Development of a high power optical cavity for optomechanical QND experiment

T Mori\textsuperscript{1,2}, K Agatsuma\textsuperscript{2}, S Ballmer\textsuperscript{3}, S Sakata\textsuperscript{4}, O Miyakawa\textsuperscript{5}, S Kawamura\textsuperscript{5}, A Furusawa\textsuperscript{6} and N Mio\textsuperscript{7}

\textsuperscript{1} Department of Advanced Materials Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8561, Japan
\textsuperscript{2} National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
\textsuperscript{3} Department of Physics, Syracuse University, NY 13244, USA
\textsuperscript{4} Center for Photonic Innovation, University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan
\textsuperscript{5} Institute for Cosmic Ray Research, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8582, Japan
\textsuperscript{6} Department of Applied Physics, School of Engineering, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo 113-8656, Japan
\textsuperscript{7} Photon Science Center, School of Engineering, The University of Tokyo, 2-11-16 Yayoi, Bunkyo-ku, Tokyo 113-8656, Japan

E-mail: npfazy@gmail.com

Abstract. In order to observe quantum radiation pressure noise and reduce it by measuring the ponderomotively squeezed light on a table-top experiment, we are developing a laser interferometer with Fabry-Perot cavities with very small suspended mirrors. As a preliminary setup, we have constructed a Fabry-Perot cavity of finesse 1300 with a suspended mirror of 20 mg. The cavity was locked stably at low laser power for which the classical radiation pressure caused little effect on the dynamics of the small mirror. For the stable operation of this cavity with higher laser power, a technique to control the motion of the small mirror, especially its yaw motion, is necessary. We describe that the motion can be stabilized through the radiation pressure of light inside the cavity, by controlling the motion of the front mirror of a Fabry-Perot cavity properly.

1. Introduction

For the detection of gravitational waves (GWs) from violent astronomical events such as a supernova explosion or a coalescence of neutron-star binaries, large laser interferometers of km-scale have been constructed and are working worldwide. Since the expected GW signals are quite weak, noise reduction techniques are of particular interest. In current laser interferometer GW detectors, the sensitivity is limited by the quantum phase fluctuations of the photons of the laser at frequencies above several hundred Hz \cite{1}. This noise is called the shot noise, and the equivalent displacement noise caused by the shot noise is inversely proportional to the square root of the laser power. Therefore, a higher laser power is needed to lower the shot noise limited sensitivity \cite{2}. It is theoretically expected that another aspect of the quantum fluctuations of the laser arises as the laser power increases, namely the radiation pressure acting on suspended mirrors. The noise is called the quantum radiation pressure noise, and arises from...
the quantum photon-number fluctuations. The quantum radiation pressure noise has not been observed experimentally yet. However, in the near future, the sensitivity of the GW detectors will be totally limited by these two noise sources [3, 4]. Techniques to reduce these quantum noises are necessary to achieve a better sensitivity.

The key to overcome the quantum noises is that the shot noise and the quantum radiation pressure noise arise from different quadrature component of a light field, namely phase fluctuations and photon number fluctuations. Therefore if these quadrature phases are correlated, one fluctuation can be reduced at the sacrifice of the other. One method that utilizes the radiation pressure as the squeezing mechanism or a variational readout has been proposed [5]. This squeezing is called the ponderomotive squeezing. The quantum radiation pressure noise can be reduced by extracting this squeezing with homodyne detection.

We are developing a system that will enable the observation and reduction of quantum radiation pressure noise based on ponderomotive squeezing. The realization of such a system is of importance for laser interferometer GW detectors for some reasons. For instance, it will allow to verify the theory of quantum fluctuations in laser interferometers. Since no one has observed the quantum radiation pressure noise experimentally yet, the measurement itself has become a subject of growing interest. Further, to demonstrate a reduction of it is also important for the verification of the theory. In addition to this, the system will be useful as a test bench for advanced techniques regarding GW detectors.

