taken. Knowing this fact, scientists need to know the accuracy and the limitations of their data-taking devices in order to have an understanding of how accurate their actual data is.

In gravitational wave detection, the most common experimental setup device is an interferometer. While an interferometer has an inherent ability to detect very small changes in distance and many advancements in interferometry have been developed to help further the field of gravitational wave research, further research on interferometry and improving its sensitivity will broaden the range in detectable gravitational waves, thus increasing the chances of detecting a gravitational wave successfully .

An interferometer relies on data taken by measuring the intensity of a laser using a photo diode. Photo diodes, like any real life device, have imperfections that reduce its performance from that of its theoretical abilities. The function of a photo diode is to convert light into voltage. Quantum efficiency is the quantification of the photo diode's ability to perform this task.

1.1 Definition of Quantum Efficiency

In order to fully understand what quantum efficiency (QE) is, a basic understanding of how a photo diode operates is necessary. A basic photo diode is a PN junction. When a photon with sufficient energy strikes the depletion region of the PN junction, its energy is absorbed and an electron-hole pair is created. Because of the intrinsic electric field present in the depletion region, the electron and its corresponding electron-hole created by an incident photon are accelerated in opposite directions. When the PN junction is connected in a circuit, this motion creates a current. Ideally, this current contains one electron for every photon that strikes the photo diode.

In reality, the current output of the photo diode is not perfect. In other words, the number of electrons in the output current of the photo diode is not equal to the number of photons in the incident light. Since the photo diode's operation is a quantum process, the examination of how well it performs its desired task can be thought of on the quantum level as well. The quantification of its performance evaluation is known as the photo diode's quantum efficiency, and is given by the ratio of the number of electrons per second, N_e, in the output current and the number of photons per second, N_P, in the light that hits the photo diode, as in the equation

$$QE = \frac{N_e}{N_P} \quad . \qquad (1)$$

The first step we took in attempting to determine the quantum efficiency of a photo diode was measuring a laser with both a photo diode and a power meter to obtain the values of N_e and N_P. This method is not original and contains an error larger than the goal of this project. It does, however, provide primary values for the quantum efficiency of the photo diode that can be used in comparison to the results of a new experimental approach that determines the quantum efficiency using radiation pressure and help to reassure its validity.

2. Theory

2.1 Theory of Using Power Meter to Measure QE

The first piece of information necessary to calculated the quantum efficiency (QE) of a photo diode is the number of electrons per second in the current being output by the photo diode. This value is found by measuring the output voltage of the current to voltage converter circuit in which the photo diode operates. This voltage, then, is simply related to the output current of the photo diode by Ohm's law. In order to be sure that the voltage used in calculating the output current is entirely a result of the incident light, though, the voltage output by the photo diode circuit with no incident light, also known as the dark voltage, V_{Dark}, is first recorded and subtracted from all voltage measurements with incident light, $V_{Measured}$. The current being output by a photo diode for a particular laser power is then given by,

$$I = \frac{V_{Measured} - V_{Dark}}{R} \quad , \qquad (2)$$

where R is the value of the resistance in the current to voltage converter of the photo diode's circuit, as shown in fig. 1. This value of resistance is measured using a multimeter.

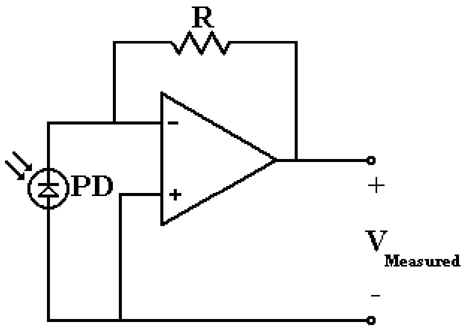

Fig. 1 – Current to Voltage Converter Circuit of Photo Diode (PD)

The desired value of the number of electrons per second in this current, N_e, then, is simply the current divided by q, the charge of a single electron, as in

$$N_e = \frac{I}{q} \quad . \qquad (3)$$

The second piece of information needed to determine QE is the number of photons in the incident light being measured. This value can be found by using the power of the laser measured with a power meter. Light power, P, can be expressed as the number of photons hitting the photo diode per second, N_p, multiplied by the power of each photon. The power of a photon is the product of its frequency, ν, and Planck's constant, h. Combining these two relations,

$$P = N_p * h * \nu \quad . \qquad (4)$$

Rearranging equation (4), the number of photons per second can be determined from the light's power and frequency,

$$N_p = \frac{P}{h * \nu} \quad . \qquad (5)$$

After using both the photo diode and power meter, the values of N_e and N_p are divided to get the photo diode's quantum efficiency as defined in equation (1).

