Squeezing in the audio gravitational wave detection band

Kirk McKenzie,1 Nicolai Grosse,1,2 Warwick P. Bowen,2 Stanley E. Whitcomb,3 Malcolm B. Gray,1 David E. McClelland,1 and Ping Koy Lam1,2

1Center for Gravitational Physics, Department of Physics, Faculty of Science, The Australian National University, ACT 0200, Australia
2Quantum Optics Group, Department of Physics, Faculty of Science, The Australian National University, ACT 0200, Australia
3LIGO Laboratory, California Institute of Technology, Pasadena, California, 91125, USA

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We demonstrate the generation of broad-band continuous-wave optical squeezing down to 200Hz using a below threshold optical parametric oscillator (OPO). The squeezed state phase was controlled using a noise locking technique. We show that low frequency noise sources, such as seed noise, pump noise and detuning fluctuations, present in optical parametric amplifiers have negligible effect on squeezing produced by a below threshold OPO. This low frequency squeezing is ideal for improving the sensitivity of audio frequency measuring devices such as gravitational wave detectors.

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Squeezed light was proposed for quantum noise reduction in interferometric gravitational wave (GW) detection over two decades ago [1]. Since then, the first generation of long baseline GW detectors - LIGO [2], VIRGO [3], GEO 600 [4] and TAMA 300 [5] have been built and recently begun operation. The second generation of detectors, such as Advanced LIGO [6], are currently in the late planning stages. The prediction that will be quantum noise limited (QNL) across most of the GW detection band (10Hz-10kHz) has led to further theoretical investigations into the use of squeezing [7, 8, 9] and other optical methods [10, 11, 12] for quantum noise reduction. However, to date only one experimental demonstration of quantum noise reduction in a GW detector configuration has been reported [13], and that result was obtained well above the GW signal band.

To be applicable to GW detectors, the requirements on squeezing include: continuous-wave (CW) at 1064nm, squeezed at the GW signal frequency, compatible with readout techniques [13], controllable phase and a high level of squeezing (∼10dB). Although squeezed light was first demonstrated in 1985 [13], a CW squeezed source at audio frequencies has not been reported until now. Laser relaxation oscillation and other technical noise sources have typically confined squeezing to the MHz range.

Two of the most successful systems for squeezing generation have been the optical parametric oscillator (OPO) and optical parametric amplifier (OPA), for example see [13, 17]. OPA and OPO have the same underlying second order nonlinearity, however, they differ in that the OPA process has a coherent seed field at the fundamental wavelength, whereas the OPO does not and is seeded only by vacuum fluctuations. In theory OPO/A systems can produce squeezed states that fulfill the GW detector requirements outlined above. Experiments to date have been able demonstrate each requirement - except squeezing in the GW signal band. The lowest frequency CW squeezing experiments reported so far include Bowen et al [13], Schnabel et al [14] and Laurat et al [20] demonstrating squeezing down to 220kHz, 80kHz and 50kHz, respectively. These experiments used either OPO or OPA, with [13, 14] relying on common mode noise cancellation techniques.

In this letter we report the generation of high purity squeezing by a below threshold OPO at sideband frequencies down to 200Hz, continuous from 280Hz to well above 100kHz, covering a large portion of the audio GW detection band. The phase of the squeezed vacuum relative to the homodyne detector was controlled without a carrier by using a noise dither locking technique, see for example [20]. The inferred squeezing level (adjusted for detection efficiency) at the OPO output was 5.5dB±0.6dB below the shot noise limit (SNL) with inferred purity of 1.3±0.1, close to a minimum uncertainty state. We compare OPO and OPA operation and find that the presence of a coherent seed field leads to dramatic degradation of the squeezing at low frequency, due to technical noise coupling. The system operating as an OPO displays immunity to the same technical noise that degrades OPA squeezing.

