LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
-LIGO-
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Experiment to Test the Feasibility of Photon Actuation for Advanced LIGO Length Control Systems

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This is an internal working note
of the LIGO Project.

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Experiment to Test the Feasibility of Photon Actuation for Advanced LIGO Length Control Systems

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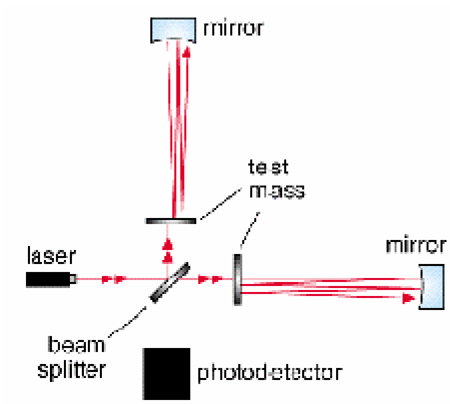
The photon actuation experiment is designed to test the feasibility of photon actuation on the end test masses of Advanced LIGO. Photon actuation would provide length control of the lower stages of the quad-pendulum mirror suspensions for Advanced LIGO while introducing minimal thermal noise. Photon actuation would correct for noise in the middle of the frequency band, with the length-control systems currently in place at the LIGO sites actuating above and below this range. The end mirror of the mode cleaner at Caltech's 40-meter site was used for this first test of photon actuation. A laser intensity stabilization control loop was designed to insure that intensity noise from the laser would not introduce significant noise to the mode-cleaner mirror. Photon actuation will then be tested on the mode-cleaner cavity to see if significant noise suppression occurs within the frequency bandwidth that was chosen.

1. Introduction

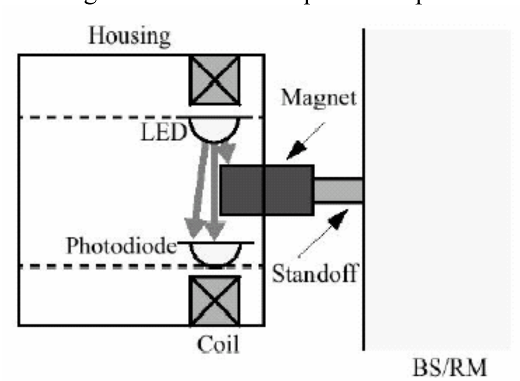
1.1 Background

The LIGO interferometers are designed to detect gravitational waves that were predicted by Albert Einstein with the theory of general relativity. These gravitational waves are predicted to yield fractional changes in length of less than 10^{-21} ($\Delta L/L$). This means that even with the 4 km arms that were installed at the sites in Hanford, Washington and Livingston, Louisiana, the LIGO interferometers must attempt to detect changes in the lengths of the arms of no more than 10^{-18} m. These distances are tiny even in comparison to the diameter of an atom ($\sim 10^{-10}$ m) or the diameter of a nucleus ($\sim 10^{-15}$ m). Thus, the LIGO interferometers require extremely precise length controls on the mirrors in their arms in order to allow the possible gravitational-wave signals to appear above the noise inherent in the system. In particular, the LIGO project uses a Michelson interferometer with Fabry-Perot cavities in the arms for higher precision (See Fig. 1). Light from the laser is split into two equal parts and then sent to the arms of the interferometer. There the light that enters the arms is stored there for hundreds of bounces, effectively increasing the lengths of the arms. If there is no gravitational-wave signal, the beams that return to the beam splitter, when combined, destructively interfere, giving no signal at the photodetector. In the presence of a gravitational wave a difference of phase would develop in the arms of the interferometer, allowing for partial constructive interference and signal at the photodetector. For general information on using interferometers to detect gravitational waves, see [1].



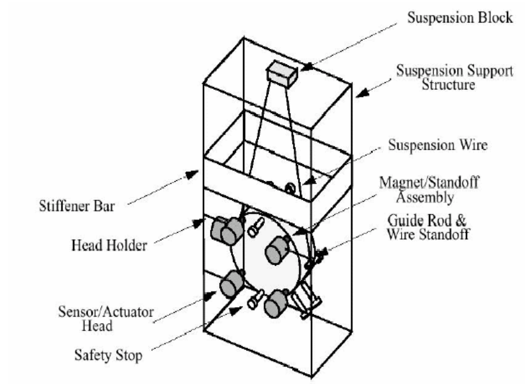
AJW, Caltech/LIGO, 6/20/02
(Figure 1 – Layout of LIGO Interferometer)

In the current LIGO system, all of the primary optics are suspended by wires to isolate them from seismic noise. At present, the mirrors' motion is controlled by the OSEMs (Optical Sensor/Electro-Magnetic actuators). These devices, as shown below, sense the position of the mirror by registering the shadow of the magnet thrown by the magnet on a photodiode. The magnet can then be actuated upon by running current through the coil that surrounds it, restoring the mirror to the equilibrium position.