2.2 Theory of Using Radiation Pressure to Measure QE

In order to measure QE without using a power meter, a different process must be developed. One possible method would be to measure the effect of radiation pressure on a suspended mirror. First, Consider the momentum of a single photon, given by its power divided by the speed of light, c,

$$p=\frac{h*v}{c} \quad . \qquad (6)$$

When a photon with this momentum is reflected by a suspended mirror, the change in momentum experienced by the mirror from that photon is twice that of the reflected photon's original momentum,

$$\Delta p=\frac{2*h*v}{c} \quad . \qquad (7)$$

Now, by multiplying this change in momentum due to each photon by the number of photons being reflected per second, N_p, the entire change in momentum of the mirror can be considered to determine the force exerted on the mirror,

$$F=\Delta p=\frac{N_p*2*h*v}{c} \qquad (8)$$

Using the relation of laser power in equation (4) and the equation of motion, then, the motion of the mirror can be described by

$$F=m*\ddot{x}=\frac{2*P}{c} \quad , \qquad (9)$$

where P is the power of the laser, m is the mirror's mass, and x is the mirror's displacement along the axis of the photons' propagation. If the power of the laser is modulated at a certain angular frequency, ω, then the response of the mirror's motion can be obtained by taking the Laplace transformation of equation (9). The result is

$$m*\omega^2*X=\frac{2*P}{c} \quad , \qquad (10)$$

where X is the displacement of the mirror in the frequency domain.

If the power of the laser used is on the order of watts or less, then the resulting motion of the mirror will be on the order of nanometers or less, depending on the exact power and the mirror's mass.

A good way to detect motion of this magnitude is a Michelson interferometer. The output voltage read by a photo diode on the Michelson interferometer's antisymmetric port as a function of the difference in its two arm lengths, X, is given by

$$V_{PD}=\frac{V_{Max}-V_{Min}}{2}*\sin\left(\frac{2*\pi*X}{\frac{\lambda}{2}}\right)+\frac{V_{Max}+V_{Min}}{2} \quad , \qquad (11)$$

where λ is the laser light's wavelength. Replacing $V_{Max}-V_{Min}$ with V_o and differentiating with respect to the independent variable, X, shows the output voltage's response to changes in the difference in arm lengths of the interferometer,

$$\frac{dV_{PD}}{dX}=\frac{2*\pi*V_o}{\lambda}*\cos\left(\frac{2*\pi*X}{\frac{\lambda}{2}}\right) \quad . \qquad (12)$$

At the mid-fringe of this signal, the response in voltage to changes in X is approximately linear, so the interferometer can be locked at this point using a feedback control loop. By doing this, the cosine term in equation (12) is held at one, and the equation can be simplified to

$$\frac{dV_{PD}}{dX}=\frac{2*\pi*V_o}{\lambda} \quad . \qquad (13)$$

Rearranging this relation shows explicitly the amount of change in the difference in arm lengths for a given change in observed voltage on the photo diode's output,

$$dX=\frac{\lambda}{2*\pi*V_o}*dV_{PD} \quad . \qquad (14)$$

Since λ is known and V_o is measured with the photo diode, equation (14) allows the change in difference in arm lengths to be calculated directly by measuring an observed change in voltage.

In the Michelson interferometer designed for this experiment, the change in difference in arm lengths of the interferometer will be dominated by the motion in only one of the two mirrors at the arms. This mirror has very little mass and should be able to be moved by the changing radiation pressure of an intensity-modulated laser. Knowing this fact, equations (14) and (10) can be combined and rearranged to determine the power of the laser,

$$P = \frac{m * c * \omega^2 * \lambda}{4 * \pi * V_o} * dV_{PD} \quad . \qquad (15)$$

Once determining the number of photons per second, N_P, in the laser can simply be found using equation (5).

After finding the number of photons per second in the laser, only the number of electrons per second, N_e, needs to be found to determine quantum efficiency. Since the value of N_P is based on the power of the laser striking the mirror on one arm of the interferometer, the photo diode must be placed in front of this mirror in order to be certain that it is measuring the laser of the same power. After taking data from the photo diode place at the correct position, the same calculations as those used in measuring QE with a power meter are used. These calculations are outlined in equations (2) and (3). Once the value of N_e is found, it can be divided by N_P to get the quantum efficiency of the photo diode.

