Form 8

Research Result Report
ICRR Inter-University Research Program 2025

Research Subject: Development of a squeezed vacuum source for quantum noise reduction in KAGRA
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Summary of Research Result : Squeezed vacuum is generated using a nonlinear optical parametric oscillator to create correlations between photon pairs in the electromagnetic field. In FY25 we assembled the critical components used to create squeezed vacuum for KAGRA – a second harmonic generator that produces 532 nm green light with low frequency and intensity noise, and a vacuum-compatible bowtie-configuration optical parametric oscillator that uses 532 nm photons to create correlated pairs of 1064 nm photons via parametric down conversion. The squeezed state is detected via homodyne detection. We tested several appropriate homodyne detectors, both of the low noise and high bandwidth variety. Our collaboration with NTHU was of great importance in obtaining and optimizing the second harmonic generator, optical parametric oscillator and homodyne detectors. We could produce approximately 6 dB of quantum noise reduction using our squeezed source in a tabletop test. Currently the phase of the squeezed state with respect to the homodyne local oscillator is uncontrolled, so the quantum noise level will oscillate above and below the shot noise level, but we can still distinguish the maximum and minimum levels of quantum noise by using a spectrum analyzer to perform zero-span measurement at 3 MHz. In the first iteration of our test, the main performance limitations were: i) sub-optimal splitting of the nominally 50:50 balanced homodyne beam splitter, ii) relative intensity noise of the green pump, which causes optical absorption related phase noise of the optical parametric oscillator, iii) laser noise of the balanced homodyne local oscillator, which causes uncertainty in the measured quadrature of squeezing, and iv) scattered light impinging on the optical parametric

oscillator crystal, which degrades the produced squeezing by encouraging competing nonlinear processes. In the second iteration of our test, we mitigated the sub-optimal homodyne splitting by using a method of polarization balanced homodyne detection, where the splitting ratio can be easily finely tuned using a waveplate. We have ordered the necessary optics to control the laser noises of the green pump and homodyne local oscillator and will test them soon.

We determined the necessary modulation equipment to purchase for phase control of the squeezed vacuum. The main consideration is the injection of control noise into the gravitational wave detection photodiode when the system is eventually assembled in KAGRA. We determined that a control sideband of 3.5 MHz is sufficient. We ordered two AOMs which will shift up +200 MHz and down -203.5 MHz, which also has the effect of strongly deflecting the zero-detuned pickoff that generates the control sideband. This is important because if this zero-detuned pickoff reaches the optical parametric oscillator it causes the same degradation effect as scattered light.

We conducted an external review on the conceptual design of the squeezed source which was initiated by Professor Aso and attended by senior staff scientists from LIGO and Virgo. We confirmed that there were no critical issues with the squeezed source layout and control system.

One issue which we are working on solving is to figure out an alternate procurement path for nonlinear crystals. The optical parametric oscillator contains a nonlinear crystal which is the generator of nonlinear optics interactions that result in squeezing. These crystals are made from periodically poled potassium titanyl phosphate (PPKTP), which must then be super polished with a surface roughness ideally approaching 1 Angstrom. These crystals are small (1mm x 5mm x 10mm) so not every optics company had the capability to polish them to standards. However, the company that had performed this service for a long time in the gravitational waves community shut down. Towards the end of FY25 we began testing PPKTP crystals super polished by different vendors in order to find a new best procurement source. This is important for the future because PPKTP crystals can suffer damage from green light absorption after long operation. When we eventually integrate the system into KAGRA we would like to do so with a fresh PPKTP crystal.