論文の内容の要旨

Control scheme for a Fabry–Pérot type interferometric space gravitational wave antenna

(Fabry–Pérot 型宇宙重力波望遠鏡の制御手法に関する研究)

氏名：長野　晃士

A gravitational wave is a ripple of space time. The existence of gravitational wave was predicted by Albert Einstein, who developed general relativity. The first observation of gravitational waves from a black-hole binary with Advanced Laser Interferometer Gravitational-Wave Observatory started a new era of gravitational wave physics, astronomy, and cosmology.

The observation frequency of the current ground-based gravitational wave observatory, such as aLIGO, is limited between ~ 10 Hz and a few kHz. The lower frequency limit is mainly determined by the seismic motion. Even below 10 Hz, some observational targets are predicted. One target is the coalescence of the intermediate-mass black holes with masses in the range between $\sim 10^3\ M_\odot$ and $\sim 10^6\ M_\odot$. The intermediate-mass black holes typically emit the gravitational waves in the frequency range between $\sim 10^{-3}$ Hz and ~ 1 Hz. The coalescence of the intermediate-mass black holes is considered to be a candidate of the origin of the super massive black hole that has been discovered at the galactic center. Another target is the early Universe. The quantum fluctuation is considered to cause the gravitational waves in the wide frequency range, for example, between $\sim 10^{-17}$ Hz and $\sim 10^4$ Hz. The observations of the gravitational waves from the coalescence of the intermediate-mass black holes and the early Universe provide new physical and astronomical information. Therefore, some space gravitational wave observatories are proposed to avoid the seismic motion.

In order to observe the gravitational waves in the frequency range between ~ 0.1 Hz and ~ 10 Hz, DECi-hertz Interferometer Gravitational Wave Observatory (DECIGO) and its precursor mission, B-DECIGO, have been proposed. The final goal of DECIGO is the observation of the gravitational waves from the early Universe. DECIGO and B-DECIGO are Fabry–Pérot type space gravitational wave antennas. Their sensitivities are enhanced by a Fabry–Pérot cavity while it requires sub-μm precision ranging for interferometer operation. This requirement level is significantly more stringent than that for other type of the space antennas such as Laser Interferometer Space Antenna (LISA). LISA utilizes an optical transponder configuration and the requirement for the ranging precision is about 10 m. Therefore, in order to operate Fabry–Pérot type space gravitational wave antennas, new advanced control scheme for precise ranging is necessary. Specifically, control topology and a longitudinal sensing scheme have to be considered.

The control topology of the Fabry–Pérot type space gravitational wave antennas should be addressed for the following reasons: First, the drag-free control of satellites to suppress the effect of dragging force is necessary. It was not clear whether the drag-free control can be engaged with all degrees-of-freedom control of the cavity. The second reason is a lack of natural reference for the control while, in ground-based detectors, the ground is a stable reference. Third, a feedback system introduces additional noises through the feedback loop. Thus, the control system has to be carefully designed, especially in the observation frequency band.

In addition, for the gravitational wave observation, a sensing method, i.e. an interferometer configuration, is also important. DECIGO and B-DECIGO utilize dual-pass Fabry–Pérot cavities to form a triangular shaped interferometer to obtain the redundancy with minimum number of the test masses. In the dual-pass Fabry–Pérot cavity, laser light is injected from both sides of one Fabry–Pérot cavity and the relative frequency of the two lasers cannot be controlled independently. This is a new interferometer configuration for DECIGO and B-DECIGO. In this interferometer configuration, since the Fabry–Pérot cavities are coupled with each other, a new scheme to obtain the longitudinal signal of all the interferometers is necessary. Therefore, the operation of the dual-pass Fabry–Pérot cavity has to be demonstrated for DECIGO and B-DECIGO.

