論文の内容の要旨

A Study of Cryogenic Techniques for Gravitational Wave Detection

（重力波検出のための極低温技術の研究）

榊原　裕介

Einstein's theory of general relativity has predicted gravitational waves, ripples of space-time curvature travelling with light speed. Evidence of the gravitational waves has been obtained in observations of binary pulsars or, possibly, recent CMB observation. However, the gravitational waves have not been detected directly yet. The direct detection of the gravitational waves is of great importance in physics to test the general relativity and in astronomy to open gravitational wave astronomy. Currently, one of the most promising methods to detect the gravitational waves directly is utilizing a laser interferometer to measure extremely small displacement ($\sim 10^{-21}$ m) of its mirrors. When the gravitational waves come to the interferometer, the differential length of its two arms changes. The first generation of interferometric gravitational wave detectors, such as LIGO in USA, VIRGO in Italy, GEO in Germany, and TAMA in Japan, have already been in operation, and several second-generation detectors are currently under construction, such as AdLIGO, AdVIRGO, and KAGRA (the Large-scale Cryogenic Gravitational wave Telescope (LCGT), a km-scale cryogenic detector project in Japan). KAGRA aims to detect the gravitational waves from coalescence of binary neutron stars more than once per year. Third-generation gravitational wave detectors, such as ET (the Einstein Telescope) in Europe, are also being planned. KAGRA and ET will enjoy two key advantages over other detectors: they will be constructed in an underground site with small seismic motion, and they will be equipped with cooled mirrors (at around 20 K in the case of KAGRA).

One of the largest advantages of the cryogenic mirrors is reduction of thermal noise. Thermoelastic noise in the mirror substrates, one of the thermal noise sources, is caused by thermoelastic damping. Thermoelastic damping is caused by heat flows between compressed (heated) and stretched (cooled) area when mirror has elastic vibration. While this thermoelastic noise is approximately constant between 300 K and 50 K, it steeply decreases below around 50 K. The thermoelastic noise finally becomes lower than other thermal noise sources, becoming dominated by Brownian noise in the coating, at around 20 K. Therefore, design temperature of the KAGRA mirrors is 20 K, where the thermal noise of the mirrors is one order of magnitude smaller than that at 300 K.

In this thesis, I have developed the cryogenic techniques to be introduced in the gravitational wave detectors:

- Reduction of cooling time (main topic of this thesis)
- Technique of a pipe-shaped thermal radiation shield (duct shield)
  - Thermal radiation
  - Scattered light noise

The cooling time of the mirrors (several months in KAGRA) is one of the most important problems in the cryogenic gravitational wave detectors. KAGRA will have heating up and cooling down of the mirrors at least once per year. During that time, KAGRA cannot observe gravitational waves, and then KAGRA will miss gravitational wave events, such as the coalescence of binary neutron stars. Thus, the long cooling time decreases observation efficiency of the detectors, and it is necessary to reduce the cooling time. In the cryogenic interferometric gravitational wave detectors, such as KAGRA and ET, thermal conductors will be used to extract heat from the suspended mirror to keep the mirror cooled. To reduce vibration via the conductor, the mass to be cooled should be heavy, and the conductor should be long and thin wires. This is the main reason why it will take a long time to cool down the mirrors. On the other hand, continuous operation of the detectors causes reflectivity of the mirrors to decrease due to adsorption of water molecules on the mirrors. In KAGRA, water molecules will come from its beam duct with room temperature onto the mirrors. These molecules adsorbed by the mirrors will decrease the mirror reflectivity, the finesse of the cavity, and then the sensitivity to the gravitational waves. Frequency of the heating up and cooling down of the mirrors to remove the water molecules is estimated to be once per 300 days. Additionally, other maintenances could be necessary because of any other unexpected troubles.

In order to reduce cooling time, this thesis describes increasing thermal radiation as a first step. There are several methods for reducing the cooling time. One of them, increasing thermal radiation is a less effective method to extract heat from the mirrors than other methods. However, increasing radiation has a great advantage that it is simpler, namely, it avoids a use of a mechanical apparatus, which could cause troubles and sacrifice a high stability required for a large-scale detector.

Thermal radiation can be increased by using a high-emissivity material. There are many high-emissivity or black coatings in the world. However, in the interferometric gravitational wave detectors, ultra-high vacuum (2×10^{-7} Pa in KAGRA) is required since scattering of the laser light by gas molecules causes noise. Thus, the coating used to increase emissivity must be vacuum compatible. One of the most promising candidates in terms of the vacuum compatibility is a diamond-like carbon (DLC) coating, which is an intermediate material between diamond and graphite.

