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Ultra-low phase noise squeezed vacuum source for gravitational wave detectors

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Squeezed states of light are a valuable resource for reducing quantum noise in precision measurements. Injection of squeezed vacuum states has emerged as an important technique for reducing quantum shot noise, which is a fundamental limitation to the sensitivity of interferometric gravitational wave detectors. Realizing the most benefit from squeezed-state injection requires lowering optical losses and also minimizing squeezed quadrature fluctuations—or phase noise—to ensure that the large noise in the anti-squeezed quadrature does not contaminate the measurement quadrature. Here, we present an audio band squeezed vacuum source with $1.3^{+0.7}_{-0.5}$ mrad of phase noise. This is a nearly tenfold improvement over previously reported measurements, improving prospects for squeezing enhancements in current and future gravitational wave detectors.

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The Advanced LIGO detectors recently ushered in the era of gravitational wave astronomy with their detection of a binary black hole merger [1]. When operating at full sensitivity, quantum noise will limit their performance throughout their detection band (10 Hz to 10 kHz) [2]. Along with thermal noise, quantum radiation pressure noise will be a limiting noise source below 50 Hz, while shot noise will dominate above 50 Hz. Reducing quantum noise is therefore essential for increasing the astrophysical reach of Advanced LIGO and the other advanced detectors under development [3,4], whose observation volume increases as the cube of the sensitivity improvement. While not part of the original Advanced LIGO design, squeezed vacuum injection has emerged in the last decade as an effective means of reducing quantum noise. In 2010, GEO 600 became the first gravitational wave (GW) detector to demonstrate sub-shot noise performance [5] and has employed squeezing in normal operations ever since [6]. In 2011, the LIGO Hanford detector demonstrated squeezing enhancement at lower frequencies, down to 150 Hz [7]. Both of these applications used squeezed light to reduce shot noise at the expense of increased radiation pressure noise. A simultaneous reduction in radiation pressure noise and shot noise, as required for the current generation of advanced detectors, can be achieved by combining a traditional squeezed vacuum source with a quantum filter cavity to rotate the squeezed quadrature as a function of the frequency [8]. Recently, a practical design for such a frequency-dependent squeezed vacuum source has been proposed [9], and the first demonstration of frequency-dependent squeezing in the GW band has been realized [10]. These advances [5–7,9,10] make squeezed-vacuum injection a viable early upgrade for advanced GW detectors and a likely component of any future detector design [11–14].

All squeezing experiments are primarily limited by optical loss, which reduces the level of squeezing by replacing the lost correlated photons with an unsqueezed vacuum. After accounting for loss, the measured quantum noise variance is given by [15]

$$V(\phi) = \cos^2(\phi)\left[1 - \frac{4\eta x}{(1+x)^2}\right] + \sin^2(\phi)\left[1 + \frac{4\eta x}{(1-x)^2}\right], \tag{1}$$

where η is the total efficiency (1–Losses), ϕ is the measurement quadrature angle, and x is the normalized non-linear coupling ($x = 1 - 1/\sqrt{g}$, where g is the non-linear gain). Here, $\phi = 0$ corresponds to the squeezed quadrature. Typically, the variance is expressed relative to shot noise in decibels (dB).

Relative fluctuations between the squeezed and measured quadratures further reduce the level of measured squeezing. If the period (τ) of these fluctuations is much longer than the measurement time (T_{meas}), they will cause the level of squeezing to drift between measurements unless the measured quadrature angle is corrected. When fluctuations with $\tau \lesssim T_{\mathrm{meas}}$ are present, the measured spectrum will be an average over a range of quadratures rather than the squeezed quadrature alone, resulting in a reduction in the maximum level of measurable squeezing. These fast fluctuations are commonly referred to as *phase noise* and are the primary focus of this Letter. The measured quadrature variance in the presence of phase noise becomes [15]:

$$V'(\phi) = V(\phi)\cos^2(\theta_{\mathrm{rms}}) + V(\phi + \pi/2)\sin^2(\theta_{\mathrm{rms}}), \tag{2}$$

where θ_{rms} is the rms level of phase noise. The effect of phase noise is to contaminate the squeezed quadrature variance with a projection from the orthogonal (anti-squeezed) quadrature. Both the GEO 600 and LIGO squeezing experiments suffered from high levels of phase noise, roughly 37 mrad each [16,17]. However, the level of measured squeezing (3.5 dB in GEO 600, 2.1 dB in LIGO) was largely unaffected due to the high level of optical loss (40% in GEO 600, 56% in LIGO) [5,7].

The impact of phase noise becomes more acute as the losses are reduced [16]. For a GW detector with 24% (12%) total loss, 37 mrad of phase noise would reduce the maximum level of squeezing by 1 dB (2 dB). Tabletop experiments with loss levels of 5% or less have measured record levels of squeezing [18–20]. Two reported phase noise levels [18,19], both around 11 mrad, degraded the level of squeezing by up to 2 dB [18].