In this thesis, the control scheme of the Fabry–Pérot type space gravitational wave antenna is studied. First, the control topology is considered with the numerical model of the Fabry–Pérot type antenna including a mechanical and opto-mechanical response, a sensing and actuation scheme, external disturbances, and sensing noises. The new model is named a *full DECIGO interferometer model*. This new model reveals that the interferometer control and drag-free control can be engaged at the same time by separating the controlled degrees of freedom with each control, and the mirror position can be used as a reference of the control. Using the model, a solution of DECIGO parameters with interferometer control achieving the target strain sensitivity of 10^{-23} $/\sqrt{\mathrm{Hz}}$ is also found as shown in figure 1. In addition, more than one-day stability is also achieved. With the sensitivity of 10^{-23} $/\sqrt{\mathrm{Hz}}$, for example, the model of the phase transition at the electroweak scale in the early Universe can be tested. Second, the dual-pass differential Fabry–Pérot interferometer is formulated and is constructed in a ground laboratory with the 55-cm-long Fabry–Pérot cavity as shown in figures 2 and 3. The operation of the dual-pass differential Fabry–Pérot interferometer is demonstrated for the first time. Moreover, it is confirmed that cavity detuning can be reduced by the cavity length adjustment as predicted by the formulation as shown in figure 4. The cavity detuning reduction is essential to minimize a laser intensity noise, which would be a major noise source in DECIGO. These results indicate that the dual-pass differential Fabry–Pérot interferometer is correctly understood with the new formulation.

This work helps conduct the detailed design of DECIGO and B-DECIGO and is an essential basis for opening the window of gravitational wave physics and astronomy in decihertz band, especially for the observation of the early Universe.

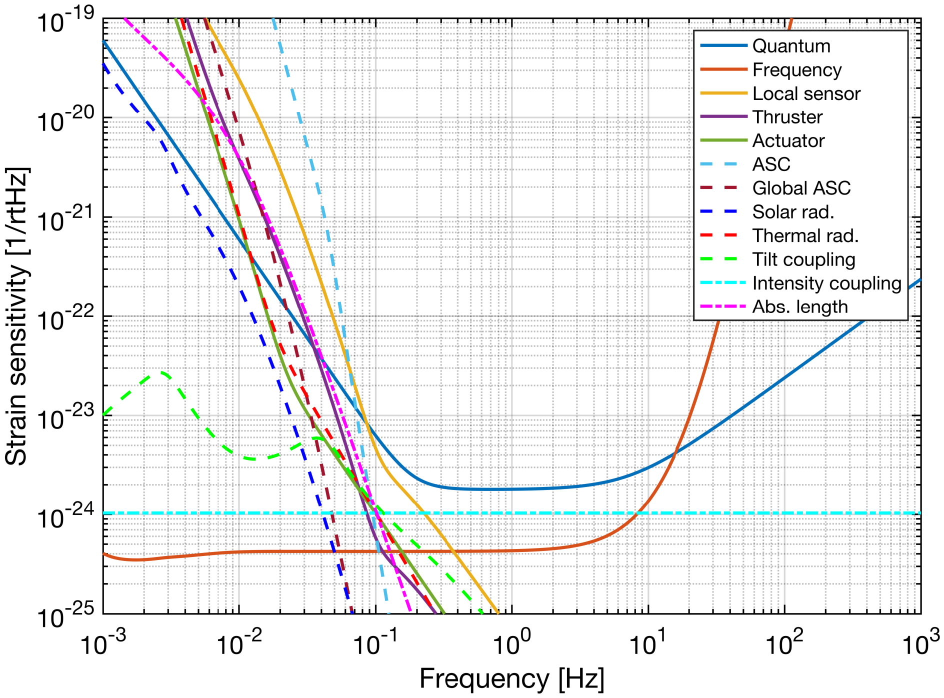

Figure 1: DECIGO noise budget with the full control implementation.