AJW, Caltech/LIGO
(Figure 2, OSEM actuator)

These OSEMs are then attached to each of the mirrors in five places, allowing for control of all degrees of freedom of the pendulum. (See figure 3)



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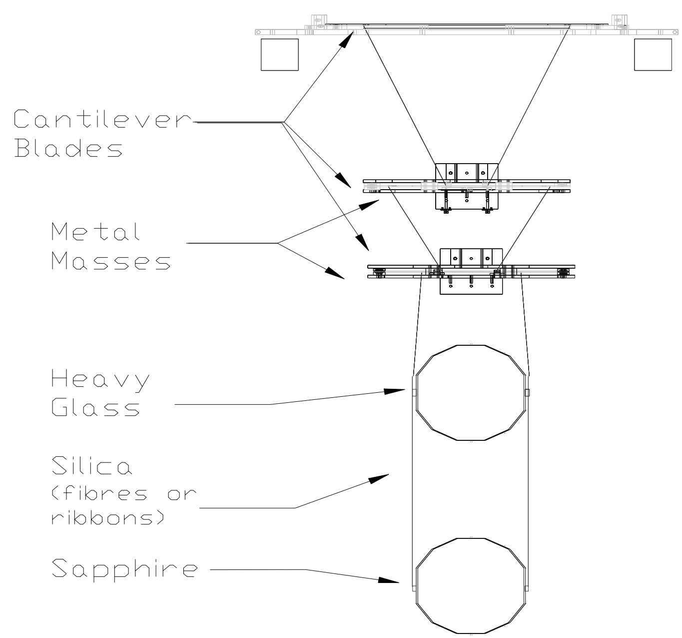
(Figure 3 – OSEM control of mirror motion)

The OSEMs can effectively damp motion of the mirror that is at low frequency (up to ~100 Hz). Yet, attaching the magnets to the mirrors greatly increases the thermal noise of the optics. Thus, for Advanced LIGO design, which is set to replace the current design as early as 2008, a method of length control that does not need to attach anything to the mirrors would be desirable. The proposed optic design for Advanced LIGO involves a quad-pendulum suspension (Figure 4). OSEMs would still control the motion of the upper stages; however, a new method would be desirable for actuation on the lowest test mass. Photon actuation would be one such method.



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(Figure 4 – Advanced LIGO optical suspensions)

1.2 Objective

Photon actuation would involve using photon pressure from a laser beam to push on the lowest stage of the quad-pendulum, thus controlling the length. Since the laser can only push on the mirror, the mirror would be offset from its normal equilibrium position. This would allow gravity to pull the mirror back if the laser power were decreased. This experiment is meant to test whether photon actuation is an effective means of damping displacement noise of a LIGO suspended optic.

