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研究課題名（英文） Innovative Quantum Noise reduction strategies for GW detectors

研究代表者

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研究成果の概要（和文）： 2015年に初めて重力波が検出され、重力波天文学の時代が到来した。この新しい研究分野によって、これまで知られていなかった方法で宇宙を探索できるようになった。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ノイズは、光の量子ノイズである。このノイズを抑制するためには、光の量子的性質を操作して、いわゆるスクイーズド真空状態を作り出すことが必要であり、私たちのグループが2020年に到達した目標である。
このプロジェクトでは、多くのノイズ源に対処し、FDSの応用におけるいくつかの制限を調査することに成功した。

研究成果の学術的意義や社会的意義

With this project, the capability of potentially reducing the quantum noise in gravitational wave detectors has been enhanced. Therefore, the capability of observing our universe via the gravitational wave channel has been increased, providing additional and new information to the general public.

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.
In 2020 our research group produced the first ever frequency dependent squeezing (FDS) for gravitational waved detectors. This project successfully addressed many noise sources and investigated several limitations to the application of FDS to gravitational wave detectors.

研究分野： Gravitational Waves and Quantum Optics

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

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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 detectors 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 more than one hundred gravitational waves have been 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 of using squeezed vacuum state injection. This technology, initially tested by our team in 2020 when we successfully realized a full-scale prototype of a frequency dependent squeezing source with frequency rotation below 100Hz, nowadays is routinely used in both LIGO detectors and proved extremely powerful. That said, there are a lot of open questions and a lot of uninvestigated limitations that prevent this technique from being used at its full potential, allowing the detection of many more GW sources.

２．研究の目的

The purpose of this research is the study and realization of a broadband quantum noise reduction scheme suitable for current and future generation gravitational wave detectors. This scheme implies the use of a coupled (three-mirrors) filter cavity as an alternative to the more complex and expensive solution of a series of two standard (two-mirrors) filter cavities. The research will be realized at NAOJ in the TAMA300 facility and will provide valuable information plus know-how for an implementation of this technology in the next generation gravitational wave detectors. This research will help the development of coupled-cavities control schemes and help develop new techniques to fight one of the most limiting noises in gravitational wave detectors: the quantum noise.

３．研究の方法

A crucial step to design a coupled filter cavity is to understand the limitations of a more standard two mirror filter cavity, since it is expected that all the noises and limitations present for the standard filter cavity will be even more impactful on a coupled filter cavity. Therefore the first step of the project is, taking advantage of the two mirror filter cavity already present at TAMA financed by JSPS (18H01235), to understand the main limitations of the standard scheme in order to derive noise suppression strategies to be applied to the coupled filter cavity. The expected noise sources are the locking noise, the scattering noise, the detuning noise and the jittering noise. All such noise sources could be reduced by employing a more sophisticated suspension for the cavity mirrors with respect to the one used for the two-mirror filter cavity (which is the same used in the TAMA300 project). In the following, the details of the investigations as well as the design of the new version of the suspension will be described.

4．研究成果

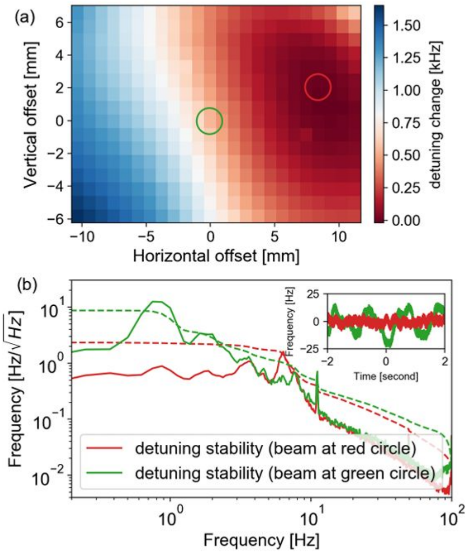


Figure 1 One example of an error source in filter cavity length control using the frequency doubled harmonic of the squeezed vacuum carrier. The beam position can cause the green and infrared beams to sense a different filter cavity length. By moving the beam position from the green to the red spot we can reduce the tuning error.

