CLIO Cryogenic Laser Interferometer Observatory

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Abstract

Cryogenic Laser Interferometer Observatory (CLIO) is now constructed to demonstrate two of three features of Large-scale Cryogenic Gravitational wave Telescope (LCGT), that are to utilize low seismic and stable environment in the Kamioka mine and sapphire mirrors at low temperature for thermal noise reduction. CLIO has a locked Fabry-Perot configuration equipped with ring mode cleaners for laser frequency stabilization and the cryogenic vacuum and cooling system using refrigerators to cool the sapphire mirrors at 20 K. The noise level of CLIO is designed to synchronize with the thermal noise of sapphire mirrors which varies from $3 \times 10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 300 K to $2 \times 10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 20 K around 100 Hz.

1. Introduction

One of main features of LCGT [2] is to utilize cryogenic sapphire mirrors to reduce mirror thermal noise which is the final barrier to reach the quantum noise level. As R&Ds for LCGT, some researches about the mirror cooling method [10] and the cryogenic mirror contamination protection [3,4], the material selection for the mirror [11] and thermal conductors [1], the quality and property check of the sapphire substrate [7,8,9], the manufacturing low loss high quality TAMA size (100 mm in diameter and 60 mm in thickness) sapphire mirrors, measurement of coating mechanical loss at low temperature [12] and the development of a low vibration refrigerator system were done. Based on these knowledge, the control of

pp. 3073–3076

a cryogenic Fabry-Perot optical cavity was demonstrated at 20 K with displacement noise level of $4 \times 10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz in Cryogenic Laser Interferometer in Kashiwa (CLIK) at ICRR [5].

Another feature of LCGT is to utilize the low seismic noise and stable environment in the Kamioka mine in Gifu prefecture in Japan. To investigate the stable operation of a km-scale interferometer, a 20m Fabry-Perot type laser interferometer (LISM [6]) equipped with one mode cleaner and 25000 finesse Fabry-Perot cavity whose corresponding storage time is 1 msec, was set there, and 120 hours successive operation was demonstrated without any controls of mirror alignment control at $2 \times 10^{-18}\mathrm{m}/\sqrt{\mathrm{Hz}}$ displacement level at 1 kHz.

Based on these R&Ds, CLIO which has a 100 m baseline and the cryogenic system is under construction in the same Kamioka mine to show the feasibility of a cryogenic laser interferometer at the displacement level around $1\times10^{-19}\mathrm{m}/\sqrt{\mathrm{Hz}}$ by reducing the thermal noise (thermoelastic noise) of sapphire mirrors.

2. CLIO Design

The Kamioka mine which is 1000 m underground has so hard and large block bedrock that its elastic wave velocity reaches up to 5000 m/sec and no fatal dislocations, which produce unexpected phase delay and wave form distortion, were not found. This benefits the high common mode rejection of the seismic motion up to 20 Hz in LISM. The temperature and the humidity variation was so small (0.1 degree and 1% per day, respectively) that the drift of the mirror alignment and the cavity length was small.

The targeted displacement noise of CLIO and expected thermal noise of sapphire mirrors at 300K and 20 K are shown in Figure 1. The displacement of CLIO at 20K is dominated by three noise sources: the seismic noise for the frequency range less than 50 Hz, the radiation pressure noise from 50 Hz to 100Hz and the shot noise above 100 Hz.

CLIO optical configuration is a locked Fabry-Perot style equipped with two mode cleaners. A 1064 nm wave length, 2 W output power Innolight laser source will be used. One short rigid mode cleaner serves as an intensity noise eliminator at two modulation frequencies. The other mode cleaner consists of a low finesse Fabry-Perot cavity whose mirrors are isolated by double pendulums, and it serves as a higher transverse mode eliminator and as a first-stage frequency stabilization reference. One of the modulation sidebands is loosely controlled to transmit through the second mode cleaner. After bouncing in a mode matching telescope, the transmitted beam (about 0.5 W) is introduced to two arm cavities whose finesse is planed to be 7500 through a beam splitter. The beam splitter and a set of optical circulating components including a polarized beam splitter and a quarter wave plate are put in individual chambers at room temperature. On the other hand, the main mirrors consisting Fabry-Perot cavities are set in cryogenic chambers. Each arm and the second mode cleaner mirrors are also alignment controlled with less than 1 Hz unity gain frequency. The mirror substrate is sapphire manufactured by Crystal Systems Inc, and its coating is still multi-layered films of SiO_2/Ta_2O_5 by Japan Aviation Electronics Industry Ltd. This combination has been verified at 20 K temperature as a CLIK optical Fabry-Perot cavity which had 3140 finesse and 0.009 cavity reflectivity [11].