3. Experimental Setup

3.1 Experimental Setup and Procedure of Measuring QE Using Power Meter

The experimental setup used to measure the quantum efficiency of a photo diode using a power meter is shown in fig. 2. Besides the laser, it consists of a Faraday isolator, two half-wave plates, two polarizing beam splitters, a power meter, and the photo diode. The laser beam is first aligned through the Faraday isolator to eliminate any back-reflections into the laser, which could cause undesired changes in frequency. Next, the beam is passed through a half-wave plate (HWP) and polarizing beam splitter (PBS). The HWP plate allows the polarization of the light to be changed, which will also change the amounts of light being transmitted and reflected by the PBS. Therefore, using the HWP, the power of the reflected light coming from the beam splitter can be adjusted. Here, another HWP and PBS combination is used to decrease the laser's power further in order to achieve a wider range of power levels within the photo diode's detection range. Finally, the light being reflected by the second beam splitter is aligned onto a photo diode or power meter to be measured.

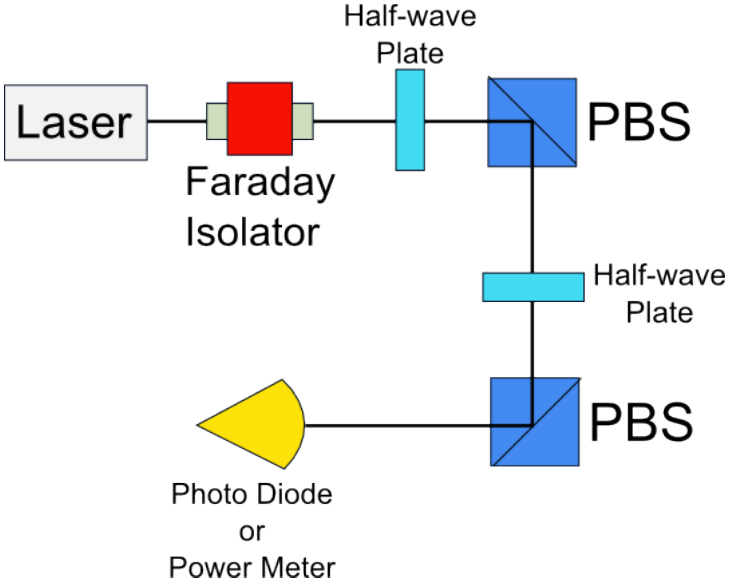

Fig 2 - Experimental Setup Used for Measuring QE with Power Meter

Using this setup shown in fig. 2, the first step required was to measure the photo diode's output without being exposed to any laser light. This value is recorded as V_{Dark}. Then, the laser light being reflected by both polarizing beam splitters is aligned onto the photo diode, and both half-wave plates are adjusted to minimize its power at the photo diode. At this minimum power, the voltage of the photo diode is recorded, and the power meter is inserted directly in front of the photo diode to measure the power of the laser at the same point. Once both the voltage of the photo diode and power of the laser are recorded, one or both half-wave plates can be adjusted to increase the power of the laser after the second PBS and both measurements are taken again. This process is repeated until the saturation voltage of the photo diode is reached. Finally, the quantum efficiency of the photo diode can be calculated at each separate power level measured and the results can be compared.

3.2 Experimental Setup and Procedure of Measuring QE Using Radiation Pressure

The experimental setup we built to measure the quantum efficiency of a photo diode utilizing radiation pressure is shown in fig. 3. The laser, along with some general optical components, was placed on an optical table. Again, a Faraday Isolator was used to eliminate any back-reflections from reaching the laser, and a half-wave plate (HWP) and polarizing beam splitter (PBS) combination allowed the power of the laser to be adjusted. Throughout the laser's path, several focusing lenses were also placed to control the size of the laser beam. Another component of interest is the 90 % beam splitter used to direct the beam toward the interferometer. This splitter allows 10 % of incident light to be transmitted. Therefore, the interfering light being directed back in the opposite direction of the injected light in the interferometer can be measured via the light transmitted by the beam splitter. This signal is the symmetric port of the interferometer.