2. Experimental design

This section describes the conceptual design of the system to observe and reduce the quantum radiation pressure noise. The main interferometer is a Fabry-Perot Michelson interferometer. In order to amplify the effect caused by the radiation pressure, the mirrors of the interferometer should be small and the finesse of the cavity should be high. We set the mass of the end mirror of the cavity to 20 mg. The main parameters of the cavity are as follows; the finesse of the cavity $F$ is 10000, the laser power injected to the Fabry-Perot Michelson interferometer $P$ is 120 mW. This leads to the design sensitivity to observe the quantum radiation pressure of about $10^{-16} \text{m}/\sqrt{\text{Hz}}$ at 300 Hz and $10^{-17} \text{m}/\sqrt{\text{Hz}}$ at 1 kHz [8]. The displacement noise spectrum due to the quantum fluctuations can be described as [5, 6, 7]

\[
 h_{\text{quantum}}(f) = \sqrt{\frac{h_{\text{SQL}}(f)}{2}} \left( \frac{\kappa(f) + \frac{1}{\kappa(f)}}{\sqrt{4\pi^2 \hbar^2 m}} \right),
\]

where $F$ is the finesse the assumptions made here are;

\[
 \kappa(f) = \frac{4P\omega_0}{r_F(1 - r_F)^2 m} \left( \frac{t_F F}{(2\pi f)\pi c} \right)^2,
\]

\[
 h_{\text{SQL}}(f) = \sqrt{\frac{4\hbar}{m(2\pi f)^2}}.
\]

Here $\omega_0$ and $c$ are the angular frequency and the speed of light, respectively, $m$ is the reduced mass of the mirrors of the cavity, $r_F$ and $t_F$ are the amplitude reflectivity and transmissivity of the front mirror of the cavity, respectively. The reflectivity of the end mirror is set to unity. The first and second term in Eq. (1) describe the quantum radiation pressure noise and the shot noise, respectively. By extracting the ponderomotive squeezing, these two noises can be partially canceled at a certain frequency. It is expected that the radiation pressure noise can be suppressed by 6 dB with the actual losses of the system taken into consideration [8].

In the design, other noises such as the thermal noise of the mirror or the suspension, laser classical noise, or seismic noise are much smaller than the quantum noise.
Figure 1. (a) Picture of the suspension with the mirror of 20 mg. The mirror is suspended by a silica fiber of 10 μm diameter. (b) Picture of one inch front mirror and 3 mm end mirror forming a Fabry-Perot cavity with a length of 80 mm. The laser comes from right to left.

3. Current experimental setup
As a preliminary setup, we have constructed a Fabry-Perot cavity of finesse 1300 with a suspended mirror of 20 mg in advance to the cavity of finesse 10000 in order to develop the control system. In the following, the main aspects of the current experimental setup are briefly described.

3.1. Small suspended mirror
Fig. 1(a) shows the suspension system of the small mirror, which is realized as a double pendulum. The mirror of 20 mg is suspended by a silica fiber of 10 μm diameter. A thin silica fiber is needed to lower the thermal noise of the fiber since silica has high mechanical Q factor. The middle mass is made of pure aluminum and also has a mass of 20 mg. The middle mass is surrounded by some small magnets in a way that its motion can be damped by eddy-current losses. Note that in Fig. 1(a) the magnets are removed. The middle mass is suspended by a 10 μm tungsten wire.

3.2. Suspended one inch mirror with coil-magnet actuators
As the front mirror of the cavity, a suspended pendulum with a one inch mirror has been constructed (see right side of Fig. 1(b)). The middle mass of this pendulum is made of copper, and is damped by eddy-current losses. Four magnets are attached to the back of the mirror holder, with each being surrounded by a coil. The motion of the mirror can be controlled by a force to the magnets exerted by a magnetic field that is produced by the coils.

3.3. Fabry-Perot cavity
The Fabry-Perot cavity consists of these two suspended mirrors, as shown in Fig. 1(b). The radius of curvature of the front mirror is one meter and the small mirror is flat. The length of the cavity is 80 mm.
Figure 2. Schematic view of the optical configuration. Core optics are set on a suspended breadboard in a vacuum chamber.

3.4. Seismic isolation system
Since the motion of the small mirror is easily excited by external vibration, an additional seismic attenuation system is necessary. Therefore, the mirrors that compose the Fabry-Perot cavity were set on the suspended breadboard of 40 cm × 40 cm. The schematic view of the system is shown in Fig. 2. This breadboard was suspended by a double pendulum, giving sufficient attenuation of the seismic motion.