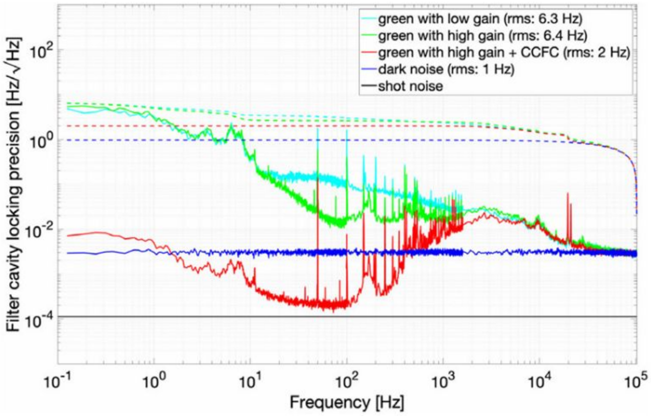


Figure 2 Controlling the filter cavity length using an infrared sensing beam that co-propagates with squeezing (CCFC). The locking precision can be improved by a factor of more than 3 when engaging CCFC control versus just green beam control.

The works of FY2021 and FY2022 resulted in two experiment publications. The first details of the control of the filter cavity length from a green beam frequency doubled from the resonant carrier (bichromatic control), published in Physical Review D (Y. Zhao et al. Phys Rev D 105 082003 (2022)). Since squeezed vacuum has no classical amplitude, copropagating auxiliary control beams are required to achieve length, alignment and input beam pointing stability of the filter cavity. The most straightforward method is to overlap the squeezed vacuum beam path with a pick-off from the frequency doubled green beam that generates squeezing. Modulation of the green beam is then used to detune the filter cavity with respect to infrared squeezed vacuum and obtain the desired frequency dependent squeezing.

The publication details several means by which the filter cavity detuning deviates from the ideal value, for example wavelength dependent optical path length differences between green and infrared. We mitigated error sources and could achieve a filter cavity detuning stability of less than 10 Hz, a factor of 3 improvement versus the original demonstration of frequency dependent squeezing using TAMA (see fig 1).

The second publication demonstrated the control of filter cavity length using infrared sidebands generated to co-propagate with the squeezed beam (coherent control), published in Physical Review D (N. Aritomi et al. Phys Rev D 106 102003 (2022)). We generate the sidebands from the same optical parametric oscillator that is used to generate squeezed vacuum, thus ensuring that the control beam has the same alignment, mode matching and almost the same frequency as the squeezed vacuum field. We confirmed the shape of the error signal according to theory, observed frequency dependent squeezing and measured a reduction in RMS filter cavity length noise from 6.8 pm to 2.1 pm. This result was predicted by a theoretical analysis of our system which was published by our group (N. Aritomi et al. Phys. Rev. D 102, 042003 (2020)).

In FY2023 we began investigation on characterization of squeezed states using machine learning algorithms developed by one of our collaborator institutes National Tsing Hua University in Taiwan. The characterization of a squeezed state via quadrature variances obtained from homodyne measurement is commonplace in gravitational wave detection, however, the fitting process suffers from correlations in the parameter estimation, undermining the reliability of reconstructing the quantum state. Since machine learning methods are rapidly expanding in quantum optics, this is also an opportunity to combine a novel means of state characterization with the only audio-band squeezer in Japan.

Eventually we can use the experience with machine learning characterization of audio band squeezing as a platform to explore more exotic non-Gaussian quantum states such as Schrodinger Cats. Non-Gaussian quantum states combined with photon counting techniques are seen as a promising avenue to explore quantum measurement of random signals such as stochastic gravitational waves, axionic dark matter and signatures of quantum gravity.