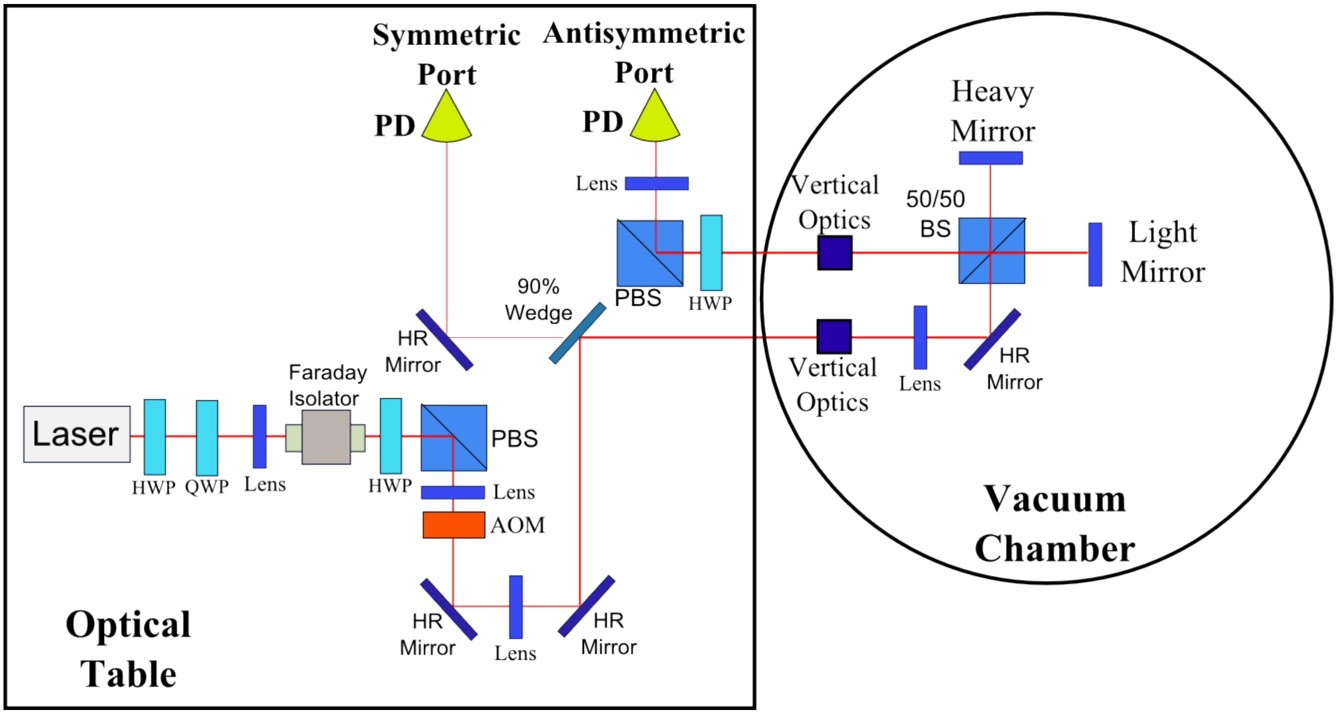

Fig. 3 - Experimental Setup to Measure QE Using Radiation Pressure

The Michelson interferometer and its components were placed in a vacuum chamber on three sets of stacks in an attempt to isolate it from unwanted noise, but the chamber has not been sealed thus far in the experiment. Since the optical table was higher than the bottom of the vacuum chamber, mirrors placed on a vertical pole, labeled “Vertical Optics” in fig. 3, were placed in the chamber to direct the laser beam down to the level of the interferometer, and then back up to the level of the table.

The 50/50 beam splitter was placed on an adjustable holder so that it could be used in conjunction with the adjacent mirror to help align the interferometer like a set of two steering mirrors.

The mirrors at the end of the two arms of the Michelson interferometer were specially designed for this experiment. The mirror labeled as the “Light Mirror” is 3mm in diameter with an actual coating area of only 2 mm in diameter. Because of its small reflective area, great care was taken to ensure that the laser size at the mirror's surface was small enough to be entirely on the mirror's reflective surface to reduce loss of power.

This light mirror is also only 1.5 mm thick and has a mass of only 20 mg. It is suspended by a silica fiber with a diameter of 10 μm in a double suspension setup using a 20 mg middle mass and eddy-current damping as seen in fig. 4. This suspension has a high Q-factor, which, along with the mirror's small mass, should allow the mirror to be moved by the intensity-modulated laser beam.

