様　式　Ｃ－１９、Ｆ－１９－１、Ｚ－１９　（共通）

科研費
KAKENHI

科学研究費助成事業　　研究成果報告書

令和　３ 年　６ 月 １５ 日現在

機関番号：６２６１６
研究種目：基盤研究(B)（一般）
研究期間：2018～2020
課題番号：１８Ｈ０１２３５
研究課題名（和文）Broadband quantum noise reduction via EPR squeezing

研究課題名（英文）Broadband quantum noise reduction via EPR squeezing

研究代表者
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国立天文台・重力波プロジェクト・助教

研究者番号：９０８１６４４８

交付決定額（研究期間全体）：（直接経費）　13,500,000円

研究成果の概要（和文）：2015年に重力波が初めて検出されたことで、重力波天文学の時代が始まった。重力波の検出数を増やすためには、重力波検出器の感度を向上させる必要がある。重力波検出器の感度を制限する最も基本的な雑音は、光の量子雑音である。このノイズを抑制するためには、光の量子的な性質を操作して、スクイーズド真空場と呼ばれる状態を作る必要がある。
本研究では重力波検出器に適応可能な周波数依存スクイーズド真空場の生成に世界で初めて成功した。この成果はPhysical Review Letter誌のハイライト論文に選ばれ、プレスリリースも行った。

研究成果の学術的意義や社会的意義
重力波天文学という新しい研究分野では今後、人類の宇宙に対する理解を深める多くの発見が期待されている。この研究分野を発展させるためには、重力波検出器を改良する必要がある。本研究では、「スクイーズド真空場」と呼ばれる量子状態を低周波で操作することに初めて成功した。この技術は、より多くの重力波イベントの検出につながるだけでなく、光の量子性に関する我々の理解を深めることにもなる。

研究成果の概要（英文）：The first detection of gravitational waves in 2015 opened the era of gravitational wave astronomy. With this new field of research, we can explore the universe in previously unknown ways and better comprehend the behavior gravity. To increase the number of detections of gravitational waves, the sensitivity of gravitational wave detectors needs to be improved. The most fundamental noise which limits the sensitivity of gravitational wave detector is the quantum noise of light. To suppress this noise, the quantum properties of light need to be manipulated in order to create what is called a squeezed vacuum state.
For the first time in the world, we achieved the production of a frequency dependent squeezed vacuum state with frequency rotation suitable for application in gravitational wave detectors. This result was published on Physical Review Letter (highlighted in Physics and Editor Suggestion) and several press releases were organized to follow-up this result.

研究分野：Gravitational Waves and Quantum Optics

キーワード：freq. dep. squeezing　filter cavity　quantum optics　gravitational wave　KAGRA

１．研究開始当初の背景

The first direct detection of gravitational waves (GWs) coming from the merging of two black holes achieved in 2015 by the two LIGO's detector of the LIGO-Virgo collaboration, opened the era of the Gravitational Wave Astronomy. This new field of science allowed mankind to explore the universe in previously unknown ways and unlocked yet uncharted possibilities to explore it.

So far almost one hundred gravitational waves were detected by the LIGO-Virgo-KAGRA network and this was possible only thanks to the many upgrades the different interferometers undergo on regular basis to improve their sensitivity. One of the most fundamental noises that strongly limits the sensitivity of current GW detectors is the quantum noise. It was recently demonstrated by LIGO and Virgo that their sensitivity is limited in a broadband way by the quantum noise. This situation is expected to be even more impactful for KAGRA since, thanks to the underground site and by the fact that KAGRA's mirror are operated at cryogenic temperature, many of the noises which affects LIGO and Virgo are further suppressed, so the quantum noise limit will be limiting KAGRA harder than how is limiting the other interferometers. In the 80s, a mitigation scheme to the limits imposed by the quantum noise was proposed. This scheme takes advantage by the use of squeezed vacuum state injection. This technology has been partially applied to current detector, but never to the fullest since, up to know, no one in the world managed to achieve the production of frequency dependent squeezed states with frequency rotation below 100Hz which is the frequency range needed for GW detectors.

