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(Form 3)

Summary of Doctoral Thesis

Yuhang ZHAO

Title

Development of a frequency dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors

Gravitational-wave (GW) astronomy started in 2015 with the detection of a binary black hole coalescence by the two Advanced LIGO detectors. Advanced Virgo came online in 2017 and recently also the Japanese detector KAGRA joined the gravitational wave detectors network. The detection of gravitational waves provides an innovate and unique insight to understand the Universe, bringing important results for fundamental physics, astrophysics, nuclear physics, astronomy and cosmology. Nowadays, Earth-based gravitational-wave detectors can reach events at a redshift about 1. The increase of their detection ability will bring more scientific benefit to all the relevant research fields. Therefore, the improvement of their sensitivity is of great importance.

Current and future gravitational-wave detectors are limited by quantum noise in a large part of their spectrum. Quantum noise in interferometers is caused by quantum fluctuations of the vacuum field entering their output port. Recently, gravitational-wave detectors have introduced the so-called squeezing, as a mitigation strategy. This technique consisted in replacing the standard vacuum field with manipulated vacuum states whose amplitude and phase uncertainties (which are equal in ordinary vacuum) were respectively increased or reduced. For such states, referred to as squeezed states, the Heisenberg uncertainty principle makes amplitude and phase uncertainties not possible to be reduced simultaneously. Squeezed states are usually represented as an ellipse in the quadrature plane. If the reduced-noise quadrature is aligned with the GW signal, the result is a reduction of the quantum noise. However, since the opto-mechanical coupling of the laser light with the interferometer test masses induces a rotation of the squeezing ellipse, by injecting a simple squeezing, known as frequency independent squeezing (where the ellipse orientation does not depend on the frequency) only one part of the quantum noise can be reduced.

A quantum noise reduction in the whole spectrum can be obtained by injecting a squeezed vacuum with a frequency dependence able to counteract the rotation caused by the interferometer so to keep GW signal always aligned with the reduced-noise quadrature. Such frequency dependence can be achieved by reflecting a frequency-independent squeezed state off a detuned optical cavity with the appropriate bandwidth. This cavity is known as filter cavity. Obtaining a rotation at low frequency is

particularly demanding, as it needs a filter cavity with high storage time. A rotation at a frequency smaller than 100 Hz, as required for advanced detectors, corresponds to a cavity storage time of more than 2 ms.

My PhD research focused on an experiment which managed to realize a source of frequency dependent squeezed vacuum, suitable for broadband quantum noise reduction of advanced GW detectors. To this purpose, a 300 m long filter cavity, has been installed in an arm of the former TAMA300 at NAOJ and a source of frequency independent squeezing has been developed. When I joined this project, the filter cavity integration and control were already achieved. I work on the cavity characterization, on the realization of the frequency independent squeezing source and on the coupling of the squeezing into the cavity which allowed to obtain the final results: a frequency dependent squeezed state with ellipse rotation at frequencies lower than 100 Hz.

Filter cavity characterization and losses measurement: optical losses in the filter cavity are one of the main limitations to the achievable squeezing level. In particular, what is important are the losses per unit length and therefore, in order to reduce such losses two approaches can be used: reduce the overall losses themselves, or increase the length of the filter cavity. Our 300m long filter cavity significantly relax the losses requirement with respect to shorter cavities, but nevertheless requires high-quality mirrors. Since this parameter is so crucial, we spent a considerable effort to fully characterize it. The measurement is performed obtaining a set of on and off resonance measurements of the reflected power. By comparing the amount of light promptly reflected by the cavity and the one reflected after circulating in it we could obtained the amount of power lost inside it and computed the cavity optical losses. The measurement result is in agreement with the expectation and has been published on PRD and I am one of the author of this paper.