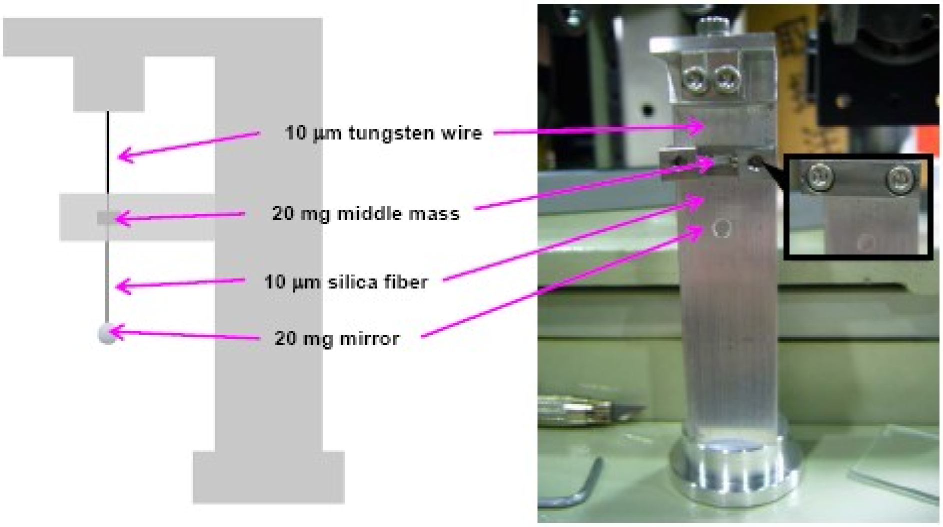

Fig. 4 - Light Mirror in Suspension

The other mirror used in the interferometer, labeled as the “Heavy Mirror” in fig. 3, is a standard, one inch diameter, high-reflectivity mirror. It is suspended using 50 μm diameter wire in a setup that also takes advantage of eddy-current damping. This mirror's mount also contains four cylindrically shaped permanent magnets on its back side that are used in conjunction with actuators to lock the interferometer. This mirror's larger mass along with its suspension and feedback control keep it from being affected greatly by the changing radiation pressure of the laser. This fact allows us to attribute changes in differences in the arm lengths of the interferometer to the motion of the light mirror.

The signal seen on the photo diode on the antisymmetric port was used to lock the interferometer at the mid-fringe of its output. This signal was fed into a servo, which changed the position of the heavy mirror using electromagnetic actuators and the permanent magnets on the heavy mirror mount.

4. Results

Fig. 5 shows the voltage of the photo diode on the antisymmetric port as we adjusted the gain of the servo and successfully locked the interferometer.

