Quantum enhancement in a prototype gravitational wave detector

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We report on an experimental demonstration of improved sensitivity of a prototype laser-interferometric gravitational wave (GW) detector by injection of squeezed vacuum into the unused (antisymmetric) port. An inferred level of 9.3 dB [1] of squeezed vacuum generated by an optical parametric oscillator was injected into a signal-recycled Michelson interferometer with its optics suspended as pendulums. A 3.0 dB or 40% improvement in displacement sensitivity was observed in a broad band of frequencies where the interferometer output was limited by photon shot noise. This demonstration was carried out in a prototype interferometer with suspended mirrors, and a readout and control system similar to those used in existing GW detectors, and is, therefore, an important step toward implementing squeezing enhancements on long baseline laser-interferometric GW detectors.

Introduction to GW detection: Laser-interferometric gravitational wave (GW) detectors such as the Laser Interferometer Gravitational-Wave Observatory (LIGO) [1, 2] are designed to measure distance changes on the order of 10^{-18} m caused by GWs from astronomical sources, such as coalescence of neutron stars and black holes, supernova explosions, and the Big Bang, providing further verification of Einstein's theory of general relativity and opening an entirely new window onto the universe [3]. The sensitivity of the currently operational gravitational wave detectors such as LIGO [1], VIRGO [4], GEO600 [5], and TAMA300 [6] is partly limited by quantum noise that arises from the Heisenberg uncertainty due to quantum mechanical fluctuations in the number of photons at the interferometer output. Future gravitational wave detectors such as Advanced LIGO [7], which are planned to be operational in the next few years, are expected to be limited by quantum noise of light at almost all frequencies in the GW detection band (10 Hz – 10 kHz).

Introduction to quantum noise: The quantum nature of light reveals itself in two effects that limit the precision of an optical measurement of mirror position: (i) *shot noise*, which typically dominates at frequencies above 100 Hz, arises from quantum uncertainty in the number of photons at the interferometer output; and (ii) *quantum radiation pressure noise*, typically dominant at frequencies below 100 Hz, that arises from mirror displacements induced by quantum radiation pressure fluctuations [8–11]. They are caused by quantum fluctuations in the phase and amplitude quadratures, respectively, of a vacuum electromagnetic field that enters the unused or antisymmetric port of the interferometer. The displacement noise associated with the shot noise and quantum radiation pressure noise of a simple Michelson interferometer on a dark fringe in the frequency domain is given by [1]

$$\Delta x_{\rm shot} = \sqrt{\frac{\hbar c \lambda}{\pi P}} \quad \text{and} \quad \Delta x_{\rm rad} = \sqrt{\frac{\hbar P}{\pi^3 c \lambda m^2 f^4}}, \quad (1)$$

where c is the speed of light in vacuum, $\hbar$ is Planck's constant, λ is the laser wavelength, m is the (reduced) mass of the mirrors, f is the measurement frequency, and P is the optical power incident on the beam splitter. The so-called standard quantum limit (SQL) [8, 9, 11, 12], can be obtained by minimizing the uncorrelated sum of the two with respect to P, given by $\Delta x_{\rm SQL} = \sqrt{\frac{2\hbar}{\pi^2 m f^2}}$.

Introduction to squeezing injection: The quantum limit can be circumvented by the injection of non-classical, or *squeezed*, states of light [13–15] into the antisymmetric port of the interferometer [13]. Following the 1981 proposal of Caves to improve the sensitivity of quantum-noise-limited laser interferometers by squeezed state injection, a handful of experimental efforts have realized the proof-of-principle on the table-top scale at MHz frequencies. The pioneering experiment was performed by Xiao *et al.* [16] using a Mach-Zehnder interferometer a few years after the first observation of squeezed states by Slusher *et al.* in 1985 [17]. Later, squeezing-enhancement in table-top realizations of Michelson interferometer configurations similar to those used in the current and future large-scale GW detectors has been demonstrated [18, 19]. Here we demonstrate improved sensitivity in a suspended-mirror prototype GW interferometer by injection of squeezed vacuum.

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[1] This value was deduced based on the measured level of squeezing and optical losses.

An important distinction between our experiment and previous efforts is that it is the first implementation of squeezing-enhancement in a prototype GW detector with suspended optics and control and readout schemes similar to those used in currently operational LIGO detectors. It is, therefore, an important step toward implementation of quantum-enhancement in long baseline gravitational interferometers. In all these experiments, including the one reported here, quantum radiation pressure noise was buried under other technical noise sources such as seismic noise and mirror thermal noise, and only the shot noise limit was accessible – i.e. not buried under technical noise – for observation of quantum-enhancement. Quantum radiation pressure noise has never been observed in interferometer experiments to date, with or without injected squeezing.

