

High accuracy measurement of the quantum efficiency using radiation pressure

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Abstract. Preliminary investigations of a novel method to measure the laser power accurately using the radiation pressure are reported here. We aim to measure the laser power within one percent error to then obtain an accurate quantum efficiency (QE) of a photodiode. Since the typical error of QE is still a few percent due to the uncertainty of measured laser power, an accurate measurement of the laser power contributes a precise estimation of the QE. Our experimental setup is a suspended Michelson interferometer, where one of the pendulums is small, consisting of a 20-mg mirror and 10- μ m fiber. The motion of this small mirror is very sensitive to changes in radiation pressure. Due to this, the number of photons in the incident (intensity modulated) laser beam can be counted accurately by measuring displacement of the mirror. We set up the apparatus, and have found a suitable frequency band for the accurate measurement. Displacement caused by the radiation pressure was observed using the feedback signal.

1. Introduction

According to a recent study about squeezing of quantum noise have made great progress and will contribute to the development of essential technology for future gravitational wave detectors [1, 2]. It is significant for squeezing experiments to make the quantum efficiency (QE) of photo diodes (PDs) high because a squeezing state is easily degraded by a small amount of optical losses including QE [3]. According to a resent study, $95(\pm 2)\%$ of QE is the main limitation of a squeezing level [4]. A PD with an expected QE of close to 99% is about to be constructed [5] and it will be the main limitation of a squeezing level. Even if high QE close to 99% is achieved, it cannot yet be measured with sufficient accuracy. Uncertainty of QE affects the measurement of squeezing level. A typical error of QE is still a few percent owing to the uncertainty of measured laser power. Our objective is to measure laser power within an error of one percent, and then to measure QE accurately. In order to achieve this we are constructing an opto-mechanical power

meter, which can count the number of photons by measuring displacement of a mirror pushed by laser photons.

2. Theory

The QE of a PD is defined as the efficiency with which light power is converted to current; $QE = N_e/N_p$. Here, N_e is the number of electrons in the output current of the PD and N_p is the number of photons in the input light. A precise measurement of N_p leads to a high accuracy of QE.

When there is an opto-mechanical system with an input laser and a mirror, N_p can be related to the displacement of the mirror shaken by input photons. We can find the displacement in the frequency domain by modulating the input power. Let us consider a photon that is reflected by a mirror. The mirror is pushed by the momentum of the photon. The equation of motion is written as $m\ddot{x} = 2h\nu/c$, where m is the mass of the mirror, x the displacement of the mirror, h the Planck constant, ν the frequency of the photon, and c the speed of light. In the frequency domain, the equation of motion is represented as

$$d\tilde{X} = \frac{2P_m \cos \phi}{mc\omega^2}. \quad (1)$$

Here, $d\tilde{X}$ is the Fourier transformation of x , ω the angular frequency of the intensity modulation of P_m , and ϕ the incident angle of the input laser to the mirror. P_m is translated to the power at DC using the modulation index, α_m , as $P_m = \alpha_m P$. Also, N_p is related to a continuous-wave laser with the power of P as $N_p = P/(h\nu)$.

When the Michelson interferometer is used as a displacement sensor, we can obtain $d\tilde{X} = dV_{PD}\lambda/(2\pi V_{pp})$. dV_{PD} is the output voltage from the PD, and V_{pp} is the peak-to-peak voltage when the arm length is changed over a half wave length. A linear response is guaranteed as long as the so-called ‘mid-fringe’ state is kept. This equation in combination with equation(1) yields

$$P = \frac{mc\lambda\omega^2}{4\pi V_{pp}\alpha_m \cos \phi} dV_{PD}. \quad (2)$$

Note that dV_{PD} includes the effect from control gain. One implication of equation(2) is that measuring the opto-mechanical response gives an accurate measurement of light power.

3. Experimental Setup

As shown in Fig.(1) and Fig.(2), our main apparatus is a simple Michelson interferometer (MI) with a tiny mirror suspended by a small pendulum. The displacement of this tiny mirror is sensitive to changes in radiation pressure, so that the number of photons from the incident laser beam can be counted accurately by measuring the displacement of the mirror.