２．研究の目的

The aim of this project is to prove the EPR squeezing technique at frequencies of interest of the GW detectors. This goal will be pursued taking advantage of the already existing TAMA300 facility and the project will be constituted mainly by three items: a frequency independent squeezed light source, a hundred-meter-long optical cavity, and a double homodyne readout system. EPR squeezing technique is one of the possible techniques that can be used to produce frequency dependent squeezed states. In order to validate the behavior of the setup in a step-by-step way, three additional milestones are foreseen. The first one is the realization of a frequency independent squeezed (FIS) light source capable of providing squeezed states starting from 10Hz, the second one is the capability of operate a 300m optical cavity (FC) within the noise requirement of the experiment, and the third is to operate both FIS and FC together and measure frequency dependent squeezing produced in the conventional (not EPR) way.

３．研究の方法

The experimental setup, sketched in Fig. 1, consists of two parts: a source of frequency-independent squeezed vacuum and a suspended filter cavity. The two are connected by an in-vacuum injection system, including suspended mirrors, which couples the squeezing into the filter cavity.

Frequency-independent squeezed vacuum source —The in-air squeezed vacuum source follows the design of the GEO600 squeezer. The core part is the optical parametric oscillator (OPO): a linear hemilithic cavity hosting a periodically poled potassium titanyl phosphate (PPKTP) crystal in which the squeezed vacuum is produced through a parametric down-conversion process. This requires a pump beam at twice the squeezing frequency, which is produced by injecting a 1064-nm laser into a second harmonic generator cavity (SHG). The main laser, a 2-W 1064-nm Nd:YAG laser, is used to pump the SHG and produce green light (with a wavelength of 532 nm) and as a local oscillator for the balanced homodyne detector, used to characterize the squeezing. A mode cleaner cavity and a Mach-Zehnder interferometer (MZ) are installed respectively to spatially clean and to stabilize in power the green pump beam before it enters the OPO. Two auxiliary lasers, frequency offset locked with the main laser, are also used. The first one (AUX1), injected into the OPO with a different polarization with respect to the produced squeezed beam, is used to control the OPO length, which is only resonant for 1064-nm wavelength. The second one (AUX2) is also injected into the OPO and copropagates with the squeezed vacuum beam up to the homodyne detector, to track the squeezing phase and lock it with respect to the local oscillator. Custom analog electronics have been developed to operate the control loops involved in the experiment. An automatic hierarchical control acquisition procedure is also implemented to bring the squeezing source in the working state within a few seconds.

