PROCEEDINGS OF SCIENCE

Quantum noise enhancement for gravitational wave detectors: Status of squeezed vacuum research at TAMA and KAGRA

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PoS(ICRC2023)1565

The current generation of gravitational wave laser interferometer detectors operate at the sensitivity limit imposed by quantum uncertainty of photon amplitude and phase quadratures. Heisenberg's principle dictates that the product of amplitude and phase uncertainty must be above a certain value, but apart from that we can still manipulate either quadrature to achieve quantum noise reduction, since the effect of amplitude and phase uncertainty is frequency dependent in gravitational wave detectors. This is the crux of the frequency dependent squeezing technique, which reduces quantum amplitude uncertainty at low frequency and quantum phase uncertainty at high frequency, where these respective quadratures each dominate. Thus, we can reduce quantum noise across the entire detection band. However, this technique is extremely sensitive to optical losses at all parts of the squeezing generation chain, and so far only a low degree of broadband squeezing has been observed. This proceeding outlines the current status of squeezing research at the former TAMA300 gravitational wave detector at the National Astronomical Observatory of Japan, where we aim to improve the level of achievable broadband squeezing. An update is also given regarding design and noise of squeezed injection for the underground gravitational wave detector KAGRA located in Gifu, Japan.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

1. Introduction

The international gravitational wave (GW) detection network of LIGO, Virgo and KAGRA has entered the fourth observing run, building up an impressive catalogue of black hole GW events [1]. Now we wish to turn our attention to binary neutron star mergers, which represent the most promising candidate for gravitational wave astrophysics with current detectors. However, even at the level of sensitivity during O3 [2], only one neutron star event was confirmed [1, 3]. The most interesting neutron star physics occur in the post-merger 1-5 kHz tidal oscillations that encode the equation of state of ultradense nuclear matter. Therefore, we must maximise the sensitivity of as many detectors as possible in this frequency range for the best science outcomes.

At the current sensitivity, interferometric gravitational wave detectors are limited by quantum noise below 50 Hz and above 200 Hz, and by Brownian motion of the test mass mirror coatings in the 50-200 Hz band [2]. Quantum noise arises due to an uncertainty relation between the amplitude and phase quadratures of photons, with quantum amplitude noise dominant at low frequency and quantum phase noise at high frequency [4]. These noises are commonly represented as an ellipse in phase/amplitude space. By reducing one noise quadrature, the other is increased, "squeezing" the noise ellipse. In the GW detector community, squeezing is achieved using parametric down conversion with an optical parametric oscillator (OPO) featuring a nonlinear crystal. During the O3 run, squeezing was successfully used to enhance the shot noise limited sensitivity [2, 5, 6], however, the degree of enhancement was limited by the associated increase of low frequency quantum noise rising above the technical noise. The observation of broadband quantum noise shows the need for frequency dependent squeezing (FDS) [7]. By squeezing the phase noise at high frequency, amplitude noise at low frequency, and a frequency dependent linear combination at intermediate frequencies, we can reduce the quantum noise across the entire detection band. The so-called rotation of the noise ellipse is accomplished by injecting squeezed vacuum into a large detuned optical cavity called a filter cavity.

2. Frequency dependent squeezing for gravitational wave detectors

Frequency dependent squeezing is accomplished using a narrow bandwidth filter cavity detuned at approximately half the bandwidth of the main detector. Noise sidebands outside the bandwidth of the filter cavity are promptly reflected, keeping their squeezed quadrature. Noise sidebands inside the filter cavity bandwidth are stored in a frequency dependent manner, causing rotation of the squeezed quadrature. While the technique of FDS had been established before, the key difficulty for GW detection lies in the frequency required for squeezing the noise ellipse. The transition between radiation pressure and shot noise dominating the quantum noise contribution occurs at approximately 100 Hz, setting the requirement for the filter cavity bandwidth. Thus, the filter cavity must be hundreds of metres long and/or have reasonably high finesse [8]. The first demonstration of FDS in an appropriately sized filter cavity was performed by Zhao, *et al.* at the former GW interferometer prototype TAMA300 located at the Mitaka, Tokyo campus of the National Astronomical Observatory of Japan [9]. As the name suggests, the arm cavities are 300 m long, which eventually was also the length chosen for the filter cavities at Virgo and both LIGO facilities. Frequency independent squeezing was generated at a level of 6.1 dB squeezing/15.9

