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The sensitivity of large scale interferometric gravitational wave detectors currently under construction, will be limited by thermal noise in the mirror-suspension system. Cryogenic cooling is made difficult because of the necessarily high laser power (5 kW) incident on the mirrors. An all sapphire system of high conductivity and low-loss has been developed. Experiments confirm that mirrors for the TAMA detector could be cooled to as low as 14.5 K. This represents two-orders of magnitude reduction in the mirror-suspension thermal noise energy.

Key words: Cryogenics; Gravitational wave detector; Laser interferometer; Thermal noise; Sapphire

1 Introduction

To attain sufficient sensitivity for gravitational wave detection, laser interferometric gravitational wave detectors, such as LIGO[1], VIRGO[2], GEO[3] and TAMA[4] are now under construction. These interferometers necessarily require mirrors suspended as test masses. One of the major noise sources is the Brownian motion of the mirror-suspension system induced by the finite temperature and acoustic losses[5]. It is expected that this will limit the detector

sensitivity at the frequencies of order tens of Hz to a few hundred Hz.

The thermal noise consists of vibrations arising from two major modes; 1, the pendulum mode due to the Brownian motion of the suspended mirror supported by a wire or a fiber, and ; 2, the mirror internal mode due to the elastic vibration of the mirror itself. Since the amplitude of the thermal noise is proportional to $(\frac{T}{Q})^{\frac{1}{2}}$, where T is temperature and Q is acoustic Q -factor, decreasing T or increasing Q will reduce the magnitude of the noise.

The use of cryogenics to reduce thermal noise by reducing the temperature and increasing the acoustic Q -factor has been widely applied to resonant mass gravitational wave detectors. However nobody has yet applied it to laser interferometer gravitational wave detectors. In this paper, we describe the feasibility of cooling a mirror when heat generation due to the absorption of high power laser light at the mirror surface is present.

We constructed an experiment to study the heat transfer from the sapphire mirror through the sapphire fiber suspension. We tested whether we could use the sapphire fiber as a heat path and the distribution of the temperature of the sapphire mirror. In the following sections, we present results of our experiment and show that the system is promising and works well.

2 Cooling the mirror

There are three common processes for transferring heat; radiation, convection and conduction. For our purposes, radiation and convection can not be used, as radiation decreases by T^4 and convection does not work effectively in vacuum. Thus, we undertook an investigation of conducting heat through the mirror suspension wires. Wire material with high thermal conductivity

and low-loss at cryogenic temperature is needed. Originally we studied highly pure aluminum which has been used as a high thermal conductor for superconducting magnets[6][7]. However, we have shifted our attention to sapphire fiber[8], because both the acoustic Q -factor and thermal conductivity of sapphire increase at low temperature[9][10].

The mirror material must also have high thermal conductivity and low-loss at cryogenic temperature. If the thermal conductivity is low, the mirror has a large thermal gradient and another noise is present due to thermal lensing[11]. Sapphire is also promising in this regards. Previous studies have also shown that a sapphire mirror can offer advantages over other materials at room temperature[12].

3 Experiment and Results

To test the effectiveness of cooling the mirror the experimental setup in Fig. 1 was implemented. To calculate the equilibrium temperature, a simple model was formed by assuming that the mirror was in thermal equilibrium, and heat transfer was totally dependent on the sapphire fiber. In addition to this, we had to consider thermal contact resistance between the mirror and fiber, as the equilibrium temperature of the mirror was larger than predictions from the simple model.

We used a sapphire cylinder of 10 cm in diameter and 6 cm in length (the same size of the main cavity mirror of TAMA)[13]. Both sides of the cylinder were optically polished and the cylindrical surface was left rough. The cylinder was put on a teflon table and wound by two sapphire fibers of $250\mu\text{m}$ in diameter. Ends of the sapphire fiber were clamped to a copper table. The teflon table

Fig. 1. The experimental setup.

was pressed toward the cylinder to maintain a tension in fibers with a set of springs. Instead of heat generation due to the absorption of laser power, we put a foil heater on the surface of one side of the cylinder. To measure the temperature we put eight thermometers on the cylinder and one on the copper table. This system was installed in a vacuum tank which was evacuated down to almost 10^{-4} Pa. The vacuum tank was in a liquid helium cryostat and the copper table was cooled to 4.2 K.

We applied four different heat powers (1.8 mW, 7.2 mW, 16 mW and 29 mW) to the sapphire mirror. Figure 2 shows how the mirror temperature changed as a function of time for an input power of 29 mW. Homogeneity of the temperature distribution was confirmed as shown in Fig. 3. Other measurements agreed within 0.2 K, which is within the calibration error of the thermometers.

Figure 4 shows the equilibrium temperatures as a function of heater power along with calculated temperatures from the simple model neglecting contact resistance. The difference between measurement and calculation is most likely caused by the thermal contact resistance. This problem may be reduced by polishing the cylindrical side of the mirror, by applying larger tension to the suspension fibers or by making a larger contact area between the mirror and

Fig. 2. The mirror temperature changes as a function of time for an input power of 29 mW.

Fig. 3. Distribution of equilibrium temperature under the case of 29 mW heat power.

Fig. 4. Summary of measured equilibrium temperatures and calculated temperatures from the simple approximation neglecting the contact resistance.

the fibers.

4 Application to the TAMA300 detector

Based on our results we estimated the potential performance of TAMA with a cryogenic mirror and we show that the sensitivity of TAMA may be significantly enhanced.

The dissipative laser power at the mirror surface was calculated assuming the following parameters of TAMA[14]; input effective laser power of 30 W and Fabry-Perot cavity of fineness of 520. If we assume that the laser light is absorbed at the surface coating, and is of the level 0.5 ppm[15], then the heat dissipation can be estimated to be a 2.5 mW. Since the length of fiber in our experiment was 5 times shorter than that of TAMA, the heat production of 2.5 mW for a TAMA mirror is equivalent to 12.5 mW in our experiment. From Fig. 4, this corresponds to an equilibrium temperature of 14.5 K. Because of the contact resistance, 14.5 K can be considered a conservative estimate. Combined with the expected improvement in the acoustic Q -factor[10], this results means that the amplitude of the thermal vibration noise in a cryogenic mirror should decrease by one order of magnitude. This is equal to extending the arm length of a room temperature TAMA from 300 m to 3 km in a frequency region where noise is determined by thermal vibration.

5 Conclusions

From our result we conclude the following,

- (i) Sapphire fiber works as an excellent heat path.
- (ii) The temperature of the sapphire test mass is uniform.

- (iii) Thermal contact resistance exists and further ways of reducing this should be investigated.
- (iv) From the current results we estimate a mirror temperature of 14.5 K may be maintained for the TAMA300 detector.

The next step of this development for the cryogenic mirror is to confirm at cryogenic temperatures that the acoustic Q -factor of the cryogenic mirror system improves as expected.

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