Amplitude (+) and phase (-) quadrature variances, $V_{sqz}^\pm = \langle (\Delta X_{sqz})^2 \rangle$, of the singly resonant OPO/A on resonance can be modeled using linearized formalism by:

$$V_{sqz}^\pm(\omega) = \left[ C_s V_s^\pm(\omega) + C_l V_l^\pm(\omega) + C_v^\pm(\omega)V_v^\pm(\omega) \right] + \alpha^2 \left[ C_p V_p^\pm(\omega) + C_{\Delta V}^\pm \Delta V(\omega) \right] ,$$

where $V_{sqz}^\pm$ contains contributions from: the seed field, $V_s^\pm$; the pump field, $V_p^\pm$; vacuum fluctuations from intracavity loss, $V_l^\pm$; vacuum fluctuation entering through the output coupler, $V v^\pm$; and noise due to detuning fluctuations in the cavity $\Delta V$, which arise from such source acousto-mechanical disturbances. Other sources, such as
FIG. 1: Schematic of the experiment. The experiment was operated in both OPO and OPA modes. The OPA seed power was varied using a variable attenuator (VA). The OPO cavity was isolated from backscatter off the photodetectors using a Faraday isolator (FI). The control electronics for the homodyne detection phase are indicated by dashed lines. SA-Spectrum analyzer, BPF-Band pass filter, ED-Envelope detector, LPF-Low pass filter, G-Gain stage, Lock-in-Load-in amplifier, PZT-piezoelectric transducer, PBS-Beam splitter, half-wave plate, DC-dichroic mirror, PD-Photodetector.

Other and \( \omega \)put coupler. The last two terms scale with loss and vacuum fluctuations entering through the input coupler, vacuum fluctuations due to intra-cavity contributions from the seed noise entering through the frequency. The first three terms in Eq. 1 are standard decay rates for \( \alpha \)rameters \( \kappa \lambda \)polarizing beamsplitter, \( \alpha \)ric oscillator/amplifier, PZT-piezoelectric transducer, PBS-Second harmonic generator, OPO/A-optical parametric oscillator/amplifier, PZT-piezoelectric transducer, PBS-polarizing beamsplitter, \( \lambda \)/2-half-wave plate, DC-dichroic mirror, PD-Photodetector.

phase matching fluctuations, are not discussed here. The denominator and coupling coefficients are given by 22;

\[
D^\pm(\omega) = i\omega + \kappa_a + \left[ \begin{array}{c} 3 \\ 1 \end{array} \right] \epsilon^2 \alpha^2 / (2\kappa_b) \mp \epsilon \beta
\]

\[
C_s = 4\kappa_{in}^a \kappa_{out}^a
\]

\[
C_l = 4\kappa_{in}^b \kappa_{out}^a
\]

\[
C_v^\pm(\omega) = |2\kappa_{out}^a - D^\pm(\omega)|^2
\]

\[
C_p = 4\kappa_{out}^a \kappa_{in}^b (\epsilon / \kappa_b)^2
\]

\[
C_\Delta^\pm = 8\kappa_{out}^a \left[ \begin{array}{c} 0 \\ 1 \end{array} \right]
\]

where the intra-cavity fundamental field, \( \alpha = \sqrt{n} \), where \( n \) is the mean intra-cavity photon number. The parameters \( \kappa_{out}^a, \kappa_{in}^a \) and \( \kappa_{in}^b \) are the decay rates of \( \alpha \) due to the output coupler, input coupler and loss, respectively. \( \kappa_{in}^b \) is the decay rate of the intra-cavity second harmonic field, \( \beta \), due to the input coupler. \( \kappa_a, \kappa_b \) are the total decay rates for \( \alpha \) and \( \beta \). \( \epsilon \) is the non-linear coupling parameter and \( \omega \) is a small frequency shift relative to the carrier frequency. The first three terms in Eq. 1 are standard contributions from the seed noise entering through the input coupler, vacuum fluctuations due to intra-cavity loss and vacuum fluctuations entering through the output coupler. The last two terms scale with \( \alpha^2 \), and show an important difference between OPO and OPA operation. That is; the fluctuations of the pump, \( V_p^\pm \), and detuning, \( \Delta \), are coupled into the squeezed field, \( V_{sqz}^\pm \), via the beat with the intra-cavity fundamental field, \( \alpha \). Thus, a below threshold OPO (\( \alpha = 0 \)) should immune to these two noise sources to first order.

