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研究課題名（和文） Demonstration of frequency dependent squeezing for next generation GW detectors

研究課題名（英文） Demonstration of frequency dependent squeezing for next generation GW detectors

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研究成果の概要（和文）： 本研究の最終目標は重力波検出器に周波数依存型スクイージング技術を導入し、感度を向上することである。そのためには、フィルターキャビティと呼ばれる、長基線で低損失の光共振器にスクイーズ場を入れる必要がある。
第一段階としてフィルターキャビティの性能評価を行い、結果を投稿論文にまとめた。その結果に基づき、300mのフィルターキャビティとスクイーズ場を生成する入射光学系を開発した。赤外のレーザー光と、その倍波である緑の光を生成し、緑の光をフィルターキャビティで共振させることで共振器を制御した。このセットアップを用いて光共振器の光損失を測定し、要求値を満たしていることを確認し、結果を論文誌に投稿した。

研究成果の概要（英文）： The final goal of this research is to demonstrate the realization of a frequency dependent squeezed vacuum source to improve the sensitivity of gravitational wave detectors. To this purpose a squeezed vacuum source should be coupled with a long optical cavity with high finesse and low losses, called filter cavity.
The first step of this research was to study the specifications of the filter cavity. The result of this study were published on Physical Review D. Based on this study a 300 m long filter cavity was built and installed. In parallel the components for the squeezed vacuum source were installed on an optical bench close to the cavity. Two laser beams, one green and one infrared were then injected into the filter cavity and the cavity was locked at the resonance using the green beam. Using this setup it was possible to measure the optical losses of the cavity. These were found to be in agreement with the requirements. The result of this test has been submitted for publication.

研究分野： Gravitational Wave Astronomy

キーワード： gravitational wave　quantum noise　squeezed vacuum　filter cavity

１．研究開始当初の背景

The detection of gravitational waves is revolutionizing our vision of the universe. With the detection of gravitational waves produced by the coalescence of two black holes, scientists began to unveil the invisible part of the universe, one of the main mysteries of physics and astronomy. The first detection of gravitational waves produced by the fusion of two neutron stars has enlightened the mechanism of creation of heavy elements in the universe. By improving the sensitivity of detectors such as KAGRA, LIGO and Virgo, it will be possible to observe these phenomena until the time of the first generation of stars and to detect gravitational waves produced by other mysterious phenomena such as supernova explosions or the primordial explosion that gave birth to the universe.

All present gravitational wave detectors are limited by the quantum noise of light. In the case of KAGRA, the underground site and the cryogenic operation will allow reducing other noise sources thus making the limitation due to quantum noise even more relevant.

The use of squeezed vacuum states to reduce quantum noise has been proposed in the early 80's. Since then squeezing has been applied successfully to the LIGO and the GEO600 detectors to reduce photon shot noise i.e. the quantum noise limiting the detector sensitivity above a few hundred hertz. To reduce quantum noise at all frequencies the squeezed state injected into the interferometer should be frequency dependent.

２．研究の目的

The purpose of this research is to develop a frequency dependent squeezed vacuum source to reduce quantum noise in gravitational wave detectors. In order to reduce quantum noise at all frequencies the squeezing where the frequency transition occurs should be around 100 Hz. To achieve this goal a squeezed vacuum state should be filtered by an optical cavity. The optical cavity should be long enough to filter the squeezed state from 100 Hz. In addition, its optical losses should be low enough to avoid disrupting the squeezed state.

３．研究の方法

First of all we fixed as goal the reduction of quantum noise in KAGRA by about a factor of two. Based on this requirement and assuming a vacuum squeezed source able to produce about 9dB of squeezing we studied the requirements for the filter cavity. Then we started the construction of the filter cavity i.e. its mirrors, its suspensions and its mirror position control system. In parallel we designed the squeezed vacuum source. We then proceeded with the installation of the filter cavity in the TAMA vacuum system. We also installed under vacuum the telescope system required to inject the light into the filter cavity. Then we used the beams from the squeezed vacuum source bench to align and lock the filter cavity. In this configuration we were able to measure the optical losses of the filter cavity.

The overall scheme of the experiment is shown in Figure 1.

