Large Scale Cryogenic Gravitational Wave Telescope

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Large scale Cryogenic Gravitational wave Telescope (LCGT) is proposed to detect directly gravitational waves from neutron binary star coalescences at 240 Mpc away from our galaxy with signal to noise ration of 10. The designed strain sensitivity is $3\times10^{-24}1/\sqrt{\mathrm{Hz}}$ at 100Hz. To realize this sensitivity, LCGT is to be set in a stable and low seismic noise environment such as the Kamioka mine, to have sapphire cryogenic mirrors and suspension fibers, and to utilize broad band RSE technique combining with power recycling technique. Two identical telescopes are set in the same site to enhance the signal confidence. We will introduce the refined LCGT design.

1. Introduction

Large scale Cryogenic Gravitational wave Telescope (LCGT)[1] is one of advanced gravitational wave detectors, such as Advanced LIGO[2], EGO[3] and a dual resonant type detector[4]. Among of them, LCGT takes a characteristic approach to utilize cryogenic (20K) sapphire mirrors and fibers to reduce mirror and suspension-wire thermal noises, which are the final barriers to reach the quantum noise level limited by the radiation pressure noise and the shot noise.

As R&D for LCGT, some research projects mainly for cryogenic techniques have been already investigated : a) mirror-cooling techniques[5], b) cryogenic-mirror durability[6] and its contamination estimation and protection[7], c) material selection for the mirror[8], d) thermal conductors[9], e) quality (optical loss) and property (thermal expansion ration upper limit, thermal conductivity, expected thermal lensing at 20K) check of the sapphire substrate[10–12], f) manufacturing low-loss high-quality sapphire mirrors (100 mm in diameter and 60 mm in thickness), g) a coating mechanical loss at low temperature[13]) the development of a low vibration refrigerator system[14]. Based on this accumulated knowledge, control of a cryogenic Fabry-Perot optical cavity was demonstrated at 20 K with a displacement noise level of $4\times10^{-16}\mathrm{m}/\sqrt{\mathrm{Hz}}$ at 100 Hz in the Cryogenic Laser Interferometer in Kashiwa (CLIK)[15] at ICRR.

In this paper, we will present the refined LCGT design based on these R&D and experiences in TAMA300[16] and LISM[17] interferometer.

2. LCGT Design

2.1. Sensitivity

A figure 1 shows the designed LCGT sensitivity. The radiation pressure noise dominates it for the frequency range from 3Hz to 100 Hz because the suspension thermal noise is suppressed due to suspension fiber cooling. Above 100Hz, the sensitivity is dominated by shot noise because the coating and internal thermal noise are also reduced by cooling mirrors at 20K. The resulted sensitivity enables the chirp gravitational wave (GW) detection from $1.4\mathrm{M}_{\odot}$-$1.4\mathrm{M}_{\odot}$ neutron star (NS) binary coalescences at 240 Mpc with a signal to noise ration of 10 at a rate of 0.3-3 events per year.

2.2. Base Environment

LCGT is set in the Kamioka mine, which is 37 km away from Nippon Ocean and situated at a height of 358 m above sea level, but in 1000 m underground from the top of a mountain. Because the ground surface noise excited by ocean waves and wind is well-attenuated there, the seismic noise level is 1/10 smaller below 1 Hz and 1/100 around 10 Hz compared with a city area. In addition, the Kamioka mine consists of such

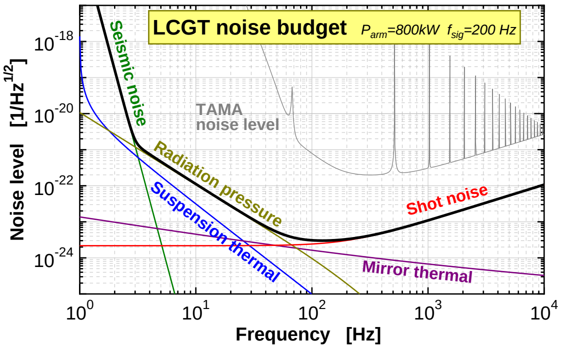

Figure 1. LCGT Sensitivity

a hard and large block bedrock of Hida gneiss that its elastic wave velocity reaches up to 5300 m/sec for P-waves and 3000 m/sec for S-waves. This benefits the high common-mode rejection of the seismic motion. Since the temperature variation in the mine is 0.1 degree per day and the humidity's is 1% per day, the resulted drift of the mirror alignment and the cavity length is almost dominated by only the Earth tidal motion ($\sim 5\mu$m in length for 100 m length) and the airs pressure change. The only apprehension concerning the underground location is the grounding for the electronics, because the gneiss is a nearly insulating material. To remedy this, a metal bar is introduced from the surface ground.