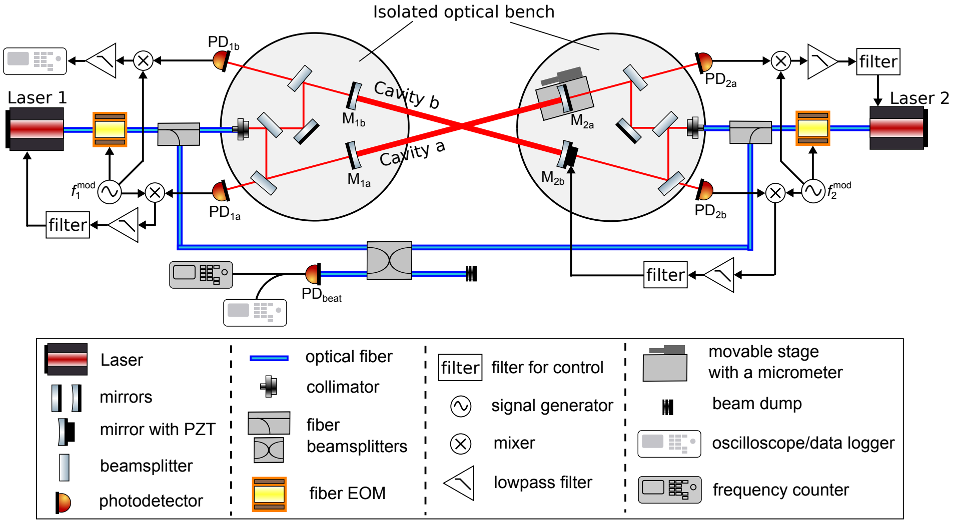

Figure 2: Schematic of the dual-pass differential Fabry–Pérot interferometer experiment.

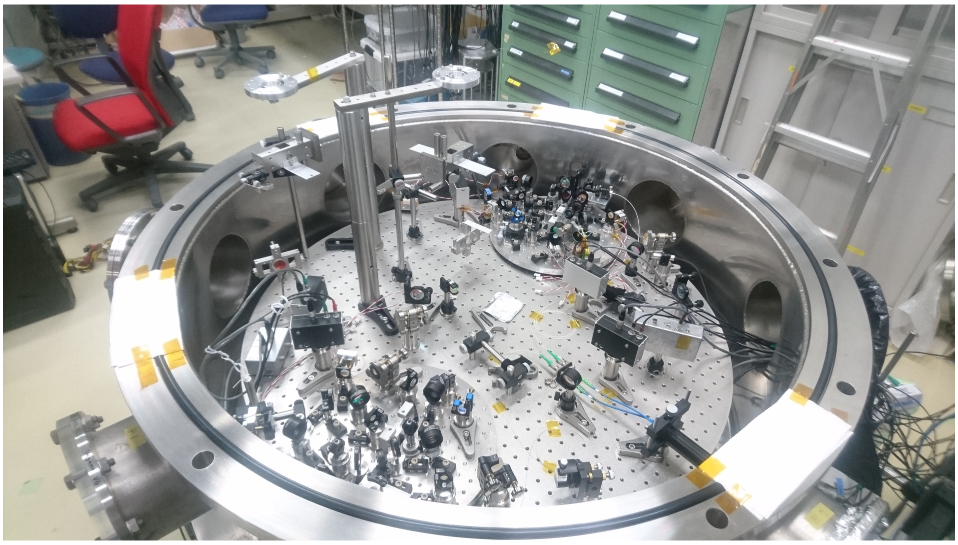

Figure 3: Photograph of the main dual-pass Fabry–Pérot cavities in the dual-pass differential Fabry–Pérot interferometer experiment.

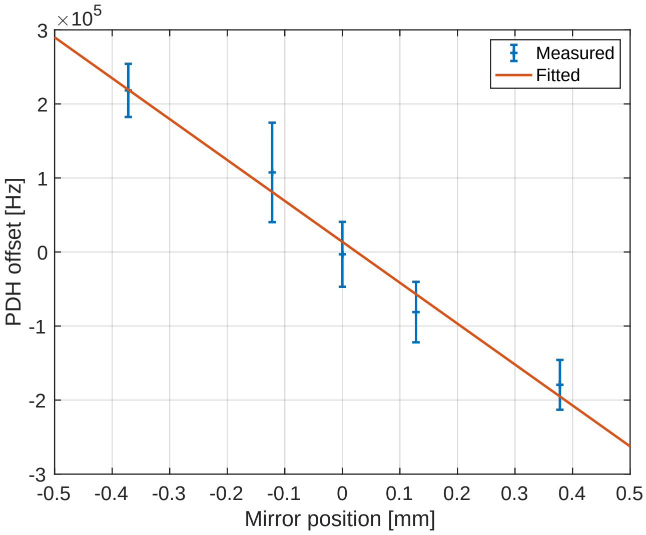

Figure 4: Measured offset of the Pound–Drever–Hall (PDH) signal at the five different cavity lengths. The offset of the PDH signal corresponds to the cavity detuning.