The losses for squeezing in Advanced LIGO are expected to be between 20% and 30% [21]. Limiting the phase noise to 10 mrad would allow for 6 dB of squeezing if the losses are in the middle of this range or lower [16]. Future GW detector designs call for 10 dB or more of squeezing [12,13], requiring that the total optical loss be brought below 10%. This motivates even lower targets for the phase noise to relax these stringent loss requirements as much as possible [16,21]. When characterized separately from the interferometer, the squeezed vacuum sources used at GEO 600 and LIGO had 9 and 21 mrad of phase noise, respectively [16,17,22]. A reduction in the level of phase noise intrinsic to the squeezed vacuum source itself is necessary for the *total* level of phase noise to meet these targets.

In this Letter, we report on a new squeezed vacuum source with $1.3^{+0.7}_{-0.5}$ mrad of phase noise that produces squeezing throughout the audio band. To our knowledge, this is the lowest phase noise ever measured with a squeezed vacuum source [16,18,22–24]. Low phase noise performance is achieved by combining an improved control scheme with a nearly monolithic optical parametric oscillator (OPO) with an intrinsically low length noise. The input fields are fiber coupled and the instrument is designed to operate under ultra-high vacuum (UHV). This design meets the demanding technical requirements for Advanced LIGO and future detectors outlined in [21].

To date, all squeezed light sources operating throughout the audio band generate squeezed vacuum rather than bright squeezed light since classical noise on the carrier field degrades the squeezing at low frequencies [25]. When producing radio frequency (RF) squeezed vacuum sidebands, active stabilization of the measurement quadrature is not required to attain high levels of squeezing [18,20]. Squeezing in the GW band does require active quadrature control since the longer measurement times involved result in an increased sensitivity to phase fluctuations at audio frequencies and below. Since a squeezed vacuum has no coherent amplitude, there is no direct way to measure the relative phase between the squeezed and local oscillator (LO) fields, which makes quadrature stabilization far more difficult.

The *coherent control* technique has emerged as the preferred means of stabilizing the measurement quadrature [26]. This scheme uses a coherent field that has been RF frequency shifted out of the squeezing band, hereafter referred to as the *coherent locking field* (CLF), whose phase is used as a surrogate for the squeezed quadrature angle.

Unfortunately, coherent control is susceptible to lock-point errors, which can give rise to phase noise [16]. Lock-point errors occur when an environmental disturbance changes the phase of the CLF differently than the squeezed field. This shifts the quadrature at the lock point relative to the squeezed quadrature, reducing the level of measured squeezing.

The phase noise of the squeezed vacuum source used during the LIGO squeezing experiment [7] was primarily dominated by lock-point errors from detuning noise in the OPO cavity [16]. The response of the squeezed quadrature to changes in detuning for a dually resonant OPO is given by [16]:

$$\frac{d\theta_{\mathrm{sqz}}}{d\Delta} = \frac{1}{\gamma_g} + \frac{1}{\gamma_r(1+x^2)}, \tag{3}$$

where Δ is the detuning of the fundamental field from resonance in Hz, γ_r and γ_g are the cavity half-width half-maximum frequencies for the fundamental and pump fields, and θ_{sqz} is the squeezing angle. Since the CLF field is frequency shifted from the resonance, its response to changes in detuning will differ from Eq. (3), leading to lock-point errors. To achieve the best phase noise performance, the OPO detuning noise must be reduced.

The squeezed vacuum source is depicted in Fig. 1. An Innolight Diabolo laser emits light at both the fundamental (1064 nm) and pump (532 nm) frequencies. The second harmonic generator (SHG) and its locking electronics are internal to the laser. The pump, CLF, and LO fields are fiber coupled from the main optics table into the vacuum chamber using single-mode fibers coated with UHV compatible polyimide [27]. Fiber coupling of the input fields will eliminate the need for active alignment control for the pump and CLF fields when our instrument is interfaced to Advanced LIGO. However, our in-air optical fibers required careful acoustic isolation to avoid adding additional phase noise.

