Cryogenic systems of the Cryogenic Laser Interferometer Observatory

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Abstract. Cryogenic Laser Interferometer Observatory (CLIO) is a laser interferometric gravitational wave detector using cryogenic cooled mirrors. In order to cool the mirrors, cryogenic environment is necessary. We made four vacuum chambers with cryogenic cooled shields inside. The mirror is suspended by a mirror suspension system with a heat path for transferring heat from the mirror to the shield. Test cooling of the chambers and the mirror suspension system has been done. After one week cooling, the chambers was cooled from 8 K to 10 K and the mirror were cooled at 21 K successfully.

1. Introduction

Cryogenic Laser Interferometer Observatory (CLIO) is a laser interferometric gravitational wave (GW) detector with 100 m arms[1]. The use of cryogenic cooled mirrors and an underground site are features of CLIO. The Japan GW group has a future detector plan, Large-scale Cryogenic Gravitational wave Telescope (LCGT)[2][3]. LCGT also is to be in an underground site with cryogenic mirrors, but the arm length will be 3km. The purpose of CLIO is a technical demonstration of LCGT.

CLIO is in Kamioka mine tunnel, 1000 m below the top of a mountain and 2 km from the mine entrance. The seismic noise at the CLIO site is $10^{-9}$m/√Hz at 1 Hz, which is smaller by two orders of magnitude than that at Tokyo. The temperature at the site is also quite stable, and its fluctuation is less than 1 degree. Those are the reasons for choosing this site. CLIO uses a locked Fabry-Perot scheme, and four cavity mirrors are to be cooled to about 20 K.
The cryogenic mirrors provide low mirror and pendulum thermal noise\cite{4}\cite{5}, and make thermal lensing negligibly small\cite{6}.

CLIO started in construction from 2002, and is a four-year project. All vacuum chambers and pipes were successfully installed in 2005 June. All cryogenic systems and two sets of mirror suspension systems have passed cooling tests. The results are described in this paper.

2. Cryogenic systems

Figure 1 shows cryogenic systems for an end mirror. Figure 2 and Fig. 3 are photographs of the systems. The cryogenic systems consist of three items. Those are a mirror tank, cryogenic pipes and refrigerators for cooling the mirror tank and a pipe.

The dimensions of the mirror tank are $1300\,\text{mm} \times 900\,\text{mm} \times 2500\,\text{mm}$. The total weight is 4 t. There is an optical bench at the higher level which is at room temperature. The base of the mirror suspension system is put on the bench. The vibration level on the bench has already been measured\cite{7}. There are two layers of radiation shields (inner and outer) in the lower level. Those are aluminum plates covered by multi-layered super insulators. The insulators are thin Mylar films coated by the aluminum. The dimensions of the inner shield are a diameter of 800 mm and a height of 800 mm. The shields are cooled by a 4K two-stage pulse-tube refrigerator\cite{8}. The cooling powers of the 1st and 2nd stages of the refrigerator are 15 W at 40 K and 0.5 W at 4 K, respectively. Thermal conductors connect the outer shield to the 1st stage and the inner shield to the 2nd stage. The target temperatures of the outer and inner shields are 100 K and 8 K, respectively. The refrigerator is in a small chamber near to the mirror tank, and a vibration-reduction technic\cite{9} is applied. There is a short vacuum pipe between the refrigerator chamber and the mirror tank. The thermal conductors go through the short pipe. Baffle plates with a hole with a diameter of 130 mm for the laser beam are attached to the outer shield.

In order to reduce the radiation heat from the laser hole, a vacuum pipe with a radiation shield is equipped. The diameters of the pipe and the shield are 400 mm and 300 mm, respectively. The end mirror tank equips one 5 m pipe and the near mirror tank equips one 5 m pipe and one 4 m pipe. The remainder of the 100 m arm pipes are not cooled. The shield is cooled by a 80 K pulse-tube refrigerator with the vibration-reduction technic\cite{9}. The cooling power is 15 W at 40 K. The refrigerator is installed in a small chamber near the middle of the pipe. The shield is cooled by a thermal conductor attached to the refrigerator. The shield of the 5 m pipe and the outer shield of the mirror tank are connected by a thermal conductor. Therefore, those shields are cooled by two refrigerators. The target temperature of the shield is 100 K. Two baffle plates with a hole of 150 mm diameter are attached at both edges of the shield.