I constructed a calculation model of KAGRA cooling system, where heat is transferred by thermal radiation and thermal conduction. Then, how the cooling time can be reduced was calculated when the DLC coating was deposited on all the masses to be cooled down except the mirror. For this calculation, the following two experiments have been conducted. First of all, calculation of radiation heat transfer depends on whether the surfaces reflect rays of radiation diffusely or specularly. A small-scale experiment, where a sphere suspended inside a sphere-shaped vacuum chamber was cooled down by thermal radiation, has shown that the experimental results are consistent with calculation using the specular surfaces. The emissivity of the DLC coating was also obtained in this experiment. Experiments in the actual KAGRA cryostat, where a sphere or a half-sized payload was cooled down by thermal radiation, demonstrated the validity of the calculation model of thermal radiation and the effect of the DLC coating on the cooling time reduction. This experimental demonstration was for the first time in the world using an actual cryogenic interferometric detector since KAGRA is only one large-scale cryogenic interferometric detector so far in the world. As a result of these experiments, the calculated cooling time with the DLC coating is 39 days while it takes 58 days without any coating as shown in Figure 1.

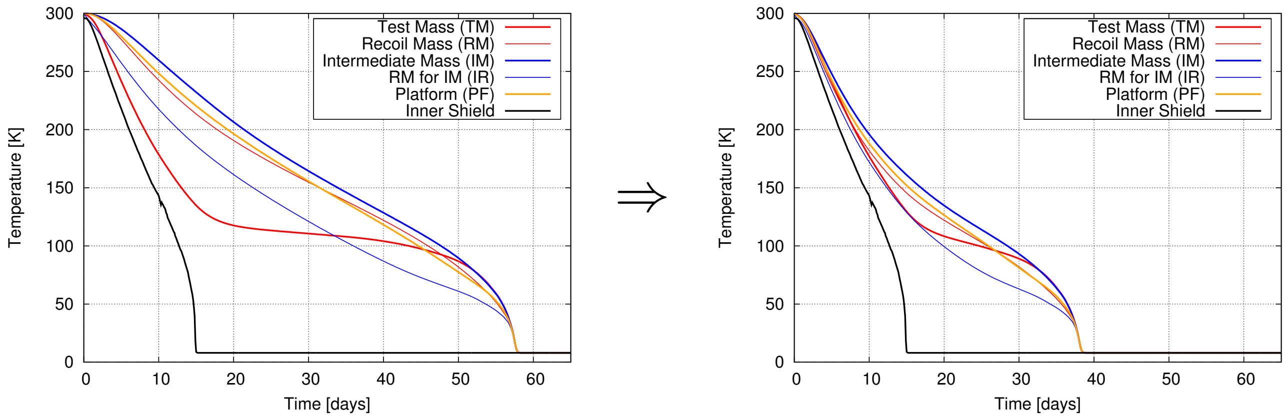

Figure 1: Calculation results of the cooling time of KAGRA cooling system. (Left) Without any coating. (Right) With the DLC coating.

There is another problem to be solved to reduce the cooling time: the duct shields are necessary to reduce extra 300 K thermal radiation. The cryostats contain only the cryogenic mirrors, and not whole of the km-scale beam ducts, because it is difficult to cool the entire interferometer for its large scale. An opening in the shield is necessary to allow the laser beam to pass through. Large amount of 300 K thermal radiation would come through the opening. On the other hand, the amount of heat extractable from the mirror will be limited by the long and thin wires. Here, I conducted the calculation of thermal radiation passing through the duct shield. The result is that inserting several donut-shaped plates (baffles) can decrease thermal radiation below the requirement of KAGRA. On a basis of the calculation, three of all the eight KAGRA duct shields have been manufactured. Using the manufactured three duct shields, I measured thermal radiation input. The measured values were consistent with the calculation and the manufactured three duct shields satisfied KAGRA requirement.

I also calculated scattered light noise caused by the duct shields. When the scattered laser beam by the mirror is reflected by something vibrating (e.g. the duct shields), the phase of the scattered light will be modulated by this vibration. If the scattered light comes back to the mirror and recombines to the main laser beam, it will affect the phase of the interferometer laser beam, and will cause noise. The calculation result satisfied requirement of KAGRA. I have demonstrated feasibility of the duct shields in terms of the thermal radiation and the scattered light noise using an actual cryogenic interferometric detector for the first time in the world.

As a conclusion, a dramatic increase of the observation duty factor from 71% to 77% has been achieved based on the reduction in the cooling time. Then, the observation time of KAGRA for the gravitational wave events has increased. This study can be applied to other cryogenic interferometric gravitational wave detectors, such as ET.