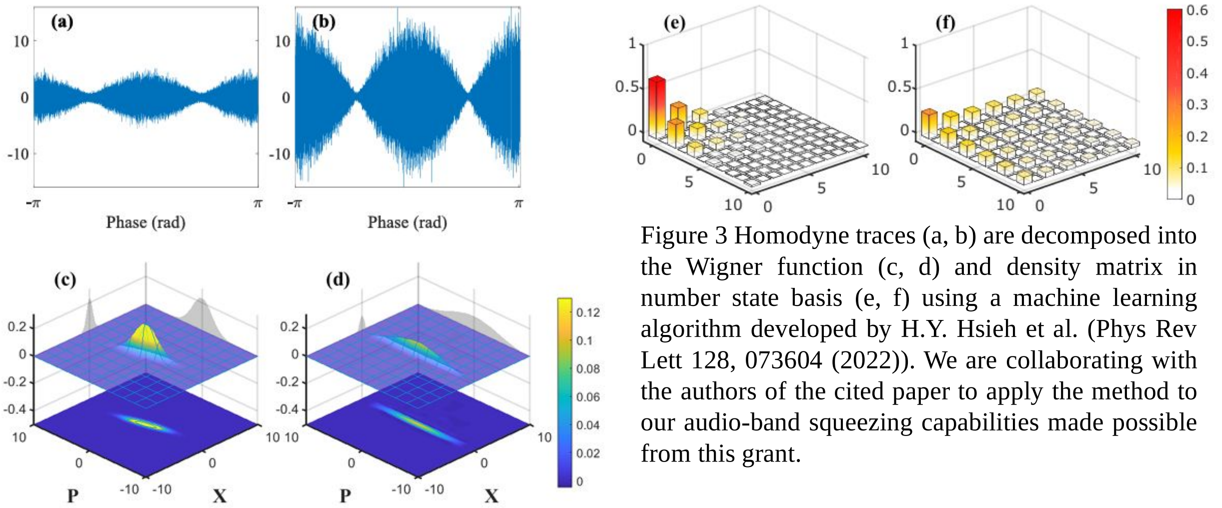


Figure 3 Homodyne traces (a, b) are decomposed into the Wigner function (c, d) and density matrix in number state basis (e, f) using a machine learning algorithm developed by H.Y. Hsieh et al. (Phys Rev Lett 128, 073604 (2022)). We are collaborating with the authors of the cited paper to apply the method to our audio-band squeezing capabilities made possible from this grant.

We currently have established the workflow for extracting a sufficient data stream using a scanned homodyne measurement saved into the data acquisition system of TAMA. We can reconstruct the density matrix of the squeezed state but currently the sampling rate and system storage are not sufficient, so we cannot reconstruct over a meaningful frequency range. The experiment could be improved with an expanded data acquisition system, which has been purchased but installation is incomplete.

Using the equipment purchased under this funding, we can continue research by lowering the optical loss of the squeezing injection path. Doing so will allow us to explore degradation from other loss sources lying beneath optical loss, such as noise of the squeezed quadrature with respect to the homodyne oscillator (phase noise), mode mismatch and spurious back reflection. These other loss sources have been flagged

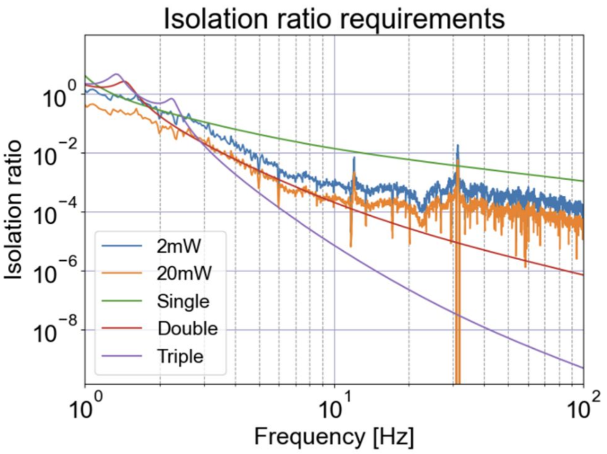
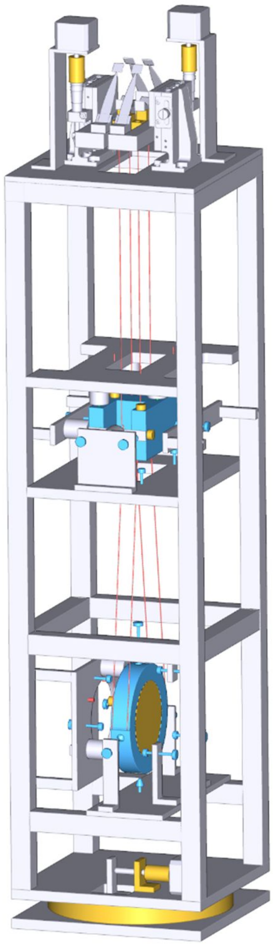


Figure 4 Isolation ratio requirements for various levels of input power and number of vibration isolation stages (single = one level, double = two levels, triple = three levels). As clear two levels of vibration isolations are sufficient to ensure the scattering isolation even with the highest expected circulating power.

as important issues to be overcome as advanced gravitational wave detectors approach their goal of 10 dB observed frequency dependent squeezing.

Another crucial result of FY2023 was the realization of a new type of suspension. As said in the previous paragraph, the noise investigation led to the design of an improved suspension for the filter cavity mirrors. It was discovered that to prevent backscattering noise to afflict the frequency dependent squeezing production, a certain level of isolation of the suspended optics is necessary, depending on the seismic vibration and on the circulating power. Such results are visible in fig. 4. Based on such results, the vibration isolation system sketched in fig 5 (left) has been designed. The vibration isolation system is based on a mini-GAS (geometric anti-spring) system which provides isolation at frequencies higher than 1Hz (see fig 5 (right)). The system has been characterized and performs as expected from simulations and in the future will be implemented within the TAMA infrastructure in place of the old vibration isolation system.