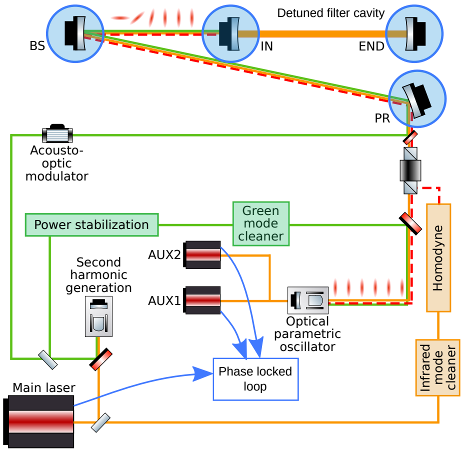

Figure 1: Simplified block diagram of the TAMA experiment: Optical components used to generate frequency dependent squeezing. For simplicity, relay mirrors are not indicated, only dichroic mirrors, suspended mirrors and beam splitters. The blue circles indicate mirrors suspended inside vacuum tanks. The squeezed beam is indicated by a dotted line and generated by injecting green into the optical parametric oscillator. The filter cavity is detuned with respect to the squeezed beam, and also has low finesse for green. The suspended mirrors have labels Power Recycling (PR), Beam Splitter (BS), Input (IN) and End (END) inherited from the original GW detector prototype. AUX lasers generate control signals for the optical parametric oscillator, filter cavity and squeezed phase.

dB antisqueezing. A noise ellipse rotation around 90 Hz was successfully achieved, with 3.4 dB resultant FDS above the rotation frequency and approximately 1 dB below the rotation frequency. The degradation of squeezing at low frequency was strongly linked to residual seismic motion of the filter cavity input mirror imparting back reflected phase noise on the squeezed beam.

With KAGRA now officially joining the observation efforts we have a much more effective platform to localize gravitational events of any direction and polarization. KAGRA has the unique situation of being located in the Kamioka mine in the mountains of Gifu, Japan [10]. This has the advantage of significantly reducing seismic noise in the region 1-10 Hz [11], which has been greatly problematic in GW detection thus far. However, due to the limited space and unlikelihood of further excavation, we are also limited on the size of a potential filter cavity and associated squeezing injection optics. Thus implementation of FDS in KAGRA requires some different approaches to LIGO and Virgo.

3. The TAMA experiment

TAMA300 was originally a prototype gravitational wave detector operating in the early 2000s. For the works in frequency dependent squeezing, we simply refer to the facility as TAMA from now on. A simplified outline of the TAMA experiment is shown in figure 1. The main difference compared to the old GW detector is the squeezer table, which produces frequency independent squeezed vacuum as well as auxiliary control beams. The squeezed beam is generated via parametric down conversion of 532 nm green light inside an OPO cavity containing a periodically-poled potassium titanyl phosphate nonlinear crystal. The green beam itself is sourced via second harmonic generation from the 1064 nm main laser, then is passed through a triangular travelling wave mode cleaner for mode shape stabilization and a miniature Mach Zender interferometer for power stabilization. The squeezer table hosts two additional phase locked 1064 nm lasers. A p-polarized beam is used for length control of the OPO/nonlinear crystal cavity, and another s-polarized beam is used for controlling the phase of the squeezed beam. The squeezed beam can be redirected to an on-table homodyne detector via the use of flipping mirrors, bypassing the filter cavity and allowing us to characterize the frequency independent squeezed performance if need be. While squeezed vacuum has no classical amplitude, we still have to control its phase using an auxiliary beam. The auxiliary s-polarized laser is used to implement coherent control (CC) of the squeezed beam. The CC beam is sent to the OPO, where it is used in two control loops - one to stabilize the green phase entering the OPO, and another to stabilize the phase of the squeezed beam with respect to the homodyne local oscillator. By passing the CC beam through the OPO, we can ensure co-propagation and mode matching with the squeezed beam.

The FDS experiment at TAMA utilizes four vacuum tanks associated with mirrors of the former GW detector - power recycling (PR), beam splitter (BS), south input mirror (IN) and south end mirror (END). IN and END form the detuned 300m filter cavity, while PR and BS are steering mirrors that are used for alignment control of the beams entering the filter cavity. The mirrors are suspended using the TAMA type-C double stage pendulums of the original detector. Alignment of the suspended mirrors is controlled globally using control beams from the squeezer and locally via red HeNe laser optical levers.