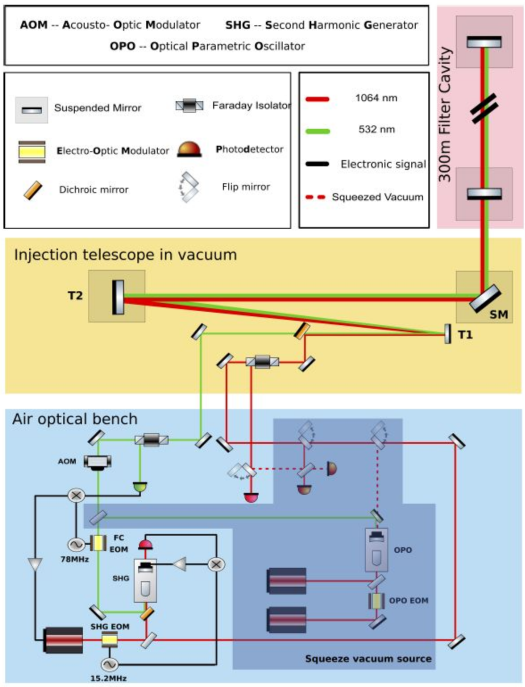

Figure 1. Experimental layout: the beams from the squeezed vacuum source are injected into the 300m filter cavity by means of the injection telescope.

４．研究成果

During the first part of the work we studied the requirement of the filter cavity in order to reduce the quantum noise in KAGRA by a factor of two. We assumed the length of the cavity to be equal to 300 m as the arms of the TAMA interferometer. We also assume a squeezed vacuum source able to produce 9 dB of squeezing. We also made realistic assumptions regarding the optical losses in injecting the squeezed state into the cavity and in detecting the frequency dependent squeezed state reflected by the cavity. Finally we consider different level of beam mismatching into the cavity.

Based on these assumption we evaluated the optical losses tolerable in the filter cavity and so the required mirror quality. In particular we studied the requirement on the mirror surface figure. We found that mirror having surface figure errors in the range of 0.5 nm to 1 nm RMS over the beam size on the mirror (about 2 cm diameter) were sufficient to achieve round trip optical losses lower than 80 ppm. We calculated that with these losses it is possible to reduce the quantum noise by 6 dB at high frequency and by

4 dB at low frequency. The limitation at low frequency comes from a combination of the mode-mismatching and of the optical losses in the filter cavity.

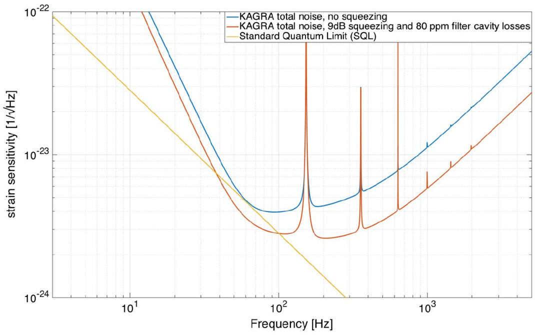

Figure 2. Effect of the use of frequency dependent squeezing on the KAGRA sensitivity

The effect on the KAGRA sensitivity is shown in Figure 2. In this study we also calculated the mirror's radius of curvatures required to avoid increasing the optical losses due to mode degeneracies in the cavity. The results of this study have been published in a paper on the journal Physical Review D and presented at several international conferences.

The following steps consisted in making the final design of the mirrors substrate geometry and coatings. We choose to use mirrors made of silica 10 cm in diameter and 6 cm thick. The coatings were chosen so to have a cavity having a finesse of 4500 for wavelength equal to 1064 nm. With this finesse the cavity has a bandwidth of about 100 Hz corresponding to the required corner frequency to be imprinted by the cavity on the squeezed state. The coatings were made to be reflective also for wavelength equal to 532 nm but with a lower finesse (about 200). This was done in order to be able to lock the filter cavity using a laser beam at 532 nm. The lower finesse makes the cavity lock acquisition easier. Four mirrors were prepared and characterized. Using the result of the mirror characterization and optical simulation the best couple of mirrors to be installed were chosen.

In parallel with the mirror preparation, the vibration isolation systems and the mirror suspensions were installed in the vacuum system and tested using old mirrors having the same size and mass. In particular the optical levers to control the mirror position both in the angular and in the longitudinal directions were designed, installed and tested. It was possible to control the mirror position with a precision of the order of one micro-radiant in angle and a few micrometers in translation.