The cooling system is based on the almost same system demonstrated in the CLIK test bench. A pulse tube cryocooler which has two cold cooling stages (4 K and 40 K) is set in a separated small vacuum tank and each cold head cools double radiation shields inside the main mirror vacuum cryostat. To minimize the periodical vibration originated from the cold head stage where helium gas acts as a displacer, a cascade isolation cold stage is set just around these two cold stages. These isolated stages are linked with 4 K and 40K heads using U-shape pure aluminum wires [6], and the 4K stage serves as the heat anchor for the rest 4 K radiation shield. The base of this tube part is fixed on the separated metal frame which is fixed rigidly on the floor and connected with the refrigerator enclosure vacuum chamber through a welding bellow. The valve unit which generates the pressure cycle is also separated from the base and fixed also on a separated metal frame. The water cooling compressor unit which circulates Helium gas for heat removal is set in a small space isolated by a concrete wall to reject its sound and vibration noise. An additional isolation mechanics will be introduced for the thermal conductors between the cold stages and the double radiation shields. To reject the mirror contamination due to cryogenic molecule adsorption, several-meter long radiation shield tubes are extended from the mirror chamber shield towards optical beam ducts [4]. An additional 80 K pulse tube type GM refrigerator assists cooling this radiation shield. It has also isolating heat link connection using copper mesh tapes between its head and the shield.

The main mirrors are cooled only by thermal conduction of a series of sapphire fibers and U-shape pure (over 6-nine) aluminum wires. The former have a role of pendulum wires which are suspended from an upper mass and wrap directly the mirrors. The latter links the upper mass to heat anchor points on 8 K radiation shield through some isolated masses.

Although the seismic noise in the Kamioka mine is smaller by 1/100 times compared with that in a city area [12], two seismic motion transmissions to mirrors should be isolated; one comes from the main mirror suspension point and the other from a ~ 8 K heat anchor point through a heat linked relay masses. For the main mirror isolation, more than one stage stack system and a triple pendulum are required to obtain less than $10^{-20}\mathrm{m}/\sqrt{\mathrm{Hz}}$ displacement at 100 Hz. These stack and suspension point are situated at room temperature area, while the upper masses and the main mirrors are situated inside the radiation shields. For the heat link path isolation, three U-shape heat link wires are relayed to the upper

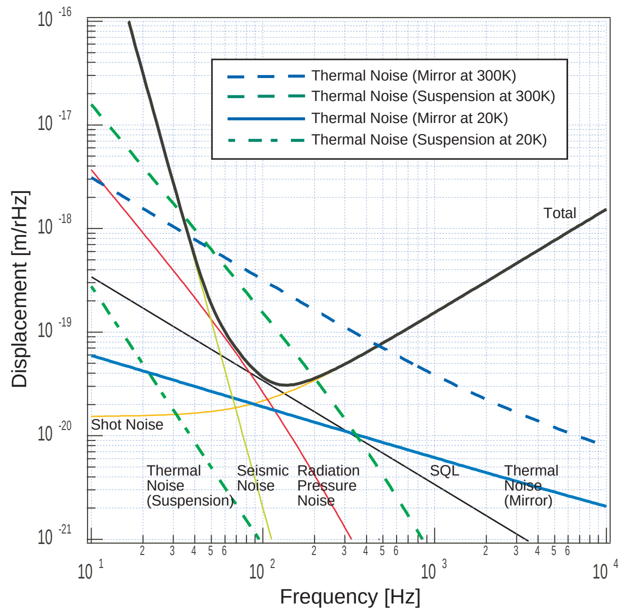

Fig. 1. CLIO expected displacement noise level.

mass of the main mirror pendulum through two masses which consist, for example, of a double pendulum upper mass and lower mass inside the 8 K radiation shield.

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