The laser has a nominal power of 500 mW. The laser path is divided using a polarized beam splitter and a half-wave plate into two paths that are used for the MI and for the input power modulation. That is why we can see displacement of the tiny mirror using the MI as the tiny mirror is fluctuated by the modulated radiation pressure. The power modulation is provided using an acousto-optic modulator (AOM). The MI is housed in a vacuum tank, which is put on vibration isolation stacks, but, for the moment, this experiment is performed in air.

A characteristic of our apparatus is to use a tiny mirror whose weight is only 20 mg and diameter is 3 mm as an end mirror for one arm of the MI. The tiny mirror is suspended by a silica fiber with the diameter of 10 μm . The fiber is glued on the mirror using UV cured resin. The suspension is the double pendulum with eddy current damping at the middle mass [6, 7]. The other arm of the MI comprises a large mirror whose weight is 50 g and diameter is 1 inch. The large suspension is also a double pendulum with eddy current damping. This mirror is controlled using four sets of coil-magnet actuators.

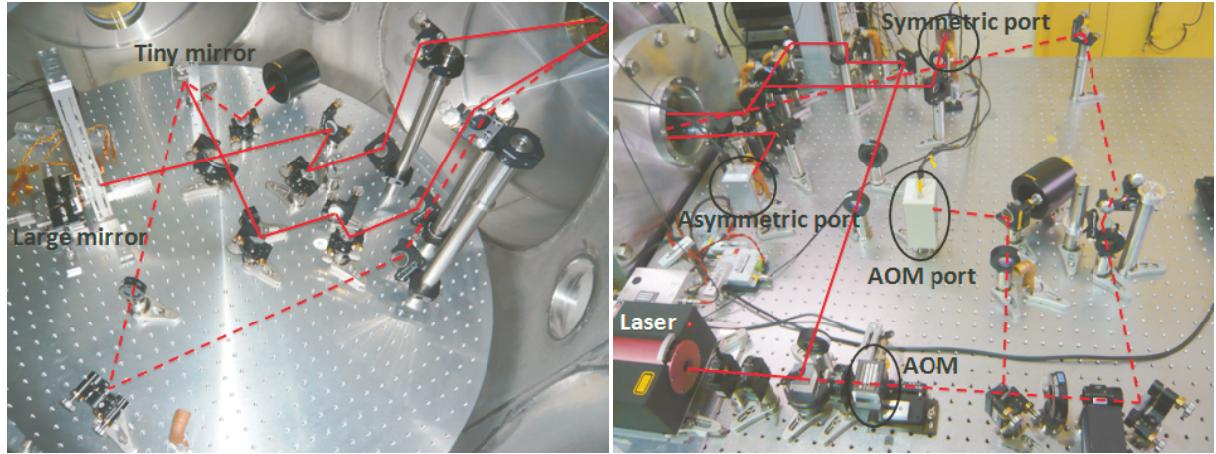


Figure 1. Optical layout.

The solid red line indicates a beam trace for the Michelson interferometer and the dotted red line is that for an intensity modulation by AOM. There are three photo detectors; Symmetric port, Asymmetric port and AOM port on an optical table.

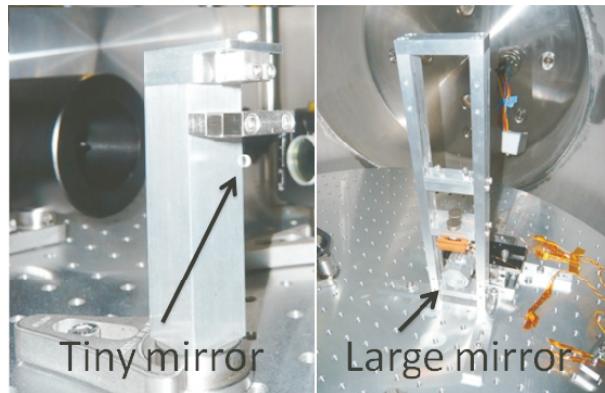


Figure 2. Suspension systems.

Left: Tiny mirror pendulum. The tiny mirror is suspended by a 10-um silica fiber. The middle mass of 20 mg is suspended by a 10-um tungsten wire. Right: Large mirror pendulum. The large mirror and its optical bracket is suspended by 50-um tungsten wires. The intermediate mass of 60 g is suspended by 70-um tungsten wires.

