

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

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The current generation of gravitational wave laser interferometer detectors operate at the sensitivity limit imposed by quantum uncertainty of photon amplitude and phase. 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 amplitude uncertainty at low frequency and 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. In this talk I will outline 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. I will also update on the design of squeezed injection for the underground gravitational wave detector KAGRA located in Gifu, Japan.

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1. Introduction

The international gravitational wave (GW) detection network of LIGO, Virgo and KAGRA has now entered the fourth observing run. Among the accomplishments of GW astronomy since the first discovery [1] are the black hole binary catalogue [3, 4], the multi-messenger observation of a binary neutron star merger [2] and an independent standard siren verification of the Hubble constant [16].

The intent of Advanced LIGO style gravitational wave detector design was to maximise the chance of detecting the strongest event, binary black hole mergers. Now we wish to turn our attention to other events that can be seen with upgrades to our current devices. Binary neutron star mergers represent the most promising candidate for gravitational wave astrophysics with current detectors, but even at the level of sensitivity during O3 [11], only one multi-messenger event was confirmed [2, 4]. 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, 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 [11]. Quantum noise arises due to a Heisenberg Uncertainty relation between the amplitude and phase of photons circulating throughout the detector [12, 14]. Quantum amplitude noise, also known as radiation pressure noise, dominates at low frequency band and quantum phase noise, also known as shot noise, dominates at high frequency. 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 [5, 11, 20], however, the degree of enhancement was limited by the low frequency quantum radiation pressure noise rising above the technical noise. The observation of quantum noise in the low and high frequency bands brought the need to implement frequency dependent squeezing (FDS) [15]. 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 detection band in a frequency dependent manner. The so-called rotation of the noise ellipse is accomplished by injected squeezed vacuum into a large scale 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 [13].

Audio band squeezed ellipse rotation was achieved by Oelker *et al.* using a 2m filter cavity [18], with a rotation frequency of about 1.2 kHz. Eventually, the first demonstration of FDS in an appropriately sized filter cavity was performed by Zhao, *et al.* at the former GW detector prototype TAMA300 located at the Mitaka, Tokyo campus of the National Astronomical Observatory of Japan [21]. As the name suggests, the arm cavities are 300m long, which eventually was also the length chosen for the O4 filter cavities at Virgo and both LIGO facilities. Frequency independent squeezing was generated at a level of 6.1 dB squeezing/15.9 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.

At the time of writing, only the two LIGO detectors are operating frequency dependent squeezing. It is in the best interest to maximise our chances of precisely observing binary neutron star events, and thus we would like to maximise the global coverage of highly sensitive operational detectors. Indeed, it can be seen in the results of GW170817 that sky localization is greatly improved for observation in three detectors versus two detectors [2]. 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 prefecture in Japan [6, 7]. This has the advantage of significantly reducing the impact of seismic noise in the region 1-10 Hz [19], which has been greatly problematic in GW detection thus far, and also has a prominent impact on FDS. However, due to the limited space and unlikelihood of further tunnel 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. Part of the works outlined in this proceeding will be about the design of the underground FDS system for KAGRA.

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. 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 532nm green light inside a linear optical parametric oscillator containing a periodically-poled potassium titanyl phosphate nonlinear crystal. The green beam itself is sourced via second harmonic generation from the 1064nm main laser, and 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 1064 nm lasers locked to the main by phase locked loop. A p-polarization laser is used for length control of the OPO/nonlinear crystal cavity, and another s-polarization laser 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 characterise the frequency independent squeezed performance if need be.

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. In addition to global wavefront sensing alignment control beams coming from the squeezer, the alignment of the suspended mirrors can also be monitored locally using red HeNe optical lever lasers.

FDS requires the injection of squeezed vacuum, which has no classical amplitude. However, we still have to control the phase of the squeezed vacuum using an auxiliary beam. The aforementioned 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 phase of green light 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 its co-propagation and mode matching with the squeezed beam.