Introduction to squeezed state generation: Squeezed states are typically generated using nonlinear crystals in sub-threshold optical parametric oscillators (OPOs). OPOs produce squeezed light by correlating the upper and lower quantum sidebands centered around the carrier frequency, in the presence of an energetic pump field. Since all GW detectors presently use high power Nd:YAG lasers sources at 1064 nm, generating squeezed vacuum states at 1064 nm is essential. To generate a squeezed vacuum field (instead of a squeezed light field), a random vacuum field is injected as a seed (instead of light) into a sub-threshold OPO pumped with a second-harmonic field at 532 nm. Observation of squeezed vacuum in the GW band has been reported by McKenzie *et al.* [20] and Vahlbruch et al. [21]; the researchers took great care to seed the OPOs with vacuum states only, thus avoiding excess classical laser noise that otherwise limits low frequency squeezing [20–22].

Introduction to interferometric GW detectors: Terrestrial GW interferometers typically comprise a Michelson interferometer with a Fabry-Perot cavity in each arm, to increase the phase sensitivity of the detector. The Michelson interferometer is operated on or near a dark fringe. Since most of the incident light returns toward the laser source, the GW-induced signal can be increased by recycling the laser power back toward the beam splitter. This is achieved by placing a partially transmitting mirror – the "power recycling" mirror – between the laser source and the beam splitter. Typical power recycling gains of 30 to 70 have be realized in presently operational GW detectors. Similarly, a partially transmissive mirror can also be placed at the antisymmetric port of the beam splitter to further enhance the GW-induced signal at the interferometer output. This "signal recycling" mirror forms a complex optical cavity with the rest of the interferometer. The frequency-dependent optical response of the detector to incident GWs can be tuned by operating the signal recycling cavity at various detunings from resonance. Signal recycling is utilized in the GEO600 detector [5], and is planned for the Advanced LIGO detector [7].

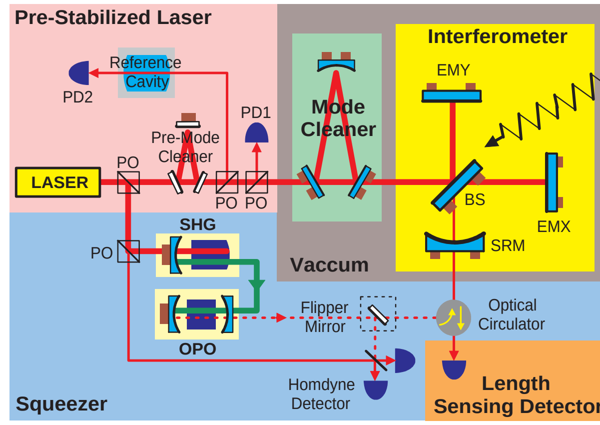

FIG. 1: Schematic of the quantum gravity-wave detector that consists of five parts (i) - (v). BS: 50/50 beamsplitter; PD1-PD5: photodetectors; PO: pickoff mirror; $\lambda/4$: quarter-wave plate; PBS: polarizing beamsplitter; SRM: signal-recycling mirror; EMX/EMY: end mirrors long the x/y axis, respectively; SHG: second-harmonic generator; OPO: optical parametric oscillator; The SHG, OPO, reference cavity, pre-mode cleaner, mode cleaner, and signal-recycling cavity are are all locked by the Pound-Drever-Hall technique. PD1-PD3 are used for the laser intensity and frequency stabilization while PD4 and PD5 are used to control the interferometer. All the mode-cleaner and interferometer optics are suspended by single loop pendulums.

The experiment reported here used a sub-configuration of the complete Advanced LIGO interferometer – a signal-recycled Michelson interferometer (SRMI), chosen in part because it is an important new feature of the optical configuration envisioned for Advanced LIGO [7, 23]. The shot noise limited displacement sensitivity of the SRMI is given in the frequency domain by

$$\Delta x_{\mathrm{SRMI}} = \frac{1}{\sqrt{|G|}}\sqrt{\frac{\hbar c\lambda}{\pi\eta P}}e^{-R}, \tag{2}$$

where G is the signal-recycling gain, given by $G = [t_s/(1 - r_s r_m e^{-2i\phi})]^2$, η is the power transmission efficiency from the signal-recycling mirror to the photodetector (including the quantum efficiency of the photodetector), and R is the squeeze factor. Here r_s and t_s are the amplitude reflectivity and transmissivity of the signal-recycling mirror, r_m is the reflectivity of the Michelson interferometer, and ϕ is the signal-recycling cavity detuning. We note that setting $G = 1$ and $R = 0$ leads to the familiar expression for the shot noise limit in a Michelson interferometer, given in Eq. 1. In the experiment described below, η, r_s, and r_m are measured to be 0.825, $\sqrt{0.925}$, and $\sqrt{0.995}$ respectively, and P and ϕ are obtained from fits to be 57 mW and 0 (or $\phi \ll 1$), respectively.