Squeezed vacuum is generated using a sub-threshold OPO with PPKTP as its non-linear medium. The OPO, which is based on the design used in [24], is UHV compatible, so it can be mounted on a suspended table within the Advanced LIGO vacuum envelope to reduce backscatter noise. Details of its construction and optical parameters can be found in [28]. This cavity is resonant for both the fundamental (1064 nm) and pump (532 nm) fields and uses a travelling wave configuration to reduce backscatter [29]. This setup achieves exceptionally low detuning noise by combining a rigid, nearly monolithic OPO with a high

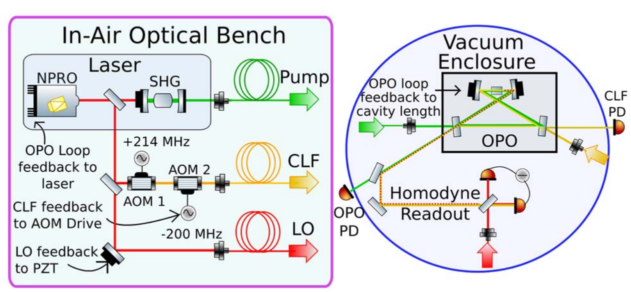

Fig. 1. Squeezed vacuum source. An Innolight Diabolo laser outputs light at both our fundamental (1064 nm) and pump (532 nm) frequencies. The pump field, coherent locking field (CLF), and local oscillator (LO) are all fiber coupled from the in-air table into our vacuum chamber. An RF-detuned CLF is obtained by passing light through two acousto-optic modulators (AOMs) with a drive frequency difference of 14 MHz. Both the OPO cavity and balanced homodyne readout are housed inside of our vacuum enclosure.

bandwidth (20 kHz) length servo employing feedback to both the laser frequency and cavity length.

The squeezed state is characterized using a UHV-compatible balanced homodyne detector. Both the readout and OPO cavity are housed on a seismically isolated breadboard to reduce OPO cavity length noise, path-length fluctuations, and backscatter. All other sensors used for control and diagnostics are housed on a separate in-air table, and the reflected CLF and pump fields are directed out of vacuum through viewports.

To control the CLF field, we developed a novel approach that provides an alternative for generating the CLF without the need for an auxiliary laser source. The CLF is generated by passing a beam at the fundamental frequency through two acousto-optic modulators (AOMs), which produces a CLF with a detuning of $\Omega = 14$ MHz. This scheme allows for an arbitrary detuning without contaminating the CLF with a noticeable amount of light at the carrier frequency [30]. Dispensing with an auxiliary laser also eliminates the dominant source of relative frequency noise between the pump and CLF fields, a significant source of phase noise if not properly suppressed.

A CLF power of 2.5 mW is injected through the rear of the cavity, and a second sideband at $-\Omega$ is produced via difference frequency generation. The signal in reflection is demodulated at 2Ω and fed back to a voltage-controlled oscillator driving one of the AOMs with a bandwidth of 20 kHz to lock the CLF phase relative to the squeezing angle. To stabilize the measurement quadrature, the LO is phase locked to the CLF by feeding back to a piezo on the LO path with a bandwidth of 10 kHz.

A typical in-vacuum squeezing spectrum is presented in Fig. 2, showing up to 6.5 dB of squeezing throughout the audio band. We note, however, that the phase noise measurement discussed below was made in air due to the limited optical power throughput of our 532 nm UHV fiber feedthrough.

From Eq. (2), the level of measured squeezing depends on the losses, rms level of phase noise, and the non-linear gain. A measurement of the squeezed and anti-squeezed quadrature variances at one non-linear gain is insufficient to determine both the level of phase noise and the optical losses. Here, both quadrature variances are measured at several non-linear gains and the data are fitted to Eq. (2) in order to determine the total loss and phase noise, as typically done to characterize squeezed light sources [15,16,18,22–24,31].

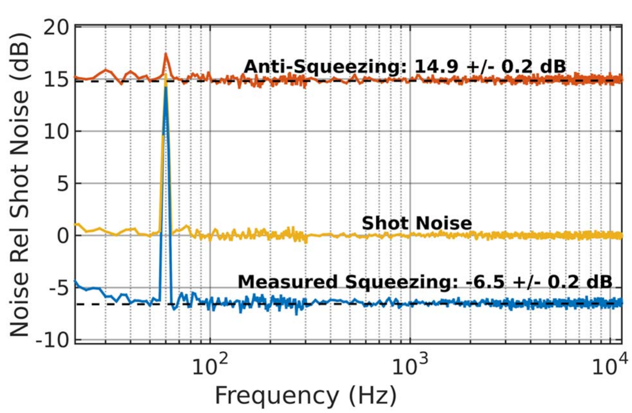

Fig. 2. Squeezed light source performance when operated under high vacuum. The dark noise is 20 dB below the shot noise with 1 mW of local oscillator power.