4. Single Fabry-Perot operation
We have succeeded in the stable locking of the single Fabry-Perot cavity owing to the seismic attenuation system described above. The input laser power was low so that the radiation pressure caused little effect on the dynamics of the small mirror; the cavity could be operated stably when the laser power inside the cavity was less than about 200 mW. The length of the cavity was controlled by the Pound-Drever-Hall locking scheme [9]. The open loop transfer function of the feedback servo is shown in Fig. 3. The unity gain frequency was at 1.3 kHz with a phase margin of about 70 degrees, which resulted in the stable locking.

The displacement noise spectrum sensitivity shown in Fig. 4 was estimated from the feedback signal applied to the coil-magnet actuators. The sensitivity was about $10^{-15}$ m/$\sqrt{\text{Hz}}$ at 1 kHz which is about two orders of magnitude higher than the expected quantum radiation pressure noise level. The sensitivity was limited by the frequency noise of the laser which was estimated to be about $5 \times 10^3 / f$ Hz/$\sqrt{\text{Hz}}$. This noise will be suppressed in a next step by a frequency stabilization of the laser using a reference cavity.

5. Control system of the angular motion of the mirror
The cavity is stable only when the input laser power is low enough not to excite the motion of the small mirror through the radiation pressure. Since the $g$-factor of the cavity is positive, the radiation pressure works as a negative spring for angular motion [10]. At high laser power, the angular antispring effect caused by the radiation pressure prevents from stable operation of the
cavity. In Fig. 5(a) it is sketched how this instability occurs. When the rotational motion of the small mirror is excited slightly, the optical axis of the cavity moves. Since the rotational motion caused by the radiation pressure of the cavity with new optical axis is the same direction as the initial rotation, the motion is excited. This happens when the $g$-factor of the cavity is positive which is the case of this experiment. This effect was measured quantitatively with the small mirror used in this experiment [11].

For the stable operation of this cavity with higher laser power, an additional system to deal with this instability is required. Here we propose a technique to control the angular motion of the small mirror through the radiation pressure of photons inside the cavity. The schematic explanation of this control is shown in Fig. 5(b). When the small mirror rotates, the optical axis of the cavity moves. Therefore, the movement can be measured by detecting the transmitted light with a quadrant photo detector (QPD). The signal is then fed back to the angular motion of the front mirror in order to move the optical axis of the cavity such that the optical axis coincides with the center of the small mirror again. In order to obtain the signal which is just proportional to the rotation of the small mirror at the QPD, a lens was inserted in front of the QPD. Furthermore, in high laser power operation, the radiation pressure pushes the small mirror to the initial position and prevents the rotation when the control of the rotational motion is worked. Here the radiation pressure can work as angular spring for the end mirror instead of antispring.

The angular instability caused by the radiation pressure at full laser power (~400 W inside the cavity) is calculated to be about 1000 times larger than the mechanical restoring force of the torsion mode of the small mirror. To maintain the stability, the control bandwidth of about 1 kHz is needed. The experiment to verify them is now under way.

6. Summary
Toward the observation of the quantum radiation pressure noise and the reduction of it by measuring the ponderomotively squeezed light, we are developing a laser interferometer with Fabry-Perot cavities with very small suspended mirrors. The prototype cavity of the Finesse 1300 was locked stably at low laser power. The size of the mirror is the smallest, as far as the authors’ knowledge, as a suspended mirror working as an optical cavity. For the stable

![Figure 4](image-url)  
**Figure 4.** Measured displacement sensitivity of the Fabry-Perot interferometer. The solid blue line is the target radiation pressure noise level, and the dotted black line is the estimated frequency noise of the laser.
Figure 5. (a) Schematic view of how the radiation pressure inside the cavity works as an angular antispring. The rotational motion of the small mirror can be excited by the radiation pressure. (b) Schematic view of how to control the yaw motion of the small mirror through the radiation pressure.

operation of this cavity with higher laser power, a technique to control the motion of the small mirror is necessary. The method of the control through the radiation pressure of photons inside a cavity by controlling the motion of the front mirror of a Fabry-Perot cavity is proposed. The experiment to verify this is now under way.

Acknowledgments
T Mori is a Research Fellow of the Japan Society for the Promotion of Science. This work is supported by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science (09J03624), and partly supported by the Global Center of Excellence for Physical Sciences Frontier, the University of Tokyo. This work is also supported by Grant-in-Aid for Scientific Research (B) (23340077).

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