Another study was made to prepare the injection system, i.e. the telescope used to inject the light from the squeezed source optical bench into the filter cavity. This telescope was made of two mirrors placed inside the vacuum system. The last mirror of the telescope is suspended and remotely controlled. Before being injected into the cavity the beam is reflected on another suspended mirror. This mirror together with the last mirror of the telescope allow to steer the beam and so to align it with the cavity axis. All these mirrors are dichroic in order to reflect efficiently both the beam at 532 nm (green) and the beam at 1064 nm (infrared). The two beams are superposed inside the vacuum chamber by using a dichroic mirror. Before recombination the infrared beam is transmitted through a large aperture low losses Faraday Isolator which allow extracting the infrared beam reflected by the filter cavity.

Finally all the components to build the vacuum squeezed source were bought, assembled and installed on the optical bench. These include the main laser and the control lasers to control the Optical Parametric Oscillator (OPO) for the squeezed vacuum generation. All these lasers operated in the infrared at 1064 nm. The OPO is made by a non-linear crystal made of PPKTP which is part of an optical cavity to enhance the squeezing generation. The OPO is pumped by a green beam itself generated by a second harmonic generator (SHG) pumped by the main laser. Before injection into the OPO the green beam is amplitude stabilized by means of a Mach-Zender interferometer and it is spatially filtered by triangular optical cavity acting as a mode-cleaner. The control laser beams are also injected into the OPO from the back port of the cavity and used to control the OPO cavity length and the squeezing angle. A portion of the main laser is extracted and sent towards an homodyne detector to characterize the squeezing level. Before reaching the homodyne detector also this beam is passed through a mode-cleaner cavity to spatially filter the beam.

Both a fraction of the green beam after the second harmonic generator and a fraction of the main laser are extracted and sent into the filter cavity. The green beam is used to lock the main laser frequency to the filter cavity length. To this purpose a Pound-Drever-Hall readout system is used. Before injection into the vacuum system, the green beam is phase modulated with an electro-optic modulator (EOM) and the green light is detected with a photodiode and demodulated at the phase modulation frequency. The detected signal is then used to feedback to the main laser frequency thus keeping the green beam in resonance with the cavity length. The infrared beam injected into the filter cavity is used to characterize the filter cavity performance. An acousto-optic modulator (AOM) placed along the green beam path allows to shift frequency of

the green beam with respect to the infrared beam. Thus by acting on the AOM it is possible to scan the infrared beam across the cavity free spectral range. By doing this it has been possible to measure the cavity linewidth and the cavity finesse. The measured values are well in agreement with the expected value. Using the AOM it is also possible to lock the infrared beam at half of the cavity linewidth in the conditions required to achieve the frequency dependent squeezing.
Finally by comparing the infrared beam reflected by the cavity when the cavity is locked and when the cavity is unlocked it was possible to measure the round trip losses of the cavity (see Figure 3). These were found equal to about 60 ppm, a value in good agreement with the expectation and sufficient to achieve the required level of frequency dependent squeezing. This result has been presented at several international conferences and has been submitted for publication to a journal.

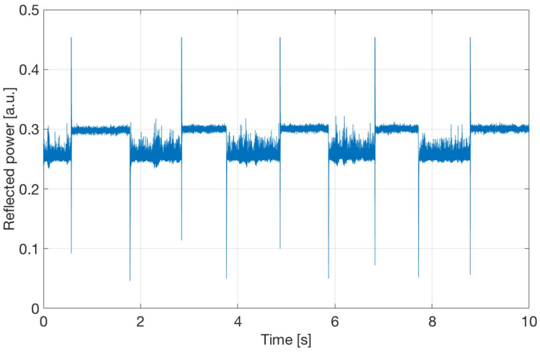

Figure 3. Laser power reflected by the filter cavity when it is locked to the laser frequency or when it is unlocked. The comparison between the two sates allows to evaluate the optical losses inside the filter cavity.

This work has been carried out in collaboration with several institutes and universities outside of Japan (in France, in Italy and in China). One PhD student from France and two master students (one from France and one from China) have done their thesis project on this experiment.
Now that all the hardware have been installed and that the test with of the filter cavity confirmed its optical performances it will be possible to start operating the vacuum squeezed source and to inject the squeezed state into the filter cavity. On the longer term the result of this experiment will be used to study the implementation of the frequency dependent squeezing in the KAGRA experiment after the first gravitational wave observations will be achieved.

5．主な発表論文等

（研究代表者、研究分担者及び連携研究者には下線）

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