2.3. Optical Configuration

LCGT utilize a Fabry-Perot michelson interferometer combining a power recycling[18] and a broad band resonant sideband extraction[19] (RSE) technique. Because the GW detector sensitivity is ultimately supposed to be dominated by shot noise and radiation pressure noise, the storage laser power inside a Fabry-Perot cavity and a signal bandwidth can be optimized to obtain the longest distance where we can detect the GW of NS binary coalescences with S/N = 10. Because 100 W injection laser power to the interferometer is assumed in the LCGT, a 400 kW storage laser power and a 200 Hz bandwidth are practically selected by setting a power recycling gain and a signal band gain to be 10 and a finesse of the cavity to be 1250. This gain distribution also can keep heat generation inside a cryogenic mirror to be 0.3 W.

A figure 2 shows the optical setup of LCGT. A 300 W, 1064nm wave length laser source is prepared. After the laser beam goes through two ring type mode cleaners, 100 W laser beam is introduced in an interferometer which has 3km arm length Fabry-Perot cavities. A recycling mirror and an RSE mirror are put at a symmetric and an antisymmetric port of the interferometer, respectively. The recombined beam is filtered by an output rigid mode cleaner and is detected to obtain GW signals. Only four mirrors and their suspension fibers, which consist of the arm Fabry-Perot cavities, are made of sapphire and are cooled at 20 K, while the rest optical components including a beam splitter are set at room temperature.

To obtain 300W laser power, 10 W power is firstly produced by an injection-locking technique from a 2W Nd:YAG master laser, and 300W power is secondly produced by an optical amplifier using a series of side-pumped Nd:YAG crystals. The alternative is a coherent addition laser. The expected original frequency noise and intensity noise are $3 \times 10^4 f^{-1}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ and $1 \times 10^{-5} f^{-0.2}$, respectively. The required frequency and intensity stabilization level is $4 \times 10^{-8}\mathrm{Hz}/\sqrt{\mathrm{Hz}}$ and 2×10^{-8}, respectively. Using the two mode cleaners as a frequency reference, the laser frequency noise is pre-stabilized, and it is hierarchically stabilized by an arm cavities common length signal. The intensity noise is stabilized by using a laser LD current control according to a sampled portion of the laser power inside vacuum area.

As a cryogenic mirror and suspension fiber material, sapphire is selected because of its high thermal conductivity, high mechanical quality factor (10^8) and resulting negligible thermal lensing effect at low temperature. The mirror has 30 cm in diameter and 18 cm in thickness, resulting weight of 50 kg. The fiber has 1.8 mm in diameter, 0.5 m in length. The required absorption loss is set to be 20 ppm/cm, which generates 0.3 W heat in one mirror. Even the loss of a coating film is same with the current value (4×10^{-4}), the coat-

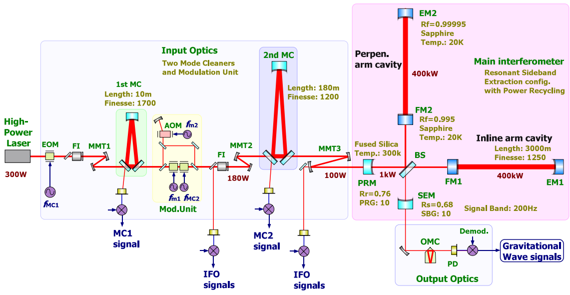

Figure 2. LCGT Optical Configuration

ing thermal noise is suppressed below the targeted sensitivity because of low temperature.

2.4. Seismic Noise Isolation

To obtain high seismic noise reduction ratio below 10 Hz, LCGT will utilize the SAS system[20]. The SAS consists of 1) an inverted pendulum for horizontal isolation 2) several Geometrical Anti Spring filters for vertical isolation at room temperature area and 3) a double pendulum containing re-coil masses which are suspended from a suspension platform in the cryogenic area. This suspension platform is situated at the final stage of the SAS system. To reduce seismic noise through heat link wires to the upper mass, a suspension point interferometer[21] will be introduced. Not only the main sapphire mirrors, but also their upper masses consist of Fabry-Perot cavities and the fluctuation to the upper masses are suppressed to the frequency noise level.

2.5. Cooling System

Instead of liquid helium and nitrogen, a low-vibration pulse tube type cryocooler[22] will be used. A cryostat housing mirrors has two radiation shields (80 K and 8 K), and these shields are cooled by the cryocooler using only thermal conduction. The targeted vibration noise level is comparable with the Kamioka mine seismic noise level. To reject mirror contamination due to cryogenic adsorption of molecules, several 10 meters long radiation shield tubes are extended from the cryostat towards optical beam ducts. A series of heat link wires, which are made of pure aluminum, are bridged between the 8 K radiation shield and the upper mass (16 K), from which the sapphire mirror is suspended, through several isolated heat link masses to isolate the seismic noise through the heat link wires. The upper mass is cooled by thermal conduction using this heat link wires. The sapphire mirror is cooled at 20 K using the four suspension sapphire fibers which are heat anchored at the upper mass. The suspension fibers are design to transfer 1 W heat.

2.6. Two Detectors

LCGT plans to have two identical detectors in the same tunnel. To obatain the signal confidence of 3σ for one GW event per year, background noise level should be 2.7×10^{-3} events per year, and a required background event for one detector should be 3.0×10^{-4} events/sec, assuming typical time window of 1 msec.

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