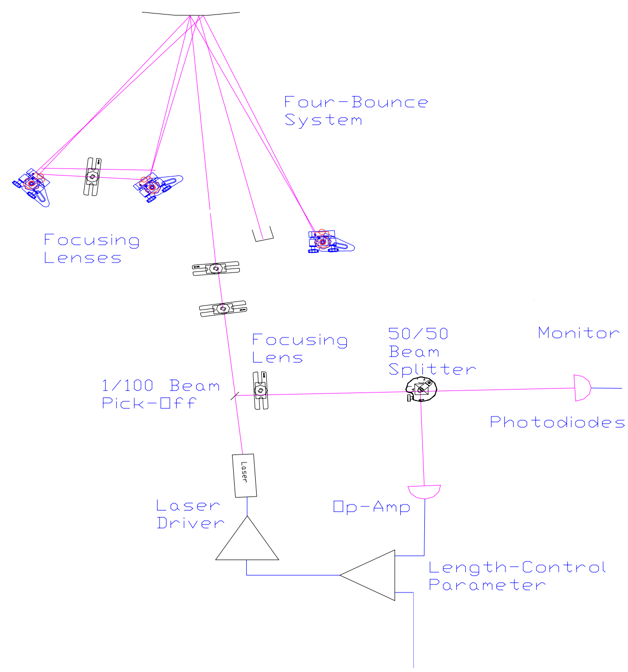
2. Experimental Procedure

The experiment will be carried out on the 40-meter interferometer at the California Institute of Technology. The 40-meter interferometer has been commissioned as a test site for Advanced LIGO research and development [3]. We will be testing the photon actuation system on the end mirror of the mode-cleaner cavity at the 40-meter site. This is partly because the optical system for the main interferometer arms is not fully in place, and partly because the mode-cleaner cavity is such a high-finesse cavity. The mode-cleaner cavity is a system of three mirrors stationed before the main body of the interferometer through which, because of resonance effects, only the TEM_{00} mode of the laser light is allowed to pass. Because the cavity is so sensitive to slight changes in length, in other words high-finesse, our experiment can be conducted with great precision on it.

In the mode-cleaner cavity of the 40-meter site, there are currently two control systems, which keep the mode cleaner in lock at the correct resonance. The OSEMs already described operate to damp the noise at low frequencies. For noise at higher frequencies, the laser beam's frequency is altered slightly by the Voltage-Controlled Oscillator (VCO) to match the cavity's resonant frequency. Photon actuation would ideally actuate in a frequency range above where the OSEMs dominate and below that in which the VCO operates. The original photon actuation design was intended to be dominant somewhere between 30 Hz and 300 Hz. In the noise spectrum measured in the 40-meter mode-cleaner cavity (Figure 5) the aim of the photon actuation experiment was to lower the noise in this frequency range from what was previously measured.

2.1 Apparatus

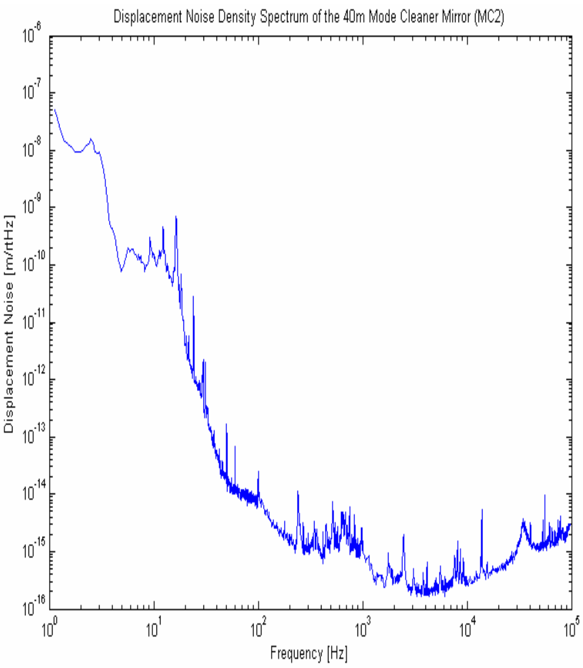
The design has been changed significantly since the beginning of the project. In the original design, the beam that was reflected from the mode-cleaner mirror was used for the feedback loop; however, the design was greatly simplified when the feedback pick-off was placed much earlier. Furthermore, because the systems noise-suppression is dependent on the laser power, the current design allows for the laser to be bounced off the mode-cleaner mirror four times, thus effectively quadrupling the laser's power. The laser is to be brought in at an angle, allowing for the reflected beam to be captured separately and redirected back to the mirror at least four times. The design for the system is shown below.



(Figure 6: Schematic of Intensity-Stabilized Laser)

In the intensity-stabilization loop, a small portion of the signal is diverted by the beam pick-off and measured by a photodiode. The error from DC in the photodiode current is then added to a length-control reference parameter. This parameter is an offset on the modulation signal given by the length control system. This combined signal is then input to the laser driver to modulate the laser intensity. Thus the length control parameter is set by the control system of the mode cleaner and then fed back on the laser intensity.

The mode cleaner cavity is a relatively low-noise cavity. The measured displacement noise of the cavity is shown below (Figure 6).