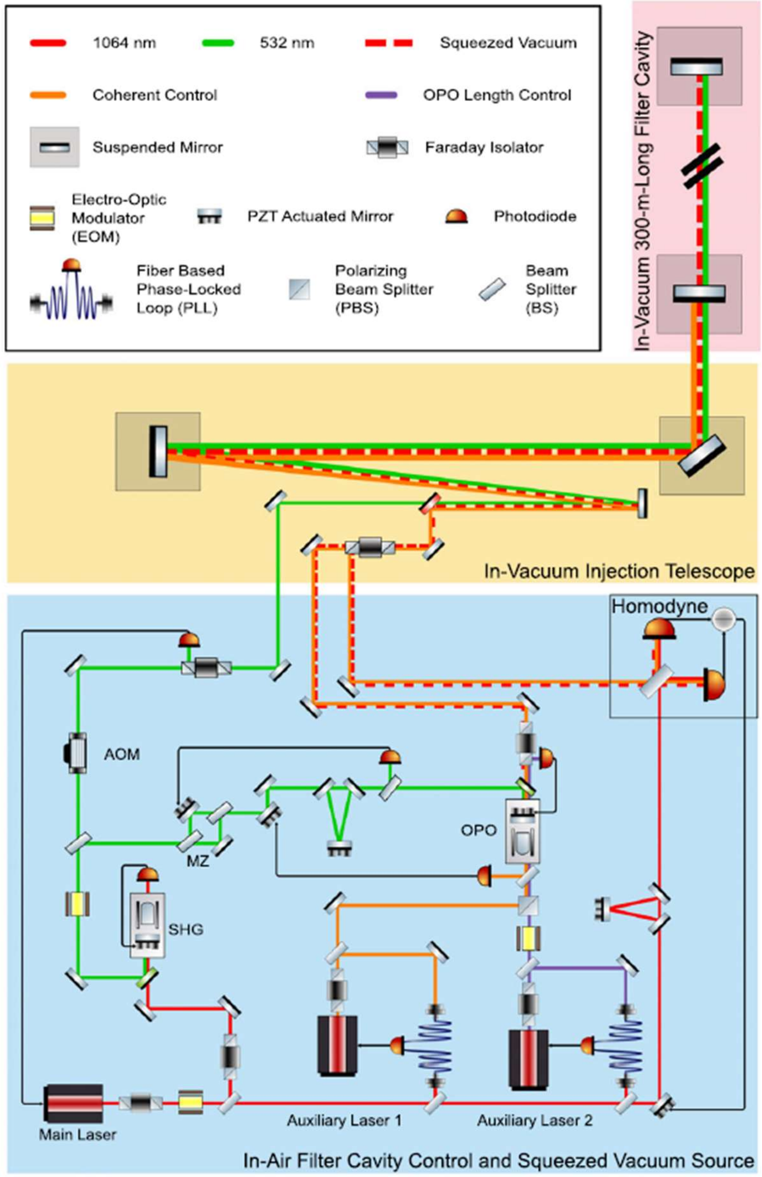

Figure 1 Schematic diagram of the experimental setup. The squeezed vacuum beam is produced by the OPO and injected into the filter cavity through the in-vacuum injection telescope. The reflected frequency-dependent squeezing is rejected by the in-vacuum Faraday and characterized by the homodyne detector. The green beam produced by the SHG is used to pump the OPO and as auxiliary beam for the control of the filter cavity.

Filter cavity —The filter cavity is hosted in one of the 300-m arms of the former TAMA interferometer and uses the already existing vacuum system. The 10-cm-diameter cavity mirrors are suspended with a double pendulum system placed on a vibration isolation multilayer stack, initially developed for TAMA and recommissioned for this experiment. Mirror motion is sensed by optical levers and coil-magnet actuators are used to align the cavity and to damp suspension mechanical resonances. To obtain a rotation around 30–70 Hz, a storage time of about 3 ms is needed. This will require either a long cavity or a very high-finesse one. The use of order 100-mlong filter cavities have been envisaged for advanced detectors, as they are more robust to length-dependent sources of squeezing degradation such as cavity losses and residual length noise. The frequency at which the rotation takes place depends on the cavity linewidth, which is inversely proportional to its length and finesse. Given the 300-m length of the cavity, the finesse is chosen to be 4400 at 1064-nm wavelength, to provide a squeeze ellipse rotation at approximately 75 Hz, corresponding to an optimal quantum noise reduction for KAGRA. Since cavity losses are a major threat to squeezing, requirements on the mirror surface quality were first determined by numerical simulations, using realistic mirror maps. After the cavity assembly, round-trip losses were measured in the range of 50–90 ppm, compliant with requirements (see next session).

Filter cavity control —The filter cavity is controlled by an auxiliary beam, picked off the green beam produced by the SHG. The cavity finesse for such an auxiliary beam is about 25 times smaller than that of the infrared one, to facilitate the lock acquisition process. The green beam is superposed to the squeezed beam at an in-vacuum dichroic mirror, as shown in Fig. 1. For the initial alignment operation, a pickoff of the main laser is temporarily injected into the OPO, to copropagate with the squeezed vacuum. The cavity is kept on resonance by acting on the main laser frequency. The error signal is obtained from the reflected green beam, using a Pound-Drever-Hall scheme, and the correction signal, processed with an analog servo, is sent to the Piezoelectric (PZT) actuator of the laser, with a bandwidth of about 20 kHz. An acousto-optic modulator (AOM) is placed on the green beam path prior to injection into the filter cavity. By driving the AOM at different frequencies, it is possible to change the relative frequency of the green and the squeezed beam and thus control the detuning of the latter into the cavity. The cavity is kept aligned with respect to the green beam using an error signal obtained from the transmitted power. Such a signal is generated by dithering the angular position of the cavity mirrors.