Development of a squeezer for gravitational wave detectors: a frequency independent squeezed vacuum source is a complex optical system based on a parametric down conversion process inside a non-linear crystal. I gave a major contribution in the construction of this system which includes four optical cavities (two of which contains non-linear crystals which require thermal stabilization), a Mach-Zehnder interferometer, two optical phase lock loops, two optical phase shifter, and eleven control loops. Our squeezer can generate 6 dB of squeezing in the whole gravitational-wave detector frequency band (from 10Hz to 100kHz). NAOJ is now one of the few laboratories in the world that can produce low-frequency squeezing suitable for GW application and it is the first within the KAGRA collaboration.

Frequency dependent squeezing measurement: in order to produce frequency dependent squeezing, we coupled the frequency independent squeezed vacuum into the filter cavity. The matching is obtained by a telescope composed of two curved mirrors, hosted in-vacuum. The filter cavity is also in vacuum and the mirrors are suspended to reduce the effect of seismic noise. The reflection from the filter cavity is characterized by a balanced homodyne detector. A squeezing level of more that 3 dB above the rotation frequency was measured, along with a squeezing level of at least 1 dB at the rotation frequency and below. Our result is crucial for the gravitational wave community as we could demonstrate a key technology that allows to improve quantum noise in the whole detection bandwidth. Moreover, since we are using a full-scale filter cavity prototype, we developed a useful experience for future implementation in GW detectors. The paper presenting this result, of which I'm first author, has been published on PRL.

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（様式８・別紙１）

Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名 Yuhang ZHAO

Title
論文題目 Development of a frequency dependent squeezed vacuum source for broadband quantum noise reduction in advanced gravitational-wave detectors

出願者は、重力波望遠鏡の感度向上を実現する周波数依存スクイージングという新技術開発に取り組み、その開発研究成果を博士論文として申請した。干渉計型重力波望遠鏡では、その観測帯域の全てにおいて、最終的には光のショットノイズと輻射圧ノイズが感度を制限してしまう。この２つのノイズの元となる光の位相揺らぎと振幅揺らぎはHeisenberg の不確定性原理を満たす関係にあり、これらのノイズを同時に低減することはできない。この問題を解決するため、それぞれのノイズが支配的となる周波数帯域が異なることを利用して、スクイーズド光の位相を周波数によって変化させることで、すべての周波数帯でノイズを低減する「周波数依存性スクイージング」という手法が提案されている。これまで、10kHz 以上の高周波においてスクイージング位相を変化させる原理検証実験は行われてきた。しかし、実際の重力波望遠鏡で必要とされる 100Hz 付近で周波数依存性のあるスクイージングを達成することは技術的に極めて難しく、出願者の研究によりついに成功したものである。この成果は、Physical Review Letters 誌に掲載されており、出願者は論文の第一著者である。また世界初の成果として、国立天文台、東京大学、総合研究大学院大学によるプレスリリースもなされた。博士論文の研究成果としては十二分であると判断できる。

本研究開発は複数のメンバーによるチームワークで達成されたものであるが、申請者はこの研究開発の主要部分全てに貢献するとともに、特にスクイーズド光を生成する部分（Squeezer）の開発では主導的役割を果たした。多くの部品の性能評価、ノイズハンティングなどを積み上げ、広帯域でコヒーレント状態と比較して直交位相振幅揺らぎを 6dB スクイーズすることに成功した。この周波数非依存スクイージング光源を種として、フィルター共振器を通すことで最終的に周波数依存性スクイージングを生成することが可能になった。そこに至るまでの装置開発や計測、考察などもすべて科学的、論理的になされており、論文として良くまとまっている。この技術を日本の重力波望遠鏡 KAGRA に導入した場合には感度にしておよそ 70%、イベント数にしておよそ５倍の改善が期待出来ることを示し、今後の重力波天文学の発展を大いに期待させる内容であった。

口頭試問についても、質問に対して概ね的確に回答しており、若手の研究者として自立して活動を行えると判断するに十分であった。発表および口頭試問は全て英語でなされており、語学力についても問題ない。以上の理由により、審査委員会は、本論文が博士の学位授与に値すると判断した。