More than twenty thermometers are installed in each system. Figure 4 shows the temperature changes with cooling at important positions at the end mirror system. In this case, top of the inner shield is cooled at 7.3 K after 5 days of cooling. The top of the outer shield and the middle of the pipe are cooled at 60 K and 44 K, respectively. Figure 5 shows the result of all systems. The 1st cryostat (end mirror) and the 4th cryostat (near) make a Fabry-Perot cavity; the mirror suspension systems have already been installed. Because of the mirror suspension system, the top of the inner shield is cooled to 10.5 K and the cooling time requires more than two days. The 2nd (end mirror) and 3rd (near mirror) are for another cavity, but are empty inside. The top of the inner shield of the 3rd system is cooled at 8.6 K. The outer shield of all systems is cooled at less than 100 K. One system uses a dry pump, and other three systems use a turbo-molecular pump with a rotary pump for evacuation. When the system cooling is finished, all pumps can be stopped, and a vacuum pressure lower than $10^{-4}$ Pa is achieved.

3. Mirror suspension system

The mirror substrate is monolithic sapphire with a diameter of 100 mm and a thickness of 60 mm. Sapphire has a mechanical quality factor of more than $10^8$ under 20 K\cite{4}, a high
Figure 1. Left: Outside view of the cryogenic system. Right: Inside view. 1, the mirror tank; 2, cryogenic vacuum pipe; 3, 4K two-stage pulse-tube refrigerator; 4, 80K pulse-tube refrigerator. a, optical bench (room temperature); b, two layers of radiation shields (outer is 100 K and inner is 8 K.); c, radiation shield (100K).

Figure 2. Outside view.

Figure 3. Inside view.

Figure 4. Result of a cooling test of the end mirror system.

Figure 5. Result of a cooling test of all mirror tanks. The mirror suspension system is installed in the 1st and 4th systems.

thermal conductivity of $4 \times 10^3 [W/m/K]$ at 20 K[10] and a small thermal expansion ratio of $7 \times 10^{-13} \times T^3 [1/K][11]$ in cryogenic temperature. $T$ is temperature. These parameters contribute to the low mirror thermal noise, low mirror thermoelastic noise and low thermal lensing effect. On the other hand, the laser absorption ratio is still high, and takes from 40 to 60 ppm/cm.
The mirror is always heated by absorption of the laser beam. The heat must be taken away to keep the mirror temperature. Since the mirror is in high vacuum and temperature is very low, thermal conduction is the only method to transfer the heat. Therefore, a heat path from the mirror to the inner shield is necessary. Since the heat path also transfers vibration of the inner shield to the mirror, the stiffness of the heat path must be small.

Figure 6 shows a schematic view of the mirror suspension system, and photographs are shown in fig. 7 and fig. 8. The mirror suspension system consists of the three-stages vibration isolation system (VI system) and three stages cryogenic suspension. The VI system uses metal blade springs made of CuBe and eddy-current damping. The resonant frequency of the spring is about 6 Hz in the vertical direction. The final stage of the VI system has five optical stages with pico-motors for mirror alignment. The masses of the 1st and 2nd stage are 5 kg and the final stage is 6 kg. The VI system is put on the optical bench in the mirror tank and is not cooled. The remaining items are suspended from the optical stages into the inner shield. The suspension wire is Bolfur, an amorphous metal wire, and the length and diameter are 800 mm and 100 micron, respectively. Bolfur is expected to avoid acoustic emissions.

