Mechanical Loss of Reflective Coating at Low Temperature

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Abstract

We measured the mechanical loss of the reflective coating of a mirror at low temperature in order to evaluate the thermal noise of the Large-scale Cryogenic Gravitational wave Telescope (LCGT). We found that the measured coating loss is independent of the temperature at between 4 K and 300 K. This means that the mirror cooling suppresses the thermal motion caused by the coating loss effectively. The thermal noise of LCGT was estimated to be smaller than its goal sensitivity limit.

1. Introduction

Thermal elastic vibration of mirrors are one of the fundamental noise sources of interferometric gravitational wave detectors. In the Large-scale Cryogenic Gravitational wave Telescope (LCGT), which is a future Japanese project [4], the mirror will be cooled (about 20 K) to suppress the thermal motion. Thermal noise depends on not only the temperature, but also the mechanical dissipation in the mirrors. The loss of the mirrors in LCGT must be small at low temperature. We have already confirmed that the dissipation of the cooled sapphire substrate of the mirrors for LCGT is sufficiently small [11]. Since some recent studies [3,5,6,12,13] proved that the mechanical loss of the reflective coating of the mirror has a larger contribution to the thermal noise than the previous expectation, some groups [2,3,9] have measured the mechanical loss of the coating at room temperature. However, nobody has measured the coating dissipation at low temperature. We measured the mechanical loss of the coating at low temper-

pp. 3111–3114

ature to evaluate the thermal noise of LCGT.

2. Experimental method

In order to measure the mechanical loss of the coating, we prepared sapphire disks with and without a coating. After measuring the decay time of the resonant motions of these disks at low temperature and calculating each Q-value, we obtained the coating loss by comparing these Q-values.

The sapphire disks were made by Shinkosya [10]. The diameter of the sapphire disks was 100 mm. The thickness was 0.5 or 1 mm. Both sides were commercially polished. The root mean square of the micro-roughness of the surfaces was about 0.06 nm. The coatings of these disks were almost the same as those of the typical end mirrors of the gravitational wave detectors. These disks were coated by means of ion-beam sputtering. The coating consisted of 31 alternating layers of SiO_2 and Ta_2O_5. The resulting reflectivity was estimated to be more than 99.99%. These coatings were made at National Astronomical Observatory of Japan (NAOJ) and Japan Aviation Electronics Industry, Ltd. (JAE). JAE has made the coatings of the mirrors of TAMA300, which is a Japanese interferometric gravitational wave detector [1].

When the Q-values were measured, the sapphire disk was supported by a nodal support system [7]. The resonant vibration was excited by an electrostatic actuator. The decay motion was monitored using an electrostatic transducer. These experimental apparatuses were fixed in a vacuum chamber. This chamber was put into liquid helium or nitrogen in order to cool the sapphire disk. The typical pressure in the cool chamber was several times 10^{-5} Pa.

We measured the Q-values of the first and third mechanical oscillation modes of the sapphire disks. The resonant frequency of the first mode was 0.52 kHz (disk thickness, 0.5 mm) or 1.1 kHz (disk thickness, 1 mm). The resonant frequency of the third mode was 1.2 kHz (disk thickness, 0.5 mm) or 2.5 kHz (disk thickness, 1 mm). At room temperature, we were not able to measure the coating loss because the internal loss of sapphire disk was too large. The data of the coating loss at room temperature was taken from the measured Q-values of the fused-silica disks with and without any coating [8].

3. Results

All of the measured coating samples had almost the same magnitude of loss. The dissipation of the NAOJ coating was as large as that of the JAE coating, which was superior in low optical loss to that of NAOJ. As a typical example, the loss of the coating by NAOJ on a 1mm thick disk is shown in Fig.1. The measured coating loss angle, which represents the magnitude of the dissipation, was about 4×10^{-4}. The experimental results of other groups at room temperature had