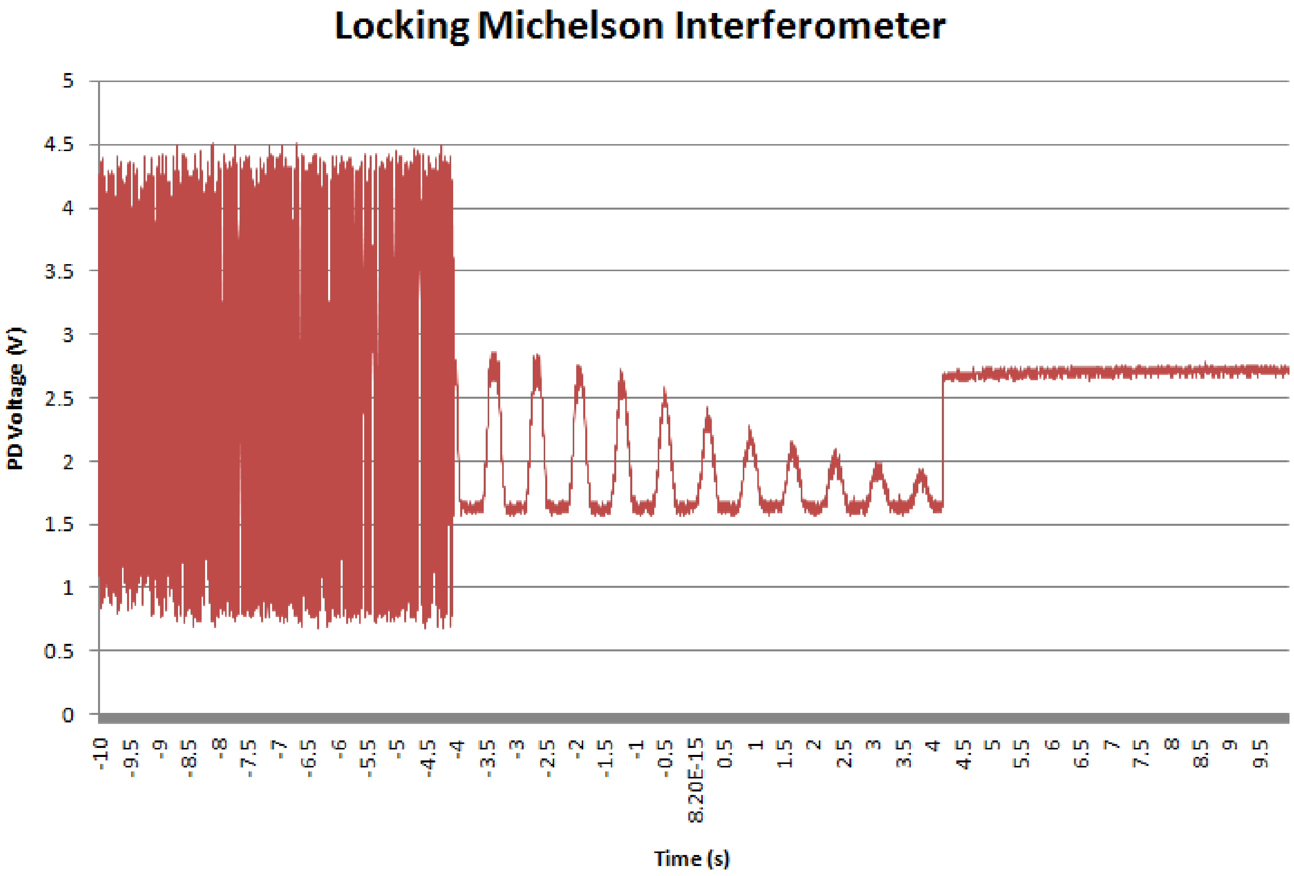

Fig. 5 - Antisymmetric Port Output While Locking the Interferometer

Once the interferometer was locked, we were able to begin modulating the laser's intensity and determine whether this modulation caused any motion in the light mirror's position. We decided to subtract the signals from the symmetric and antisymmetric ports and adjust the power of the laser on the antisymmetric port using the HWP and PBS until the difference between the two signals was minimized (approximately zero). This signal resulting from the subtraction was the signal that we measured in attempting to observe motion due to radiation pressure.

After minimizing the difference signal, we first measured the response of the interferometer at a modulation frequency of 2 kHz as a control for the experiment. At this high of a frequency, the mirror should not be able to move fast enough due to changing radiation pressure, so we should not see any changes in the measured signal when different amplitudes of intensity modulation are applied to the laser beam. Then, after ensuring that changes in amplitude of the modulation do not dominate the signal being measured, the laser's modulation frequency can be decreased. At a low enough frequency, such as 2 or 20 Hz, the mirror should exhibit some resonant motion due to the laser's modulation, which should be apparent by measurement of the subtracted signal with an FFT.

4.1 Results of Measuring QE Using Power Meter

We were able to measure the QE of the laser at power levels less than 2.0 mW without causing our photo diode to be saturated. These power levels correspond to photo diode voltages less than 14.2 V. The measured value of resistance in our op-amp current to voltage converter was 9.97 kΩ. Fig. 6 shows a graph of QE for different power levels of the laser with error bars of ± 3%.