4．研究成果

As described in the previous section, several milestones were defined for this project and in the following the achievement for each as well as the related publication will be described.

Filter cavity round trip losses characterization (FY 2018)

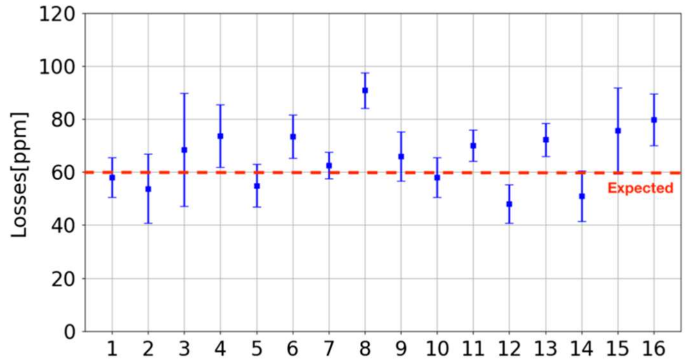

Figure 2 Summary of the round-trip loss measurements. The scattering of the results may depend on different alignment conditions of the cavity from one day to another. The measurements have been taken on different days over about two months. (PHYSICAL REVIEW D 98, 022010, 2018)

The first milestone achieved was the operation of the filter cavity (300m long optical cavity) and its characterization in term of optical losses. The measurement highlighted round trip losses in the range between 50-90 ppm and such measurement was very much in agreement with the expected losses obtained from simulation starting from the mirror maps. This result was published in Physical Review D and was of particular interest for the gravitational wave research community since it was the first experimental validation of the very crucial parameter of round trip losses for filter cavities. All the frequency dependent squeezing setup designed for LIGO, Virgo and KAGRA used this result as a starting point for their design.

Frequency independent squeezed vacuum source realization (FY 2018-2019)

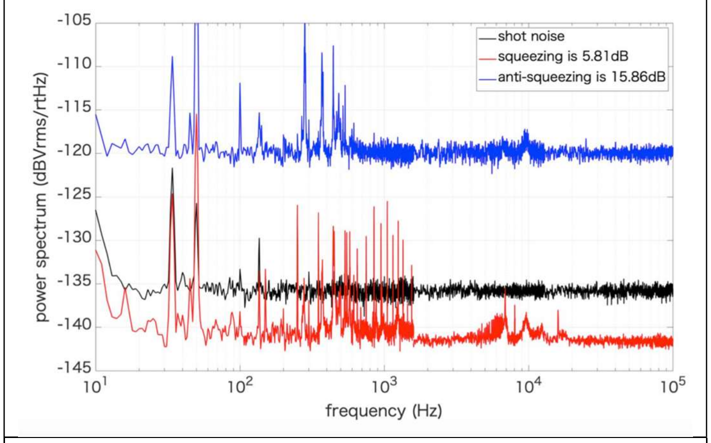

Figure 3 : Frequency independent squeezing measurement (August 2019). The black spectrum is the shot noise reference, the red spectrum is showing the squeezed quadrature, while the blue one shows the anti-squeezed one.

The second milestone was the realization of a frequency independent squeezed light source. This result was achieved in record time (less than two years) compared to other laboratories and even if was not published, since this technology was already proved in early 2000, it was of great importance since this was the first realization of frequency independent squeezing at audio frequencies within the KAGRA collaboration. A maximum squeezing level of 6.1 +/- 0.2 dB below shot noise (and 15.9 +/- 0.2 dB of antisqueezing) down to 10 Hz was measured in January 2020, only one year after the first squeezing measurement performed in January 2019. This unbalance in squeezing and anti-squeezing is due to the presence of optical losses and phase noise.