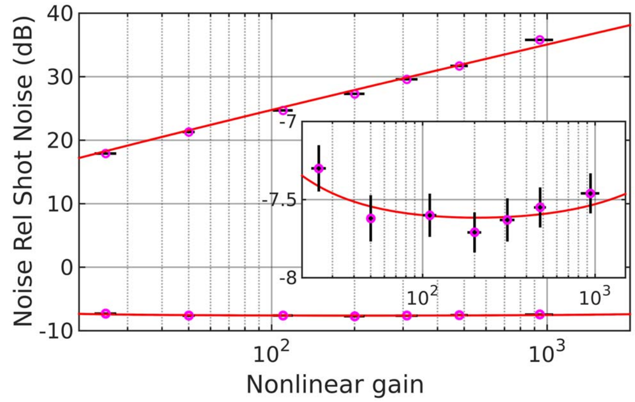

Fig. 3. Data and fit for the phase noise characterization measurement. The red traces correspond to the theoretical values for squeezing and anti-squeezing as a function of non-linear gain for $\eta = 0.829$ and $\theta_{\mathrm{rms}} = 1.3$ mrad. The sub-figure shows a closeup of our fit for the squeezing data.

The data and fit are presented in Fig. 3. At each point, three parameters are measured: the non-linear gain, the squeezed quadrature variance, and an anti-squeezed quadrature variance. During the measurements, the level of pump power in the cavity is carefully stabilized to hold the non-linear gain constant and to avoid exceeding threshold (90.5 ± 1.2 mW of incident power).

The non-linear gain at each point is estimated by injecting a small seed field through the rear of the cavity and directly measuring the level of parametric amplification of the seed amplitude. The temperature is tuned at the beginning of the measurement to ensure co-resonance for the pump and seed fields and is allowed to settle prior to making measurements. Afterwards, we monitor the level of variability in our non-linear gain for several minutes to determine the horizontal error bars.

In order to determine the level of squeezing (anti-squeezing), the mean quadrature variance is computed over a frequency range where all spectra were completely free of technical noise (between 2 and 10 kHz). If present, technical noise will cause the variances to deviate from Eq. (2) and adversely impact the accuracy of our phase noise estimate. A shot noise reference spectrum is also taken after each pair of quadrature spectra. The vertical error bars are typically around 0.15 dB and represent the quadrature sum of the standard deviations for the shot noise and squeezing (anti-squeezing) spectra between 2 and 10 kHz. All spectra are averaged 2000 times and are taken over a 100 kHz bandwidth using a frequency binning of 125 Hz, resulting in a measurement time of 16 s.

The data are fitted to Eq. (2) by performing a Markov-chain Monte Carlo regression yielding $\theta_{\mathrm{rms}} = 1.3^{+0.7}_{-0.5}$ mrad and $\eta = 0.829^{+0.024}_{-0.026}$. Median values of the appropriate posterior probability distributions are quoted, with error bars defining 68% credible intervals. Table 1 lists all known sources of loss [32] and phase noise in this experiment. The total values are in good agreement with our measurement. Further discussion of our phase noise and loss budget can be found in Supplement 1.

Combining a high bandwidth length servo with a low length noise OPO cavity reduces the total phase noise contribution from detuning noise by almost two orders of magnitude compared with the previous LIGO squeezer [16]. A reduction in SHG length noise should be possible by switching to a well-designed

Table 1. Loss and Phase Noise Budget

Source of Loss	Value (%)
OPO escape efficiency	2 ± 1
Propagation losses	1 ± 0.2
95% homodyne visibility	10 ± 0.5
Photodiode quantum efficiency	5 ± 3
Total efficiency	$\eta = 0.83 \pm 0.03$
Source of Phase Noise	**Value (mrad)**
OPO detuning noise	0.35 ± 0.1
OPO control sidebands	0.35 ± 0.1
SHG length noise	1 ± 0.3
CLF shot noise	0.9 ± 0.3
Total phase noise	$\theta_{\mathrm{rms}} = 1.4 \pm 0.5$

stand-alone SHG and length servo. The impact of shot noise on the CLF loop can be reduced by lowering the CLF detuning. This improves the signal-to-noise ratio by coupling more of the CLF field into the OPO cavity.

This squeezed vacuum source meets the phase noise goals for Advanced LIGO and the more stringent targets for achieving 10 dB of squeezing with future GW detectors [21]. Additional sources of phase noise will arise when the squeezer is interfaced to the interferometer, such as RF phase noise from the interferometer control sidebands and lock-point errors due to alignment fluctuations between the squeezed and interferometer fields [16,17]. The impact of alignment fluctuations in GW detectors can be mitigated by obtaining the quadrature control signal in transmission through the output mode cleaner cavity [6,17,21] and by using active alignment control [33], both demonstrated in GEO 600.

To summarize, we have presented a fiber-coupled and UHV-compatible squeezed-vacuum source with record phase noise performance. When combined with a suitable filter cavity [9] and with further seismic isolation to limit technical noise from scattered light [21], this squeezed vacuum source can take full advantage of progress in optical loss reduction in the upcoming years, thus meeting the needs of the GW community for the foreseeable future.

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See Supplement 1 for supporting content.

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