4. Sensitivity and Control

In order to measure the radiation pressure response within an error of one percent, it is necessary for the signal to be above the noise floor by nearly two orders of magnitude. Figure(3) shows a superposition of the sensitivity of the MI and calculated displacement of the tiny mirror by radiation pressure modulation when the displacement noise was measured in the air. To have a sensitivity with wide range and fine resolution, data was taken in three frequency ranges (10-100 Hz, 100-800 Hz and 800-6400 Hz) and then combined. Displacement by radiation pressure is estimated using equation(1) with an intensity modulation of 50 mW (peak-to-peak). The modulation index of the AOM is about 17%, so 17% of the incident laser power can be used as an intensity modulation. The nominal power of our laser is 500 mW. If we use 400 mW for the modulation path, then we will get a modulation of 68 mW. Taking some dispersion loss into account, 50 mW is chosen as a typical value of this experiment. We found that this was sufficient to measure the radiation pressure response as the dominant signal, especially in the range between 200 Hz and 500 Hz.

The Michelson Interferometer was locked at the mid-fringe using the symmetric port signal. Contrasts are about 95% in the symmetric port and asymmetric port as well. As shown in Fig.(4), the unity gain frequencies are 100 Hz, 130 Hz and 190 Hz, corresponding to 30 degrees,

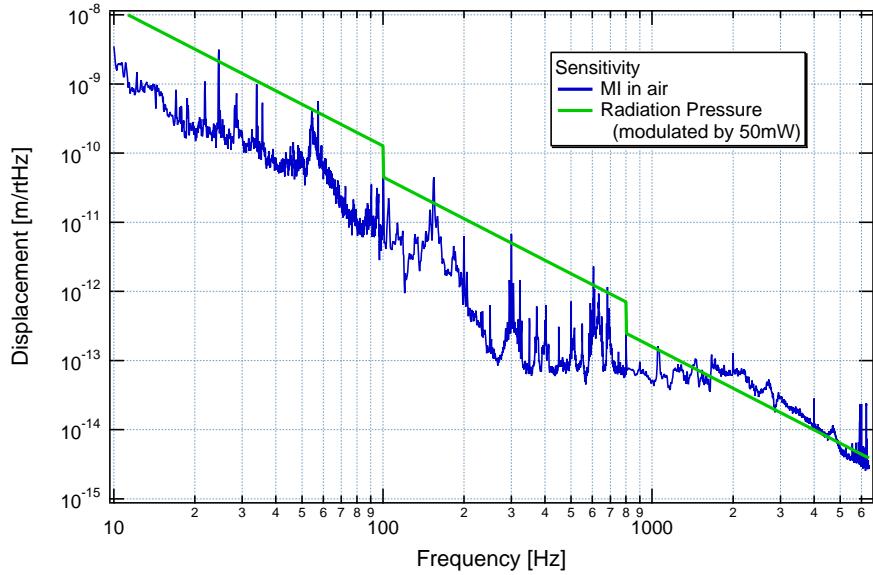


Figure 3. The sensitivity of MI and radiation pressure estimation.

The green line indicates a radiation pressure estimation. Note that jumps of the line at 100 Hz and 800 Hz are caused by differences of the integration time. Integration time of each frequency bin is 16 s below 100 Hz, 2 s between 100 Hz and 800 Hz, and 0.25 s above 800 Hz.