A schematic of the experiment setup is in Fig. 1. A Nd:YAG laser operating at 1064nm was split into two beams. One beam is used to pump the second harmonic generator (SHG). The other was spatially and temporally filtered by a mode-cleaner cavity and used as the seed beam for the OPA and as local oscillator (LO) for the homodyne detector. The OPO/A and SHG are constructed out of type-I phase-matched MgO:LiNbO\(_3\) hemilithic crystals. The curved surface of these crystals were coated for high reflectivity (HR) and the flat surface coated for anti-reflectivity (AR) at both 532nm and 1064nm. In both the SHG and OPO/A, standing-wave cavities were formed at 1064nm between the HR surface of the crystal together with an external mirror of reflectivity \( R_{HR} = 96\% \) at 1064nm and \( R_{GR} < 4\% \) at 532nm. The OPO/A was pumped with 100mW of 532nm light which double passed through the crystal giving a measured classical gain of 5. Results were taken in OPO mode, and in OPA mode whilst varying the seed power from 1nW-6\( \mu \)W. The squeezed state was detected on the
homodyne detection system which had 96.5% fringe visibility. Whilst in OPO operation a Faraday isolator was inserted between the OPO cavity and the photodetectors to reduce LO backscattered light. The photodetectors were built around ETX 500 photodiodes with 93% quantum efficiency. The common mode rejection of the homodyne detector was over 55dB.

The control electronics for the homodyne detection phase are indicated by dashed lines in Fig. 1. This error signal was generated by dithering the LO phase and demodulating the difference photocurrent noise power. The noise power was detected using a spectrum analyzer (Agilent-E4407B, zero span at 2MHz, RBW=300kHz, VBW=30kHz) then demodulated with a lock-in amplifier (Stanford Research Systems (SRS)-SR830) and filtered before being fed back to PZT1. The stability of the homodyne detection phase enabled us to take results without locking the OPO/A cavity - which typically stayed on resonance for 10 seconds. All data, except that in Fig. 3, was recorded on a dynamic signal analyzer (SRS-SR785).

The OPO squeezing spectrum from 100Hz-100kHz is shown in Fig. 2. Trace (a) shows the squeezing spectrum obtained without an isolator in front of our homodyne detection system. We observed large peaks between 300Hz and 700Hz due to low frequency noise contamination. This contamination is attributed to light from the LO backscattered from the photodetectors feeding into the OPO cavity. We note that even with the photo-detectors tilted away from retro-reflection, the scattering from the front face of the detectors, which is estimated to be of the order of 1pW, is sufficient to seed the crystal and causes parametric amplification. With the Faraday isolator in place noise coupling via parametric amplification is eliminated, as shown by Trace (b). The squeezed beam experiences an extra 9% transmission loss through the isolator. Similar to Fig. 2, electronic noise is still present at 150Hz and 250Hz.

The OPA spectrum from 2kHz-100kHz is shown in Fig. 5 for three different seed powers, 1nW, 700nW and 6µW. The data were recorded for optimal squeezing at 50kHz. The 1nW seed power spectrum resembles the...
OPO spectrum, with the exception of one added feature at 34kHz. The spectrum of the 700nW seed power shows the feature at 34kHz has increased in amplitude with additional excess noise at other frequencies thereby limiting squeezing to above 10kHz. The feature at 8kHz was also present the pump intensity noise spectrum and is expected to have coupled into the squeezed field via the intra-cavity fundamental field. As the seed power was increased further, the noise floor and features in the spectrum continued to increase; by seed power 6µW there is no longer squeezing below 10kHz. The noise power increase of the OPA spectrum with seed power is evident in Fig. 6, which shows the mean noise power between 5-6kHz as a function of seed power. The experimental points indicated by ‘x’ can be compared with a model which has linear dependence on seed power, given by the solid line. Although there are large uncertainties expected in the experimental data, since the OPA cavity was not locked, the data is not inconsistent with the linear trend predicted by the theory in Eq. 1.

In summary, we have presented results demonstrating OPO squeezed vacuum down to 200Hz. The phase of squeezed vacuum was controlled using a noise locking technique. Such squeezed states could already be of use for reduction of shot noise in first generation GW detectors. The comparison of the OPO and OPA results highlights the immunity of OPO and the sensitivity of OPA to technical noise. The direction of our future research will be to implement an OPO cavity lock, increase the level of squeezing and probe frequencies lower than 100Hz for use in second generation GW detectors.

In addition to the possible application to GW detectors, low frequency squeezed light could potentially be used to enhance many measurement devices with optical readout. These include atomic force microscopes and thermo-optical spectrometers. Many long-standing experimental goals in quantum optics, such as the inhibition of atomic decay and sub-Doppler cooling of two-level atoms, could also be facilitated using broadband low frequency squeezing.

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[28] The notation \[^3\] means multiply by 3 for the amplitude quadrature or 1 for the phase quadrature.
[29] The OPO squeezing spectrum continues to 10’s of MHz, as reported in [22].