4. Current results and future works of the TAMA experiment

The original filter cavity demonstration of Zhao, *et al.* used a pickoff of the on-table green beam as a means to implement Pound-Drever-Hall [12] locking. However, green has low finesse in the filter cavity and does not sufficiently co-propagate with the squeezed vacuum. A solution involves the CC laser injected into the OPO. The CC laser is detuned from the main laser by Ω_{CC}, and interactions with the OPO generate a second sideband detuned by $-\Omega_{\mathrm{CC}}$. By nature of being generated inside the OPO, the second CC beam also has the virtue of ensuring co-propagation and mode matching with the squeezed beam [13]. The two CC sidebands have a different resonant condition at the filter cavity and acquire a differential phase. Beating of the CC sidebands can then control the filter cavity length.

The effectiveness of the CC filter cavity locking method has been demonstrated using the TAMA filter cavity, detailed in Aritomi, *et al.* [14]. The acquired error signal matched very well compared to predictions. Compared to using the green lock, the length noise of the filter cavity was reduced from 6.8 pm to 2.1 pm.

While we have established that length control using the green beam generally has more noise than with the infrared beam, green control does have some advantages in simplicity, being visible as well as having a lower finesse in the filter cavity which makes acquisition easier. The filter cavity detuning must be kept stable to ensure the proper frequency dependence of the noise ellipse rotation however. With two separate wavelengths of light used for FDS and control, it is possible for the green and infrared beams to sense differing detuning of the filter cavity. We have investigated some of the noise sources present in the green control in an attempt to make green lock a viable contingency, detailed in Zhao, *et al.* [15].

In particular, we have found that the green and infrared beam axes inside the filter cavity have a differing optical path due to various fluctuations of the mirror coating. We could reduce some of the offset through positioning of the beam spot on a more stable point. Drift of the main laser frequency can also cause a difference in the relative filter cavity detuning witnessed by infrared and green. Specifically, when the filter cavity unlocks then relocks, the green and infrared will cross a different number of free spectral ranges. However, in a full scale GW detector, the squeezing main laser is phase locked to the interferometer main laser, so this should be less of a problem in full scale implementation. We also identified about 4 Hz of detuning drift from the electro-optic modulator used to produce the Pound-Drever-Hall modulations. We have since replaced the previous modulator with a wedged version to remove this source of detuning drift.

5. Design of frequency dependent squeezing in the underground environment of KAGRA

At frequencies below approximately 20 Hz, FDS is limited by a combination of spurious light from the detector and residual seismic motion at the filter cavity suspended mirrors, known as backscattering noise. Spurious light comes from the dark port of the interferometer and can pass through the output Faraday isolator to reach the filter cavity. Residual seismic noise from the motion of the suspended mirrors back-reflects the spurious light, interfering with squeezed vacuum components of the same frequency. Because the squeezed vacuum and interferometer main laser are detuned a half linewidth versus the filter cavity, the sensitivity of reflected power and phase to the input mirror motion is much higher than for a resonant cavity or relay optic. Therefore, it is critical that we reduce the amount of dark port light propagating through the squeezer as well as the residual seismic motion of the filter cavity mirrors. Fortunately in KAGRA the seismic noise is greatly reduced compared to above-ground detectors [11]. The filter cavity seismic isolation requirement is set by the allowed amount of degradation that is imposed on the squeezing. We follow McCuller and Barsotti of Advanced LIGO to allow for 6 dB resultant FDS with a safety factor 10 [16]. The amount of tolerable backscatter is also relaxed in frequency bands where quantum noise does not dominate, proportional to levels of other noises.

We have found that 3 Faraday isolators on the squeezing path are necessary to keep the levels of spurious light acceptable for dark port power up to 20 mW typical of GW detectors. Due to the reduced seismic noise at KAGRA, we can use just a dual stage pendulum instead of a triple stage suspension, despite the available space allowing for a filter cavity of only 85 m. The performance of different suspensions in conjunction with 3 isolators is shown in figure 2. Having fewer suspension stages greatly simplifies the control system operation and stability.