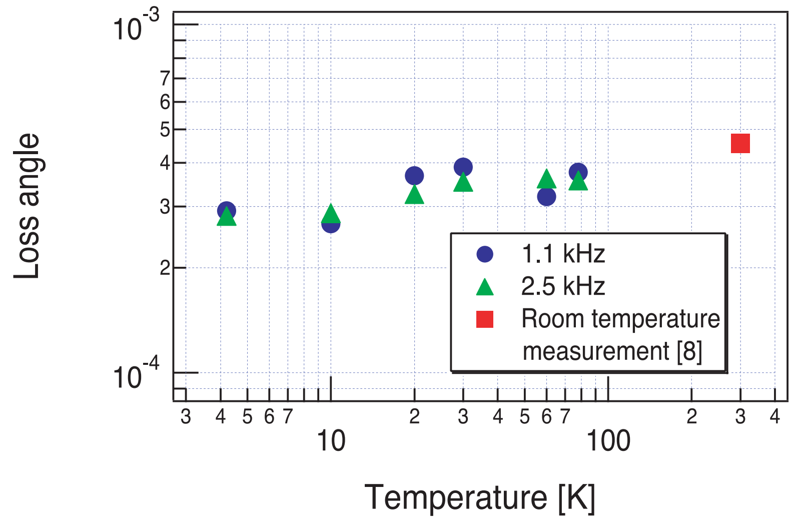

Fig. 1. Mechanical loss of a NAOJ coating on a 1mm thick disk as a function of the temperature. The results of the JAE coating were almost the same as that of the NAOJ coating. The loss angle is the magnitude of the dissipation in the coating. The circles and triangles show the coating loss derived from the Q-values of the first and third modes of the mechanical oscillation, respectively. The square represents the result of a room-temperature measurement [8].

similar values [3,9]. According to our measurement, the coating loss is almost independent of the temperature between 4 K and 300 K.

4. Discussion

The coating loss does not depend on the temperature. This means that the amplitude of the thermal motion caused by the coating loss is proportional to the square root of the temperature. The thermal noise at 20 K is four-times smaller than that at room temperature. Therefore, the cooling mirror is effective to decrease the thermal noise of the coating. This is the advantage of a cryogenic interferometer. According to the obtained value of the coating loss, the thermal noise of the coating loss in LCGT is below the goal sensitivity limit of LCGT, as shown in Fig.2. If the mirror was at room temperature, the thermal noise was larger than the goal sensitivity.

5. Conclusions

We measured the mechanical loss in the reflective coating of the mirror at low temperature in order to evaluate the thermal noise of the LCGT interferometer. The measured coating loss angle was 4×10^{-4} and was independent of the temperature between 4 K and 300 K. This proved that the thermal vibration

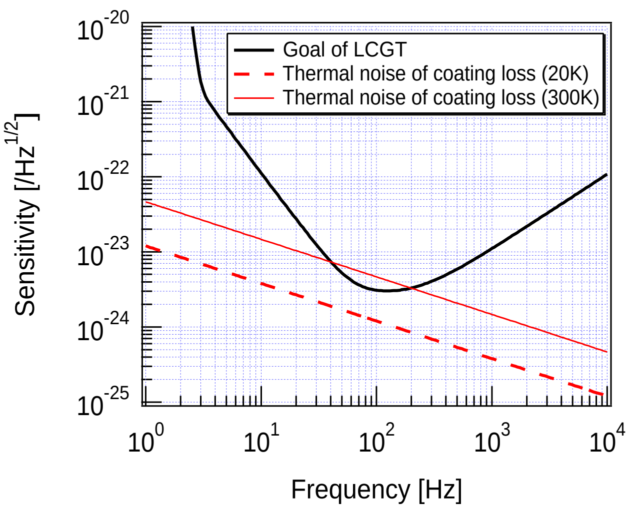

Fig. 2. Thermal noise of the coating loss in LCGT. The solid thick line is the goal sensitivity of LCGT. The dashed line represents the thermal noise of the coating loss at 20 K. The thin solid line shows the thermal noise of coating loss at 300 K.

caused by the coating loss is proportional to the square root of the temperature. Thus, the cooling reduces the thermal motion effectively. This is the advantage of a cryogenic interferometer. The thermal noise of the coating in LCGT is smaller than the goal sensitivity limit. The coating loss has turned out to be a non-serious problem in LCGT.

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