There are four masses suspended in the inner shield. The mass of the magnet stage, the cryo-base, and the upper mass is 1 kg. Mass of the mirror is 2 kg. The current mirror suspension wire is 99.999% purity aluminum wire, and the suspension length and wire diameter are 400 mm and 1 mm, respectively. The resonant frequency of the blade spring made of CuBe between the cryo-base and the upper mass is about 6 Hz. Magnet-coil actuators are used for cavity length control of the mirror. The heat paths take a "U" shape, because of the small stiffness.

Figure 9 shows temperature changes with cooling of the end-mirror suspension system. No laser beam is incident in this cooling process. Since the estimated laser absorption is about 1 mW, the temperature distribution is not changed much from this cooling. The mirror is cooled at 21 K. Cooling the mirror takes 7 days. The thermal conductivity of the heat paths, the measured temperature gradients and an assumption of perfect contact between the wires and the masses make it possible to evaluate the heat flows in the suspension. Figure 10 shows the current heat path design, the measured temperatures and the evaluated heat flows. All of the heat paths are 99.999% purity aluminum wires. The parameters of the heat paths are summarized in Table 1.

According to the fig. 10, 6 mW heat is transferred from the damping stage to the inner shield. We think that thermal conduction from the optical stages at room temperature through the Bolfur wires is the major source of this heat; 34 mW heat between the upper mass and the cryo-base comes from the mirror. This is inconsistent from the evaluated heat of 290 mW from the mirror. We think that there is large thermal contact resistance between the mirror and the suspension wires, because the mirror is just put on the thick wires. Thus, 290 mW heat is not correct. Without any contact resistance, the mirror could be cooled at 13.4 K. We believe that radiation from the laser hole is the major origin of this heat, even though 34 mW is larger than our estimation.

### Table 1. Heat-path parameters. All wires are 99.999% purity aluminum wire.

| From                  | To              | Number | Diameter | Length or Radius of "U" shape |
|-----------------------|-----------------|--------|----------|------------------------------|
| Mirror                | Upper mass      | 4 (2 loops) | 1 mm     | length of 400 mm             |
| Upper mass            | Cryo-base       | 8      | 0.5 mm   | radius of 20 mm              |
| Cryo-base             | Inner shield    | 4      | 1 mm     | radius of 100 mm             |
| Damping stage         | Inner shield    | 4      | 1 mm     | radius of 50 mm              |
Figure 6. Schematic view of the mirror suspension system. Left: Mirror suspension system in the mirror tank. Right top: the three stages of the vibration isolation system on the optical bench in the mirror tank. 1: three stages vibration isolation system. 2: optical stages with pico-motors for the mirror alignment. All stages are suspended by metal blade springs made of CuBe. The motions of all stages are damped by magnets. Right bottom: cryogenic part of the suspension system. a: the damping stage for eddy-current damping to the cryo-base. b: cryo-base and upper mass. There are metal blade spring between the cryo-base and the upper mass. The damping stage and the cryo-base are suspended from the optical stages at room temperature independently. Four suspension wires suspend each mass. The mirror is suspended from the upper mass.

4. Summary
The CLIO cryogenic systems have been completed and have passed cooling tests. The inner shield is cooled at about 8 K without any suspension, and the cooling time is 5 days. With suspension, the temperature is 10 K and the cooling time is 7 days. Two sets of the mirror suspension systems have also been installed and cooled. The mirror was cooled at 21 K, even though there is the contact resistance. We have found that 34 mW of heat is absorbed in the mirror.

We have confirmed that the cryogenic systems and the mirror suspension system took an important step toward full operation of CLIO.

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Figure 7. Photograph of the vibration isolation system on the optical bench.

Figure 8. Photograph of the damping stage, the cryo-base and the upper mass.

Figure 9. Result of a cooling test of the mirror suspension system in the 1st system.

Figure 10. Measured temperatures and evaluated heat flows in the suspension system. The arrows show the heat flow. Measured temperature of the inner shield and all suspended masses are shown at the right side of the figure. This evaluation assumes perfect contacts between the wires and the masses. No laser beam is incident.

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