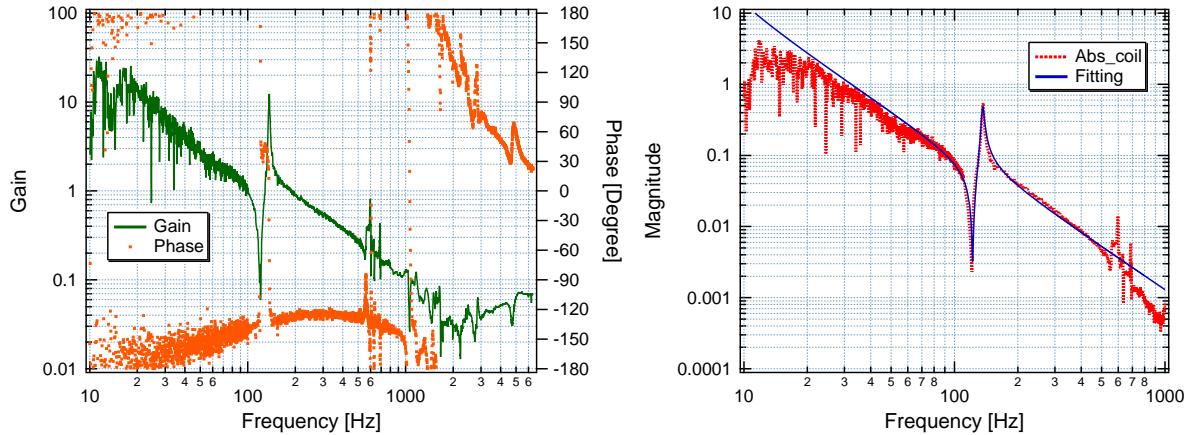


Figure 4. Measured transfer functions.

Left: Open loop transfer function of the MI servo. Right: Transfer function from the coil-magnet actuator to the photo detector at the symmetric port, which is fitted using data between 80 Hz and 500 Hz.

220 degrees and 50 degrees of phase margins, respectively. A transfer function from the coil-magnet actuator to photo detector is translated to the actuator response using a fitting function of f^{-2} . There is a structure like the parasitic resonance around 130 Hz. This might be a coupling motion with the pitch mode of the large mirror. There are no structures between 200 Hz and 500 Hz, so that fine measurements are possible in this region. The stability of the control is still not sufficient. Disorder below 100 Hz of Fig.(4) comes from shortage of the measurement

average. When unsteady large noise (mainly seismic noise) occurs, the locking of MI easily fails.

From the sensitivity and control, we can now expect an accurate measurement between 200 Hz and 500 Hz owing to fine measurement of the transfer function, lower noise, and higher stability.

5. Radiation Pressure

We compared feedback signals when the modulated incident laser power was ON using AOM at 430 Hz, and when it was OFF. There was no explicit difference between them except for the peak at 430 Hz as shown in Fig.(5). We confirmed that this peak can be moved by changing the modulation frequency. Thus the radiation pressure is observed in the feedback signal. However, the scattering effect has not yet been investigated.

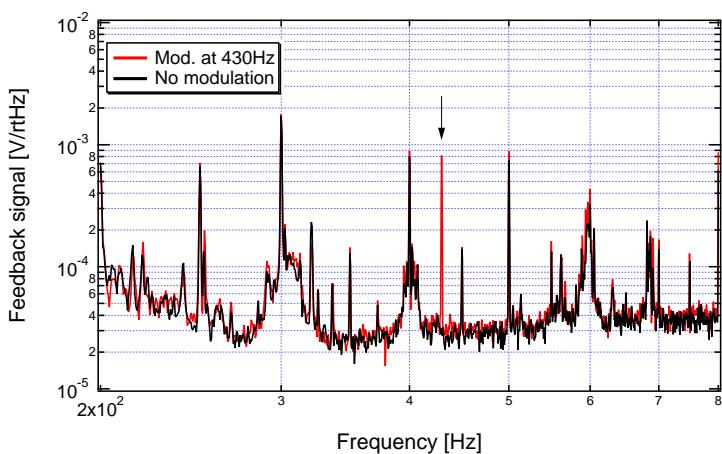


Figure 5. The feedback signal with and without modulated input laser.

The black arrow indicates the peak signal by modulated radiation pressure at 430Hz.

6. Summary and Future Plan

We are constructing a new kind of power meter to measure the fine QE of a PD, and have obtained promising results. We found that the frequency region between 200 Hz and 500 Hz is suitable for an accurate measurement. In that region, the transfer function can be measured accurately and noise of the MI is less than the modulation signal by nearly two orders. The modulation signal of the radiation pressure was observed by feedback signal.

The next step is a detailed examination of the accuracy of each measurement. We will investigate the errors due to measurement of mass (tiny mirror), deviation from free mass approximation, scattering and absorption from the mirrors, intensity noise of the laser, and deviation from mid-fringe lock. Noise hunting and suppression should broaden the frequency band where accurate measurement is possible. Beam centering at a mirror spot will suppress a coupling with a pitch mode, and then increase stability of the lock.

7. Acknowledgments

This work is supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (09J03624), and Young Scientists B No. 21740201.

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