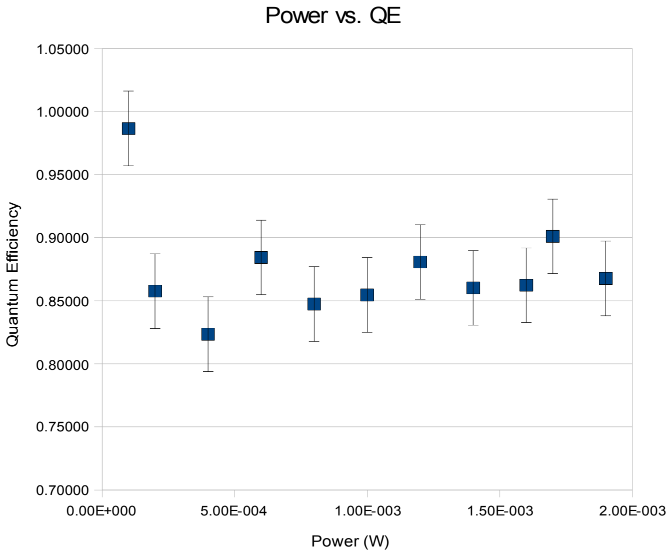

Fig. 6 – Plot of QE vs. Power

4.2 Results of Measuring QE Using Radiation Pressure

As seen in fig. 7, the difference signal of the two ports of the interferometer measured by an FFT shows no noticeable difference at 2 kHz as the amplitude of the signal driving the AOM is varied from 0 to 5 volts at the same frequency. Only a slight difference is witnessed at the maximum driving amplitude of 10 volts. These results show that responses at lower frequencies with may be witnessed motion of the light mirror due to changing radiation pressure.

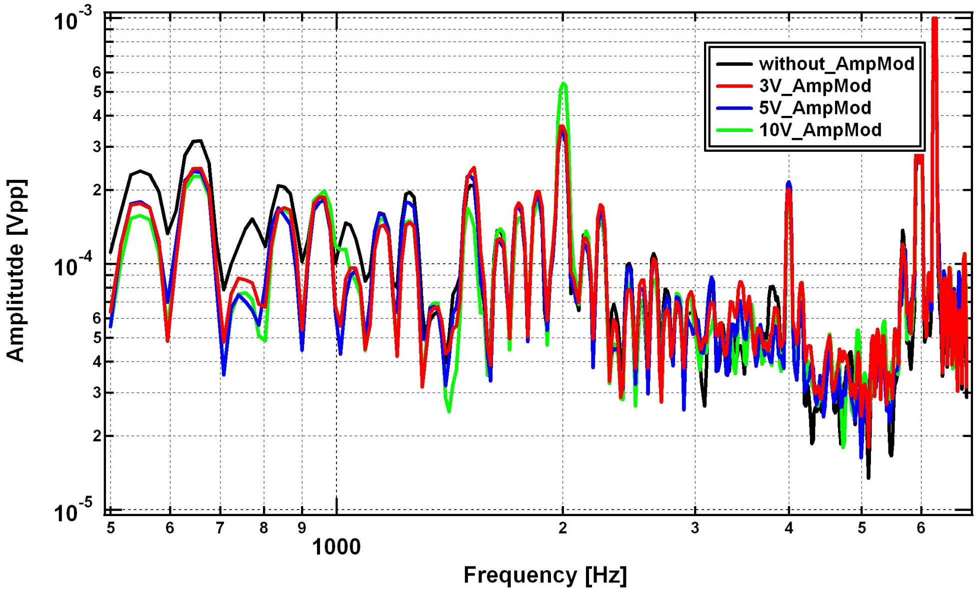

Fig. 7 - Interferometer's Response to Different Amplitude Modulation at 20 kHz.

Figs. 8 and 9 show the output with the AOM being driven at 20 Hz and 2 Hz, respectively, each with amplitudes varying from 0 to 10 volts. At these frequencies, we expect that a large enough change in radiation pressure should produce observable harmonic motion of the light mirror. As these figures show, however, the amplitude of the interferometer's response does not increase as the amplitude of the modulation increases. Therefore, we can conclude that no significant motion in the light mirror is currently being caused by the effects of radiation pressure.