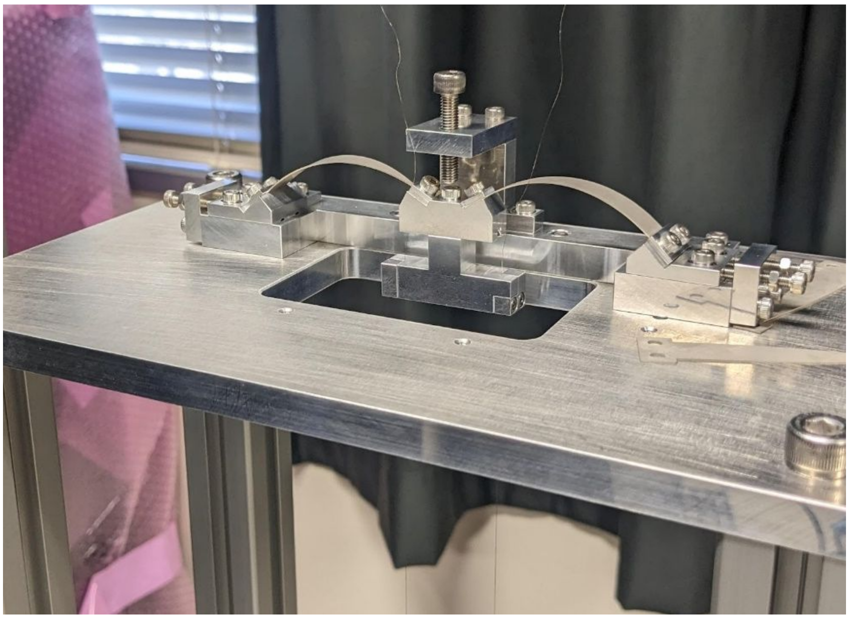


Figure 5 (left) 3D drawing of the vibration isolation system. In the top is visible the mini-GAS stage; in the center the second vibration isolation stage is visible; in the bottom the suspended optics is sketched.
(right) A picture of the mini-GAS stage is presented. The two metallic plates that form the spring elements of the suspension are visible in the center of the picture. A careful design of the angles, compression and loads for the two blades is crucial to ensure the optimization of the vibration isolation properties of the system.

５．主な発表論文等

〔雑誌論文〕　計4件（うち査読付論文　4件／うち国際共著　4件／うちオープンアクセス　2件）

１．著者名 Zhao Y.、Capocasa E.、Eisenmann M.、Aritomi N.、Page M.、Guo Y.、Polini E.、Arai K.、Aso Y.、van Beuzekom M.、Huang Y.-C.、Lee R.-K.、Lueck H.、Miyakawa O.、Prat P.、Shoda A.、Tacca M.、Takahashi R.、Vahlbruch H.、Vardaro M.、Wu C.-M.、Leonardi M.、Barsuglia M.、Flaminio R.	４．巻 105
２．論文標題 Improving the stability of frequency-dependent squeezing with bichromatic control of filter cavity length, alignment, and incident beam pointing	５．発行年 2022年
３．雑誌名 Physical Review D	６．最初と最後の頁 082003-1/11
掲載論文のDOI（デジタルオブジェクト識別子） 10.1103/PhysRevD.105.082003	査読の有無 有
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１．著者名 Aritomi N.、Zhao Y.、Capocasa E.、Leonardi M.、Eisenmann M.、Page M.、Guo Y.、Polini E.、Tomura A.、Arai K.、Aso Y.、van Beuzekom M.、Huang Y.-C.、Lee R.-K.、Lueck H.、Miyakawa O.、Prat P.、Shoda A.、Tacca M.、Takahashi R.、Vahlbruch H.、Vardaro M、Wu C.-M.、Barsuglia M.、Flaminio R.	４．巻 106
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３．雑誌名 Physical Review D	６．最初と最後の頁 102003-1/7
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２．発表標題
Demonstration of filter cavity lock with CC sidebands

３．学会等名
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Y. Zhao

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３．学会等名
GWADW

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Y. Zhao

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KAGRA F2F

４．発表年
2021年

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２．発表標題 Status of TAMA Filter Cavity
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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

共同研究相手国	相手方研究機関