Experiment overview: This experiment was carried out at the LIGO Caltech 40 meter prototype GW detector [23]. A schematic of the experiment is shown in Fig. 1. Its major components are (i) an intensity- and frequency-stabilized Nd:YAG Master Oscillator Power Amplifier (MOPA) laser with a throughput of 5 W at 1064 nm that serves as the light source for both the interferometer and the squeezed vacuum generator; (ii) a triangular optical cavity – or mode cleaner – which consists of three free hanging mirrors with a cavity half-length of 13.5 m; (iii) a test interferometer configured as a SRMI, comprising a 50/50 beam splitter, two high-reflectivity end mirrors, and a signal-recycling mirror, all suspended as single loop pendulums; (iv) a squeezed vacuum generator – or squeezer – that consists of a second-harmonic generator (SHG), and optical parametric oscillator (OPO), a monitor homodyne detector, and an optical circulator to inject the generated squeezed vacuum field to the interferometer; and (v) a high quantum efficiency photodetector to sense differential motion of the interferometer mirrors.

Interferometer: Each optic of the interferometer is suspended as a single loop pendulum mounted on a passive vibration isolation system within a single vacuum volume with a pressure of 10^{-6} torr. At frequencies above the pendulum resonant frequency ($\sim$ 1 Hz), the suspensions attenuate seismic noise, causing the optics behave as inertial free masses. The mirrors are held in place by feedback control designed to suppress low-frequency seismically driven motion. Magnets affixed to each optic are surrounded by current-carrying coils that actuate on the mirror positions and angles. Adaptations of Pound-Drever-Hall locking are used to keep the mirrors of the interferometer at the desired operating point, with one exception. The Michelson interferometer is locked on a dark fringe using a static differential offset such that a small amount of the carrier light exits the signal-recycling cavity, while the signal cavity is locked on a carrier resonance. This dc component of the carrier light at the antisymmetric port acts as a local oscillator field for a GW-induced signal to beat against – this is the so-called "dc readout" scheme [7].

Squeezer: The OPO is a cavity composed of a 10 mm long periodically-poled $KTiOPO_4$ crystal with anti-reflection coated flat surfaces and two external coupling mirrors. Periodically poled $KTiOPO_4$ is chosen as a squeezing material because it has advantages in performance and long term stability over the more conventionally used $MgO{:}LiNbO_3$ [24]. The OPO has a linewidth of 53 MHz and the crystal is maintained at 33.5 °C to optimize parametric down-conversion at 1064 nm. The OPO is vacuum-seeded and pumped by 320 mW of second-harmonic field, which is generated by SHG from the same laser source that is incident on the interferometer. An auxiliary laser that is frequency-shifted by 642 MHz with respect to the carrier frequency is used to lock the OPO cavity in a TEM_{00} mode. This frequency-shifted light is orthogonally polarized to the vacuum field that seeds

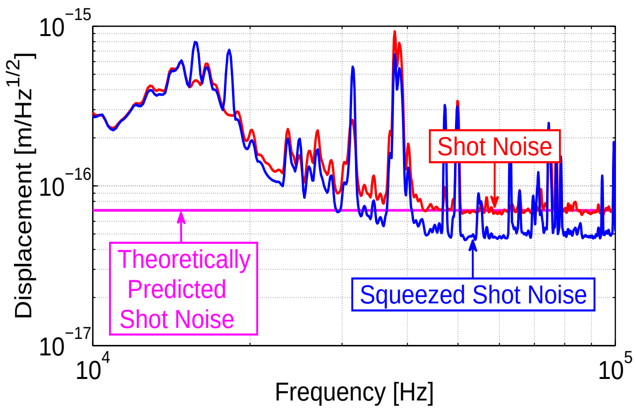

FIG. 2: (Color online) The noise floor of the signal-recycled Michelson interferometer with (blue) and without (red) the injection of squeezed vacuum. The theoretically predicted shot noise level based on the measured optical power is also shown (magenta). The interferometer is shot-noise-limited at frequencies above 42 kHz. Injection of squeezing leads to broadband reduction of the shot noise by a squeeze factor of $R = 0.34$ in the shot-noise-limited frequency band.

