Study of Heat Links for a Cryogenic Laser Interferometric Gravitational Wave Detector

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Abstract

Heat links are used in order to cool mirrors of Large-scale Cryogenic Gravitational wave Telescope (LCGT). In order to evaluate the mirror fluctuation of vibration caused by the heat link, we have measured the size effect about thermal conductivity of pure aluminum and copper wires and their mechanical losses and Young's moduli at low temperature. By this measurement we can design the noise introduced from the heat link made sufficiently small by using reasonably a large number of wires with small diameter as the heat link.

1. Introduction

In Large-scale Cryogenic Gravitational wave Telescope (LCGT) [2,3], cryogenic mirrors are adopted to reduce the thermal noise of mirror internal, pendulum modes and optical coatings. In order to maintain the mirror that is heated by absorption of the laser power at low temperature (about 20 K), a heat link is inevitably used between the intermediate mass at 14 K which suspends the mirror by the sapphire fibers and the radiation shield at 8 K which covers the suspension system. However, the heat link introduces the mechanical vibration of the radiation shield which vibrates almost as much as the ground. This trade-off depends strongly on the thermal conductivity dependence on a wire's diameter, that is the size effect. The cross sectional area of the wire is proportional to the square of the diameter. On the other hand, the U-shape heat link wire's spring constant is proportional to the forth power of the diameter. Therefore, keeping the total thermal conductance to be constant, a large number of wires (number of N) with small diameter can reduce the amount of the introduced seismic noise by $1/N$ in the case of no size effect, while $1/N^{1/3}$ with the size effect that the thermal conductivity is proportional to the diameter of the wires. Because this factor affects a lot on the heat link design, we have measured the size effect of

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pure aluminum and copper wires which are expected to be the best materials as thermal conductor. In addition to this measurement, we have also measured their mechanical losses and Young's muduli at low temperature that determine the magnitude of the thermal noise of the heat link.

2. Size effect

We have measured the size effect by measuring Residual Resistance Ratio (RRR), since the thermal conductivity is proportional to RRR at low temperature. RRR is an index of quality of pure metals and defined as a ratio of electrical resistivity at 300 K to 4.2 K.

The measured samples were 99.999 % aluminum wires of ϕ1.99 mm, ϕ1.00 mm, ϕ0.50 mm and ϕ0.20 mm, and 99.99999% copper wires of ϕ1.00 mm and ϕ0.20 mm. We have measured their electrical resistances both at 300 K and at 4.2 K by the four-wire method, and calculated RRRs.

Table 1 shows the RRRs of samples, where specific represents specific ratio to RRR of ϕ1.00 mm wire. This result proved that the size effect of pure aluminum and copper wires whose diameters are larger than 0.2 mm is not dominant in a magnitude affecting the design of the heat link for the cryogenic mirror. This result is also reasonable because the mean free path of the free electrons is much smaller than 0.2 mm.

Table 1. RRRs of samples.

	Diameter[mm]	0.20	0.50	1.00	1.99
Al	RRR	2900	4800	5500	6200
	Specific	0.53	0.87	1.0	1.1
Cu	RRR	960	-	4100	-
	Specific	0.23	-	1.0	-

We have also measured thermal conductivity of samples directly by the longitudinal heat flow method [5]. This result agreed with theoretical plots from the measured RRRs [1]. Thermal conductivity of an aluminum wire with RRR-5000 is larger than 2×10^4 W/m/K.

3. Mechanical loss and Young's modulus

We have measured the resonant frequencies and the amplitude decays of the pendulum mode vibration for samples of aluminum and copper wires with 0.20 mm diameters and 125 mm lengths at 293 K, 78 K and 8 K suspending about 500 mg aluminum masses. We can calculate Q-values and Young's moduli of samples from the measured values and the dissipation dilution theorem [4].

Table 2 and 3 show resonant frequencies (f_{R}), Q-values of pendulum mode (Q_{P}), Q-values of samples themselves (Q) and Young's moduli (E) at each temperatures (T).