4. Current results and future works of the TAMA experiment

4.1 Coherently propagating control of filter cavity length

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 [10] locking. However, the filter cavity has low finesse for green, and does not sufficiently co-propagate with the squeezed vacuum. A solution presents itself with the CC laser that is 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 $-\Omega_{CC}$. 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 [8]. The two CC sidebands have a different resonant condition at the filter cavity and acquire a differential phase. We can use the beating of the CC sidebands to control the filter cavity length.

The effectiveness of the CC filter cavity locking method has been demonstrated using the TAMA filter cavity [9]. 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.

4.2 Improvement of green filter cavity length control

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 [22].

In particular, we have found that the green and infrared beam axes inside the filter cavity combine with various fluctuations of the coating to produce a differing optical path length for green and infrared. We could reduce some of the offset through optimal positioning of the beam spot on a more stable point of the coating surface.

Drift of the main laser frequency can cause some drift of the relative detuning of the filter cavity as 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 gravitational wave detector, the squeezing main laser will be phase locked to the interferometer main laser, so we expect this to 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

KAGRA is located in the tunnels of the Kamioka mine, where the level of seismic noise is greatly reduced compared to above-ground detectors [19]. This has good consequences for the backscattered light spectrum, which is a major noise source for FDS that is directly dependent upon residual seismic motion of the filter cavity input mirror.

5.1 Backscattered light

FDS is limited by two main technical noise sources. At frequencies below approximately 20 Hz, the noise spectrum is dominated by a combination of spurious light from the detector and residual seismic motion at the suspended mirrors, known as backscattering noise. Above 20 Hz, the noise spectrum is dominated by reinjected sensing noise as a result of the requirement of voltage controlled oscillators for the filter cavity length controls.

We turn specifically to backscattering, which sets a strict limit on the filter cavity suspension and length control parameters. Nominally, a GW interferometer is operated at the dark fringe in order to maximise common mode rejection. However, a small amount of optical power inevitably leaks from the dark port. The amount of residual light at the fundamental mode of the main laser frequency is of the order of milliwatts to tens of milliwatts, in addition to higher order modes and offset control beams. Past the dark port of detector is the output Faraday isolator, consisting of two polarized beam splitters and a Faraday rotator. Squeezed vacuum is injected into the main interferometer through one of the polarized beam splitters of the Faraday isolator, however, this also offers a path for the spurious light from the dark port to reach the filter cavity. When stray light reaches the filter cavity, it acquires residual seismic noise from the motion of the suspended mirrors, and interferes with squeezed vacuum components at the same frequency. 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.

The seismic isolation requirement of the filter cavity is set by the allowed amount of degradation that is imposed on the squeezing. We follow the guidelines set by McCuller and Barsotti for Advanced LIGO, in that we want to allow for eventual 6 dB resultant FDS with a safety factor of 10

[17]. The amount of tolerable backscatter noise is also adjusted depending on the dominant noise sources - we can relax the requirement in areas of the sensitivity curve where quantum noise does not dominate. The strictest backscattering requirement is located at 50 Hz, where radiation pressure noise is expected to dominate, as well as the entirety of the shot noise limited frequency band.

We have found that 3 Faraday isolators are necessary to keep the levels of spurious light acceptable, and that this is broadly satisfactory for a range of predicted dark port output power levels. Due to the reduced seismic noise level at KAGRA, we also find that we can stay within the tolerable margin of backscattered light using only a dual stage pendulum instead of a triple stage suspension, despite the filter cavity being shortened by a factor of 3.5. Having less suspension stages greatly simplifies the control system operation and stability, which is a boon for the integration of auxiliary optics.

Some level of suspension is also required for the injection optics. Since the relay optics will only have some damping or a single stage suspension, the level of residual seismic noise will be higher than for the filter cavity. However, motion of the relay optics does not impose the drastic phase change of reflection from a detuned optical cavity, so the impact of residual motion is also not as large. The position with respect to the additional squeezing 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, although the requirements are not particularly strict. A 4 Hz or lower resonant frequency would provide the required isolation. In KAGRA, we have a 1 Hz single stage isolation system for the transmission monitoring optics that detects beams passing through the end test masses.

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.

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