論文の内容の要旨

論文題目　Development of a high power optical cavity for optomechanical quantum nondemolition measurement

(輻射圧を利用した量子非破壊計測のための高パワー光共振器の開発)

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Background. For the detection of gravitational waves 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 gravitational wave signals are quite weak, noise reduction techniques are of particular interest. In current laser interferometer gravitational wave detectors, the sensitivity is limited by the quantum phase fluctuations of the photons of the laser at frequencies above several hundred Hz. 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. 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 gravitational wave detectors will be totally limited by these two noise sources. 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 has been proposed. 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 gravitational wave 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 gravitational wave detectors.

Experimental setup. As a preliminary setup, we have constructed a Fabry-Perot cavity of finesse 1300 with a suspended mirror of 20mg, in preparation for the cavity of finesse 10000, in order to develop the control system (see Fig. 1). The mirror of 20mg is suspended by a silica fiber of 10 micro meter 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 20mg. The middle mass is surrounded by some small magnets in a way that its motion can be damped by eddy-current losses. The motion of the small mirror is watched locally by an optical lever. As the front mirror of the cavity, a suspended pendulum with a one inch mirror has been constructed. 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. The mirrors of the cavity is set up in a vacuum chamber in order to lower the noise caused by air fluctuation or dust, and to attenuate acoustic waves that disturb the motion of the mirrors. They are set up on a suspended breadboard to attenuate seismic motion. Schematic view of the optical configuration is shown in Fig.2.

Results and discussions. 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. The displacement sensitivity is shown in Fig. 3.

The optical antiangular effect caused by the radiation pressure sets an essential limit to the accumulating power inside the cavity. However, it can be overcome by controlling the yaw motion of the front mirror actively and modifying the dynamics of the end mirror by the radiation pressure. The control of the yaw motion through the radiation pressure inside the cavity was demonstrated. It was confirmed that the control system surely worked and that the yaw motion of the end mirror was damped by the radiation pressure (see Fig. 4). This result strongly suggests that the method is useful in higher laser power cavity. This technique becomes the basis of a high laser power cavity to observe the quantum radiation pressure noise.

On the other hand, from the view of optomechanics, this can be said to the verification of the trapping of the rotational motion of a mirror through the radiation pressure by active control. It can be said that a new kind of optomechanical experiment is demonstrated here.

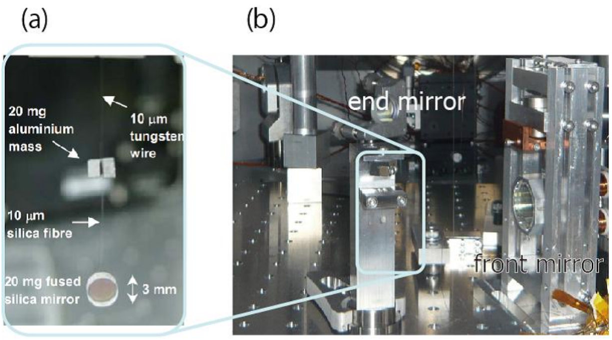

Figure 1. (a) Picture of the suspension with the 20mg mirror. The mirror is suspended by a silica fiber of 10 micro meter diameter.

(b) Picture of the one inch front mirror and 3mm end mirror forming a Fabry-Perot cavity with a length of 80mm.

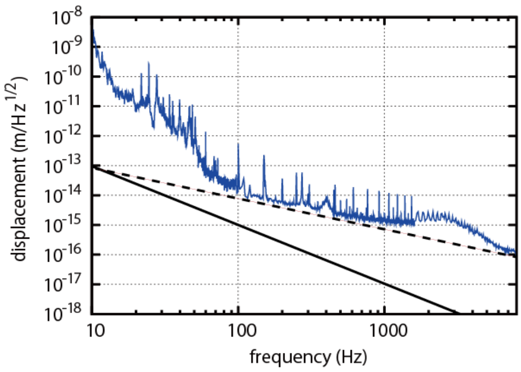

Figure 3. Measured displacement sensitivity of the Fabry-Perot interferometer is shown in the blue trace. The solid black line is the target radiation pressure noise level, and the dotted black line is the estimated frequency noise of the laser.

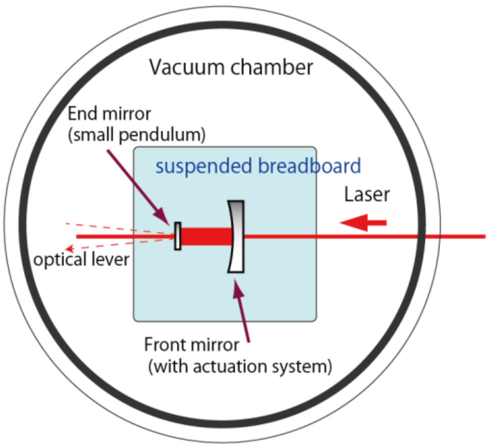

Figure 2. Schematic view of the optical configuration. The mirrors of the Fabry-Perot cavity are set in a vacuum chamber, and on the suspended breadboard. The optical lever locally watches the motion of the small suspended mirror. Beams are guided to outside of the vacuum chamber and detected by photodetectors.

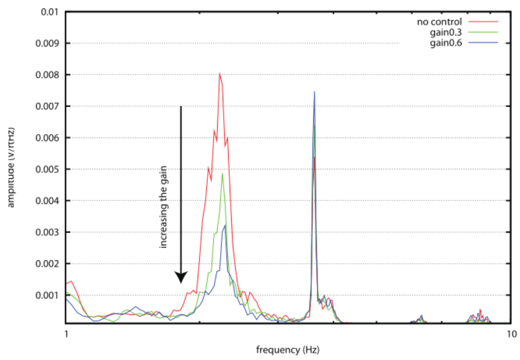

Figure 4. The spectrum of the yaw motion of the end mirror detected by the optical lever. It is observed that the yaw motion at 2.25Hz is damped by the control through the radiation pressure inside the cavity.

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