Some isolation is also required for the injection and relay optics, which have at most a single stage suspension. However, their residual motion does not impose a drastic change in optical phase compared to reflection from a detuned optical cavity. The position with respect to squeezing Faraday isolators does not matter, since to return to the interferometer the added noise power has to pass through the squeezing isolators anyway. We find that the injection optics require a single stage isolation at 4 Hz or lower resonant frequency to provide the required isolation. In KAGRA, we have a 1 Hz single stage isolation made for the transmission optics system that detects beams passing through the end test masses. Additionally, the OPO is another significant contributor to

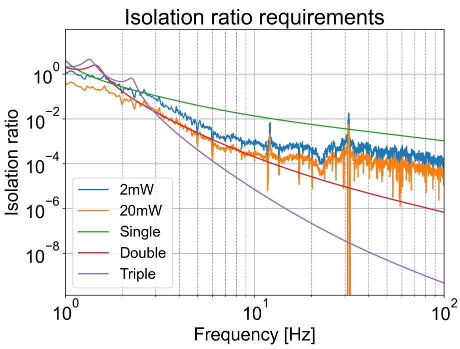

Figure 2: Filter cavity isolation requirement to prevent degradation of FDS enhancement via backscattering: The jagged lines indicate the upper limit of residual filter cavity mirror motion necessary to prevent backscattered light from affecting 6 dB total FDS, and are calculated from the measured seismic motion inside the Kamioka mine. The requirement is shown at two levels of nominal interferometer dark port power - milliWatts to tens of milliWatts is typical for advanced GW detectors. A double pendulum can satisfy the requirement for ~ 3 Hz and above.

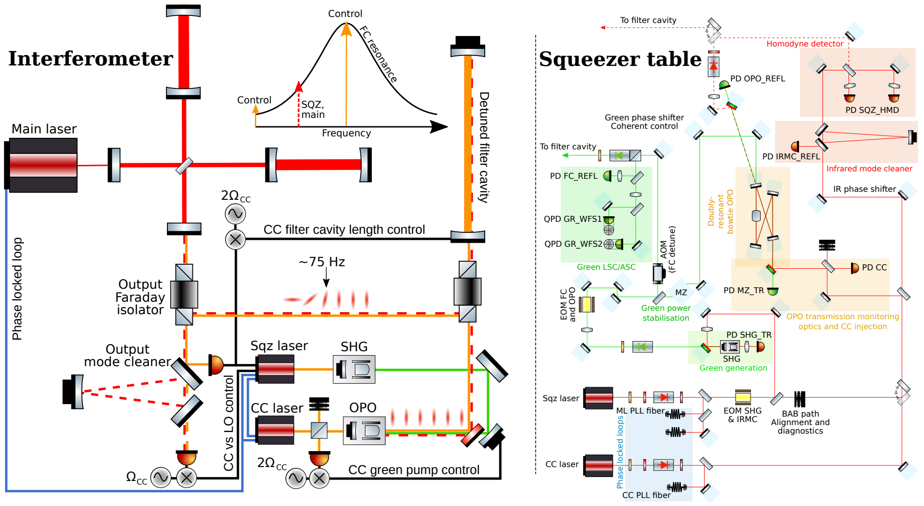

Figure 3: Integrating FDS into a gravitational wave detector: The left panel shows the layout of a GW detector employing the coherent control scheme described in section 4, with a diagram of the control beam frequencies compared to the filter cavity resonance. The right panel shows a detailed layout of the optics expected for the squeezer table.

backscatter, and we plan to replace the linear OPO cavity of TAMA for a bowtie-shaped cavity to geometrically reduce back-reflection.

Studies are currently being undertaken regarding integration of FDS into the underground environment of KAGRA. A scheme of the coherent control system and new squeezer table is shown in figure 3. In particular, the coherent control signal is planned to be extracted from the reflection of the interferometer output mode cleaner. As mentioned, the squeezer table must save space while accommodating a new bowtie OPO design. We are also designing low loss in-vacuum Faraday isolators that are important for preventing optical and backscattering losses.

6. Summary

At the TAMA experiment we have demonstrated improvement in the length stability of the filter cavity for frequency dependent squeezing. Length control in both cases of green and infrared were improved, and upgrades to the system were outlined. In addition, we report on the design of squeezing for the underground KAGRA detector. One of the main results is that a filter cavity in the tunnel can tolerate back-reflected phase noise using only a double stage pendulum, which will greatly simplify the implementation.

7. Acknowledgements

The experimental works described in this proceedings paper were supported by JSPS Grant-in-Aid for Scientific Research (no. 15H02095, 18H01235, 21H04476).

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