Table 2. Q-values and Young's moduli of an aluminum ϕ0.20 mm wire.

T[K]	f_R[Hz]	Q_P	Q	$E \times 10^{-10}$[Pa]
293	1.567	792.3	151.6	3.3
78	1.594	1193	260.7	4.3
8	1.596	1567	345.6	4.3

Table 3. Q-values and Young's moduli of a copper ϕ0.20 mm wire.

T[K]	f_R[Hz]	Q_P	Q	$E \times 10^{-10}$[Pa]
293	1.683	1603	479.4	10
78	1.764	1606	581.2	15
8	1.727	4856	1623	13

4. Discussion

The size effect of pure aluminum and copper wires whose diameters are larger than 0.2 mm was not detected in a magnitude affecting the reasonable design of the quiet heat link for the cryogenic mirror. When we use 30 U-shape aluminum wires with 0.50 mm diameters and 63 cm lengths as the heat link that can convey the heat more than 1 W, the seismic noise introduced by the heat link is estimated by calculation based on the default design of LCGT as shown in Fig. 1, where we consider both the mechanical vibration noises caused by the vertical motion of the intermediate mass and horizontal. The seismic noise dominates the sensitivity of LCGT at around 4Hz. However, this frequency range is out of the observation band (20 Hz-2 kHz). The thermal noise of the heat link estimated from measured Q-value and Young's modulus is much smaller than the goal sensitivity of LCGT.

5. Conclusions

The size effect of pure aluminum and copper wires whose diameters are larger than 0.2 mm was not dominant. The mechanical noise introduced by the heat link is able to be made smaller than the goal sensitivity of LCGT. Therefore, we can install the heat link for LCGT without degrading its sensitivity.

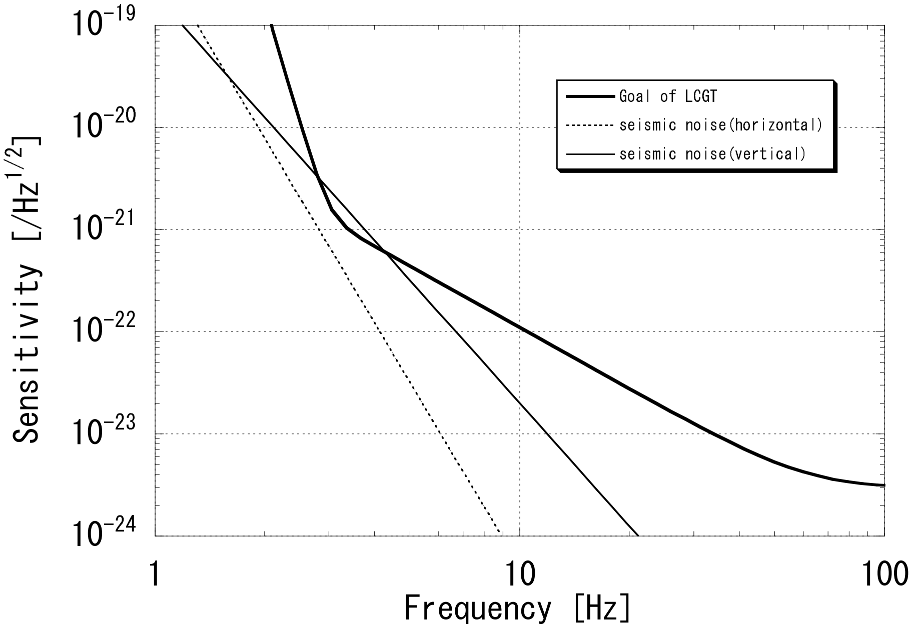

Fig. 1. Mechanical vibration noise introduced through the heat link. The thin line represents the mechanical vibration noise caused by the vertical motion of the intermediate mass. The broken line represents the mechanical vibration noise caused by the horizontal motion of the intermediate mass. The solid line is the goal sensitivity of LCGT. The thermal noise of the heat link is not shown in this figure because it is much smaller than the goal sensitivity.

References

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