Frequency dependent squeezing measurement (FY 2019-2020)

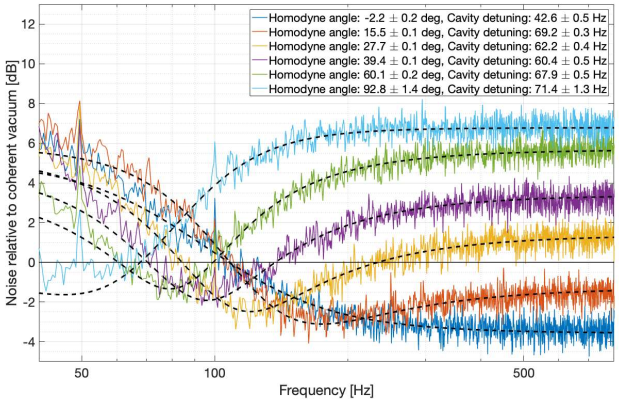

Figure 4 : Noise spectra of the frequency-dependent squeezing, measured for different homodyne angles. (Phys. Rev. Lett. 124, 171101 (2020))

At the beginning of 2020 we achieved, for the first time in the world, a measurement of frequency dependent squeezing with rotation frequency below 100Hz. This result was published on Physical Review Letter at the end of April 2020 and was featured in Physics and Editor suggestion. Moreover, this result was followed by several press release and articles in international journals (such as Nature, American Optics Society, etc.). This result is not important only since it is the world first measurement, but also because it represent the first test on a real-size prototype of a key technology which will be used in LIGO, Virgo, KAGRA and it is planned for all the third generation GW detector.

This measurement (Fig. 4), together with the characterization studies which followed, highlighted the importance of alignment control and locking accuracy for the filter cavity. Given the importance of this topic for GW community, since no study about it was previously performed, it was decided to divert some time on it. The next two milestones (not originally planned) are related to this topic.

Alignment and length control of the FC: theoretical study (FY 2020)

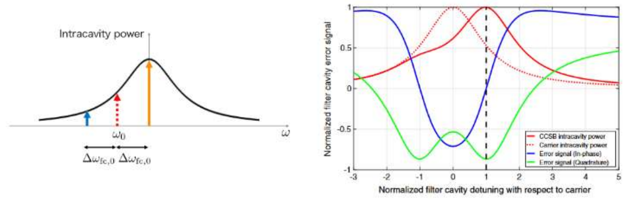

Figure 5 Adapted from PHYS. REV. D102,042003 (2020). (left) Frequency relationship inside the filter cavity. Reddashed line is carrier, orange and blue lines are coherent control sidebands. (right) Normalized filter cavity length signal.

Within this project, a novel approach to alignment and length control of the FC was envisaged. This control is particularly innovative since it does not relay on auxiliary beams as other schemes previously proposed but on the coherent control sidebands which are already present in all the squeezing schemes present in literature. The result of the theoretical study was published in Physical Review D and this scheme will be used as control scheme for FC in KAGRA and as one of the option in Virgo.

Alignment and length control of the FC: experimental validation (FY 2020)

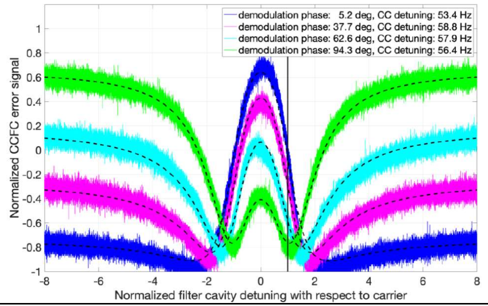

Figure 6 CCFC error signal for different demodulation phases. As expected from the theoretical model (dashed curves) the in phase signal has a zero crossing point at the correct CC detuning frequency. (to be published)

The novel control scheme proposed theoretically and published by the group on PRD has been theoretically tested. This represents the last experimental result obtained within the timeframe of the project. The experimental validation was successful and highlighted the capability of this new scheme (called filter cavity coherent control or CCFC) which, as a preliminary result, seems equal or better than the one of the more conventional control schemes. A paper describing this experimental result is being written and will be submitted to PRD.

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掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevLett.124.171101	査読の有無 有
オープンアクセス オープンアクセスではない、又はオープンアクセスが困難	国際共著 該当する

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Naoki Aritomi

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４．発表年 2021年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

－

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７．科研費を使用して開催した国際研究集会

〔国際研究集会〕　計0件

８．本研究に関連して実施した国際共同研究の実施状況

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