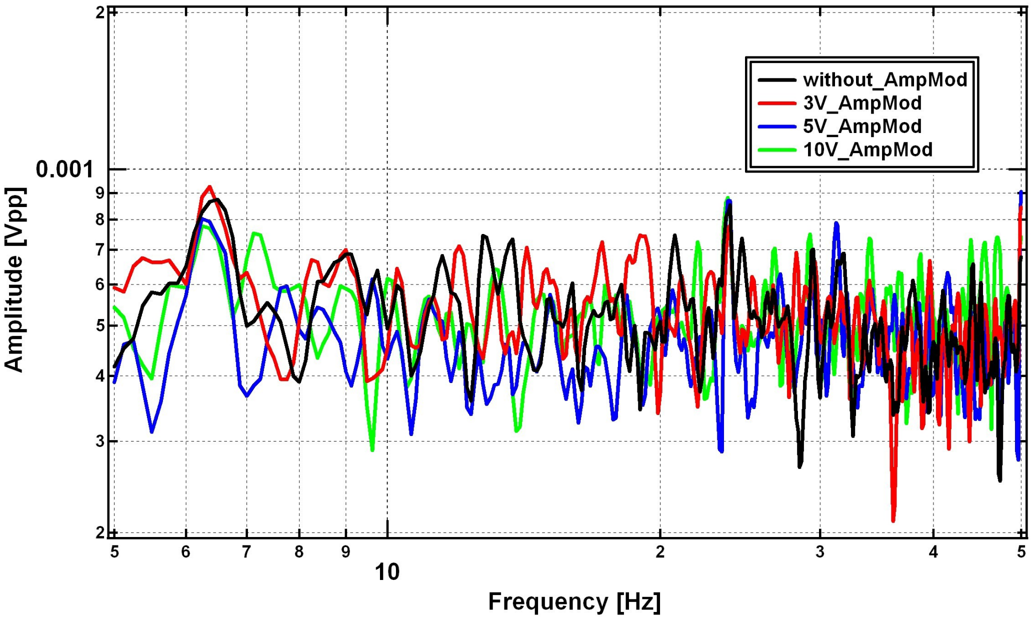

Fig. 8 - Interferometer's Response to Varying Amplitude Modulation at 20 Hz

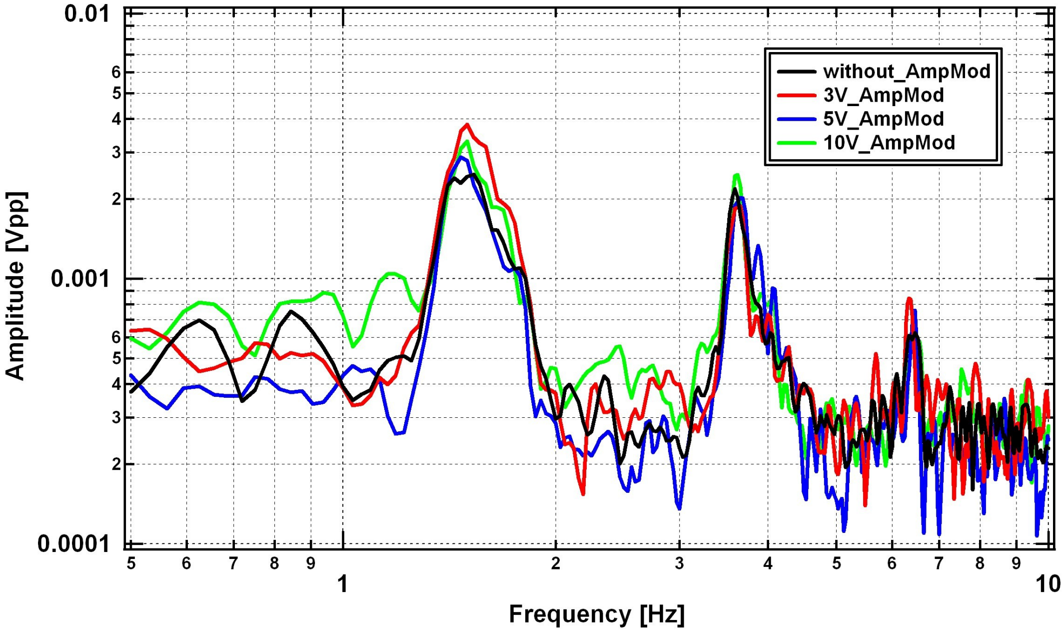

Fig. 9 - Interferometer's Response to Varying Amplitude Modulation at 2 Hz

5. Summary and Future Work

We were attempting to measure the quantum efficiency of a photo diode using an entirely new method that relies on moving a mirror with radiation pressure. We were able to build and lock a Michelson interferometer that we believe should be able to detect motion due to changing radiation pressure. We were also able to observe an output signal that was unaffected by high frequency modulation. To date, however, we were unable to produce any data that suggests motion of a mirror due to the effects of radiation pressure.

This project will, though, be continued in my absence, and changes will be made that will hopefully produce the desired results. Some possible changes include increasing the power of the laser in the interferometer, achieving better alignment of the interferometer, and placing the interferometer in vacuum. Since this experiment has never been performed before, no proof exists that it will produce a conclusive effect, but every possible effort will be made to achieve such data.

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