(Figure 7: Displacement Noise of the Mode-Cleaner Cavity)

Thus, the intensity noise from the photon actuator laser must not cause more than this level of noise. In our optimal actuation range, the above condition would require causing no more than 10^{-16} m/rtHz in displacement noise. Mirror displacement can be related to laser power by the formula:

$$P = \frac{2\sqrt{2}\pi^2 mcf^2}{\cos\theta} x_{rms}$$

If we operate at 100 Hz and small angles ($\cos\theta \approx 1$), then our laser intensity noise would have to be no higher than 10^{-3} W/rtHz. For Advanced LIGO, where photon actuation would be used on the end mirrors of the interferometer arms, the optics will be much quieter, requiring a much more stable laser. It has been estimated that the intensity noise for an Advanced LIGO photon actuator laser will have to be below 10^{-7} W/rtHz.[2]

For the photon actuation experiment on the mode-cleaner cavity the noise requirement is not very stringent. Nevertheless, it was the aim of the experiment to develop a simple intensity-stabilization loop that could meet the requirements for Advanced LIGO. To do this, there were two primary concerns:

1. Sensitivity of the optical system to fluctuations in the beam angle leaving the laser

2. Sensitivity of the photodiode voltage to fluctuations of the laser beam across its surface.

2.1.1 Beam Displacement Noise:

The first condition above requires that small changes in the height and angle of the laser beam leaving the laser would not affect the height of the beam at either the photodiodes or the mode-cleaner mirror. Since the entire optical setup is firmly bolted to a table at a fixed height, the main concern is with angular fluctuations of the beam.

If one assumes that the beam will always remain at small angles to the optical axis (paraxial approximation), one can use matrix optics to define the system. Propagation through an arbitrary array of components becomes a linear problem. Thus, the final height and angle depend only a weighted sum of the initial height and angle:

$$h' = Ah_0 + B\alpha_0$$
$$\alpha' = Ch_0 + D\alpha_0 .$$

One can convert this equation into a vector equation by defining an input ray vector with initial height and angle and a 2x2 matrix with the linear coefficients as entries. The multiplication of the two yields a vector giving the final height and angle:

$$\begin{bmatrix} h_1 \\ \alpha_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} h_0 \\ \alpha_0 \end{bmatrix}$$

Minimizing the fluctuations of the height of the beam as the initial angle fluctuates amounts to setting B = 0. The other parameters can then be set to give the desired spot size. This is done by careful selection of the focal lengths of the lenses in the system, as well as the distances between these lenses.

2.1.2 Optimal Beam Spot Size at the Photodiodes:

To minimize errors in the photocurrent due to changes in the position of the laser beam on the photodiode surface, an analysis was done to determine the optimal beam spot size at the photodiode. A Mathematica model was created to estimate this beam size. The current from the photodiode depends on two parameters – the total power, P, hitting the photodiode and the average responsivity, R, of the photodiode surface. These two parameters are related to the photocurrent, I, by the equation:

$$I = PR$$

Errors in either parameter will ultimately effect the signal coming from the photodiode and thus the effectiveness of the intensity-stabilization loop. Consequently, if the laser spot is too large, small changes in the position of the spot on the photodiode would cause a large portion of the laser energy to miss the photodiode altogether, causing variations in P. On the other hand, if the spot becomes too small, the beam will begin sampling the unavoidable variations in the responsivity of the photodiode surface, causing a shift in R. Then with power and responsivity with errors:

$$P = P_0 + \Delta P$$
$$R = R_0 + \Delta R$$

The photocurrent is given by:

$$\begin{aligned} I &= (P_0 + \Delta P)(R_0 + \Delta R) \\ &= P_0 R_0 + \Delta P R_0 + P_0 \Delta R + \Delta P \Delta R \\ &= P_0 R_0 + \Delta I \end{aligned}$$

where ΔI is the error in the photocurrent. This error is caused by a displacement of dx across the photodiode surface. Thus, assuming a diameter d for the laser beam, from geometry it can be worked out that:

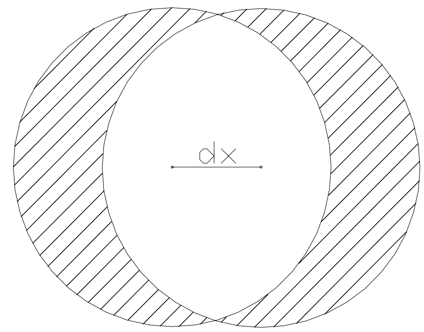
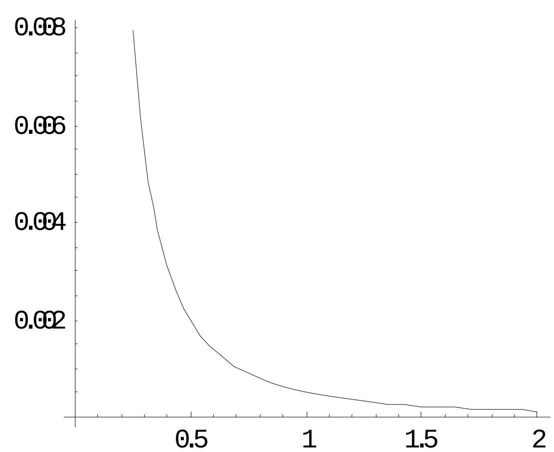


Figure 8.

$$dA = \frac{1}{4}\pi d^2 - \frac{1}{2} d^2 \arccos(\frac{dx}{d}) + \frac{1}{2} dx\sqrt{d^2 - dx^2}$$

Where dA is the area of the laser beam, which is comprised by one of the shaded regions in figure 8. This new area could have a slightly different average responsivity, thus changing the total responsivity being sampled by the laser beam. To estimate what error this would cause in R, a grid was created and dA/A percent of it was allowed to vary ±2% of the normal responsivity (value given by manufacturer). For each value of dA/A from .01 to 1, 1000 grids were created and the standard deviation of each set was used as the value of ΔR for that percentage. This yielded a function for ΔR depending upon dx and d. Assuming small fluctuations, thus dx = .01 (1% of photodiode side length of 2 mm), ΔR is given in Figure 9.



(Figure 9 - ΔR versus Relative Beam Diameter [dimensionless])

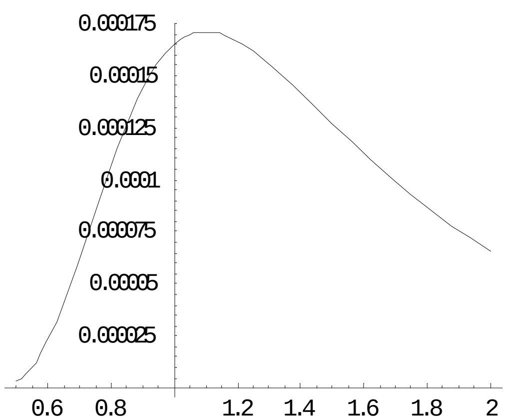
To estimate the fluctuations in incident power with a displaced beam, a TEM_{00} Gaussian beam with intensity profile given by:

$$Intensity = \frac{8e^{-\frac{8(x^2+y^2)}{d^2}}}{d^2\pi}$$

was integrated over a square area that was displaced from the center of the beam by dx to yield incident power with a displacement. The power with displacement was then subtracted by the power with no displacement to yield ΔP:

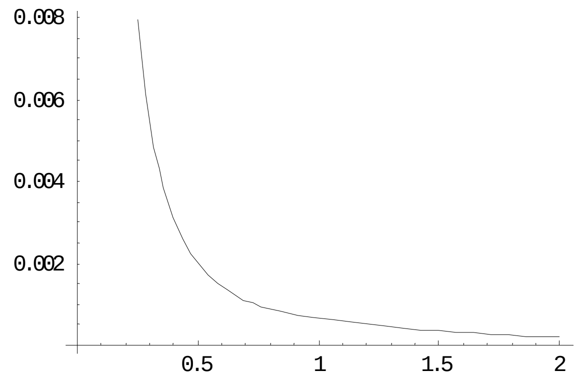
$$\Delta P = \iint (I)dA' - \iint (I)dA$$

Where dA' is the displaced area and dA is the area with the beam centered. This again depends only on dx and d. For dx = .01, ΔP is plotted below:



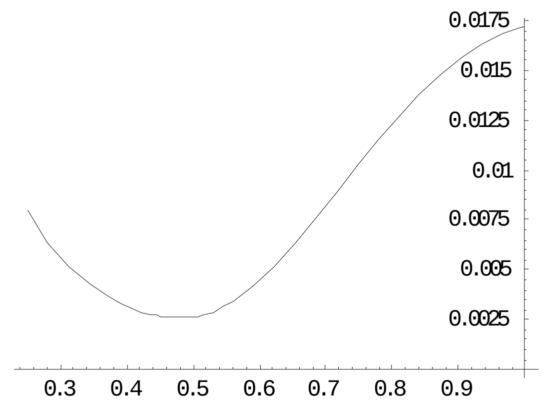
(Figure 10 – ΔP versus Relative Beam Diameter [dimensionless])

where ΔI is the change in current with a displacement dx and diameter d. Again, for dx = 1% of photodiode surface, ΔI is plotted below:



(Figure 11: Relative Change in Photocurrent vs. Relative Beam Diameter (dx = 1%))

It should be noted that the curve changes significantly for larger deviations. For example, for dx = 10% of the photodiode surface:



(Figure 12: Relative Change in Photocurrent vs. Relative Beam Diameter (dx = 10%))

This effect is attributed to the fact that for high values of dx, the power lost off of the side of the photodetector rises, overpowering other effects. For our experiment, though, changes of no more than 1% of the photodiode diameter are expected and the first graph should be used. The graph then shows that the larger the relative beam spot size, the less should be the photocurrent noise. At the same time it is desirable to capture a large majority of the laser energy, so a 1/e^2 beam diameter that is the size of the photodetector was chosen.

2.2 Intensity-Stabilization Loop

The laser intensity stabilization loop was then set up using two SR560 low-noise pre-amplifiers from Stanford Research Systems in series. Voltage was read from either a GAP 2000 or a PDA 255 photodiode.

The voltage from the photodiode was then fed into an SR560. The photocurrent was AC coupled, so that only fluctuations from DC were amplified. Furthermore, a narrow bandpass filter was applied at the first SR560, allowing only frequencies close to 100 Hz to pass through. The gain of the feedback was also altered at the first SR560 – there was a gain of 1 at the second SR560.

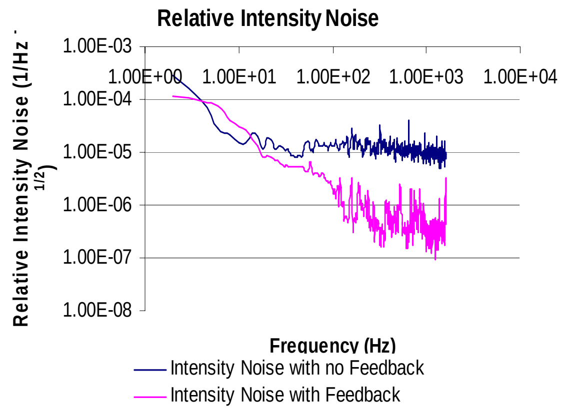
The output from this SR560 was then input into another SR560 where it was subtracted from a reference voltage. In the fully operational system, the reference voltage would come from the length-control system of the mode-cleaner. In the preliminary tests of the intensity stabilization, however, the reference voltage was maintained by an SR785 Signal analyzer.

The signal leaving the second SR560 was then input as the laser driver modulation signal. The laser driver board was specifically designed for the particular 500 mW Nd:YAG laser that was used. One of the pins in the laser driver was capable of taking a modulation signal.

It was found that to keep the laser around its mean intensity of 250 mW, the input signal had to be maintained at 600 mV. This signal was then set at the signal analyzer and any variation in the laser intensity would create a fluctuation in the voltage from the photodiode. This fluctuation would be fed back on the laser intensity, correcting for any deviation from the desired value.

3. Results

The relative intensity noise readings for the 500 mW, ND:YAG laser with and without stabilization is shown below:



(Figure 13: Laser Intensity Noise measured in and out of loop)

The relative laser intensity noise was measured to be near 10^{-6} in the target frequency range (~100-200 Hz). This far exceeds the requirements for testing photon actuation on the mode-cleaner (10^{-3}). Without significantly increasing the complexity of the intensity-stabilization loop, the intensity noise of the laser could be brought down to the level needed for the end test masses of Advanced LIGO (10^{-7}).

In conjunction with this work, a Simulink model of the control loop was developed by Aidan Crook. With this model, an appropriate filter to integrate the intensity-stabilization loop with the current control loops in the mode-cleaner was designed. [4] If the Simulink model holds, photon actuation should be an effective means of damping motion of a suspended test mass.

5. Future Work

Due to time restrictions, the experiment could not be carried out over the summer; however, in the near future the experiment will be performed to determine whether the design developed above will be effective in stabilizing the suspended optic in the mode-cleaner.

If this test is successful, the next step will be to test photon actuation on an end test mass (ETM), first at the 40-meter interferometer and then at a LIGO site.

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