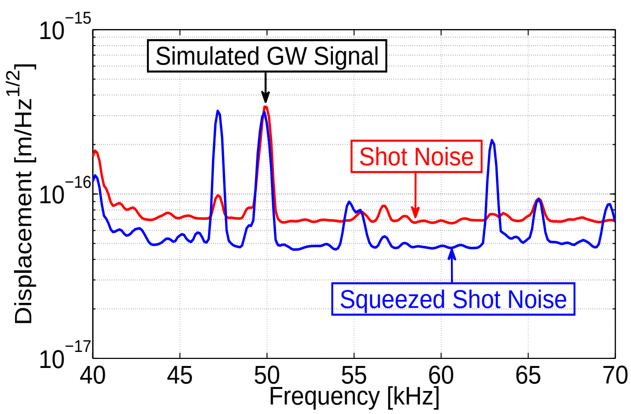

FIG. 3: (Color online) A zoomed graph of the noise floor of the interferometer with a simulated GW signal at 50 kHz with (blue) and without (red) the injection of squeezed vacuum. The broadband shot noise floor is reduced from 7×10^{-17} $m/\sqrt{Hz}$ to 5×10^{-17} $m/\sqrt{Hz}$ by the injection of squeezing while the strength of the simulated GW signal was retained, resulting in an increase in signal-to-noise ratio or detector sensitivity by the same squeeze factor.

the OPO cavity in a TEM_{00} mode and to the pump field. Both the SHG and OPO cavities are locked by the Pound-Drever-Hall locking technique.

Readout: The balanced homodyne detector is used to monitor the generated squeezed vacuum field before injection to the interferometer. It is composed of a 50/50 beamsplitter and a pair of photodiodes with matched quantum efficiencies of 93%. With a coherent local oscillator field that is mode-cleaned by an optical fiber, the homodyne efficiency of this readout is 99.2%. The squeezed vacuum field is injected into the antisymmetric port of the interferometer via an optical circulator, a mode-matching telescope, and steering mirrors. The interferometer output is detected by the length sensing photodetector with quantum efficiency of 93% and bandwidth of 5 MHz. The squeezing phase is locked to the amplitude quadrature of the interferometer field by the noise-locking technique [25], using a PZT-actuated mirror.

Results: The noise floor of the interferometer is shown in Fig. 2. The comparison between the measured noise floor without squeezing and the theoretically predicted noise floor based on the measured optical power of 100 μW indicates that the interferometer is shot-noise-limited at frequencies above 42 kHz. At frequencies below 42 kHz, the noise is dominated by laser intensity noise and uncontrolled length fluctuations of the interferometer. The peaks at frequencies above 42 kHz are also due to the interferometer length fluctuations. In addition, the laser power at the antisymmetric port is changed to verify the $\sqrt{P}$ scaling of the shot noise. In the shot-noise-limited band, the detector sensitivity is 7×10^{-17} m/$\sqrt{\text{Hz}}$. Systematic uncertainty in the displacement calibration of about 10% does not affect the relative improvement achieved by squeeze injection that was observed.

The result of the quantum-enhancement in the interferometer is also shown in Fig. 2. The comparison between the two spectra shows that the noise floor of the interferometer is reduced by the injection of the squeezed vacuum field by a squeeze factor of $R = 0.34$ in the shot-noise-limited frequency band. Fig. 3 shows the noise floor with a simulated GW signal at 50 kHz, with and without injected squeezing. The broadband quantum noise floor is reduced from 7×10^{-17} m/$\sqrt{\text{Hz}}$ to 5×10^{-17} m/$\sqrt{\text{Hz}}$, while the strength of the simulated gravitational wave signal is retained. This corresponds to a 40% increase in signal-to-noise ratio (SNR) or detector sensitivity. (the same squeeze factor). Other peaks in the squeezing spectrum are due to optical crosstalk between the interferometer and OPO, arising from inadequate isolation of the OPO from the interferometer output.

In summary, we have demonstrated quantum-enhancement in a GW interferometer configuration with several features of Advanced LIGO, improving the Heisenberg-limited detection sensitivity from 7×10^{-17} m/$\sqrt{\text{Hz}}$ to 5×10^{-17} m/$\sqrt{\text{Hz}}$, with a squeeze factor of 0.36. We have shown a factor of 1.4 increase in SNR with a simulated GW signal. In the currently operational kilometer-scale detectors this would correspond to a factor of $1.4^3 = 2.7$ increase in detection rate for isotropically distributed sources. The measurable squeezing effect was limited to frequencies above 42 kHz in this experiment, since the quantum noise is masked by classical noise at lower frequencies. However, squeeze-enhancement is expected to be effective on the quantum noise at lower frequency as well. This implementation of quantum-enhancement in a GW detector prototype with the suspended optics and control and readout schemes used in the currently operational LIGO detectors firmly establishes the feasibility of squeezing injection as an attractive technique for future improvements to existing GW detectors worldwide.

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