Recovery of continuous wave squeezing at low frequencies

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We propose and demonstrate a system that produces squeezed vacuum using a pair of optical parametric amplifiers. This scheme allows the production of phase sidebands on the squeezed vacuum which facilitate phase locking in downstream applications. We observe strong, stably locked, continuous wave vacuum squeezing at frequencies as low as 220 kHz. We propose an alternative resonator configuration to overcome low frequency squeezing degradation caused by the optical parametric amplifiers.

Squeezed states of light have the potential to improve the sensitivity of interferometric [1], spatial [2] and spectroscopic [3] measurements. In almost all experiments to date the squeezing has been observed at frequencies above 1 MHz, at lower frequencies most laser sources are classically noisy. Many interesting spatial and interferometric signals occur in the Hz to kHz regime [4, 5], to study these dynamics it is useful to produce squeezing at lower frequencies. Two experiments using pulsed laser light have produced squeezing in the kHz regime [6, 7]. However, for applications that involve resonators or have peak power limitations (e.g. optical damage) such as advanced gravitational wave detection [8], the squeezed light should be continuous wave.

In this paper we report the demonstration of continuous wave squeezing in the kHz regime. By operating a pair of optical parametric amplifiers (OPAs) within a Mach-Zehnder interferometer we produced a squeezed vacuum at frequencies as low as 220 kHz. In this configuration it was possible to produce bright sidebands on the squeezed vacuum. These sidebands acted as a phase reference that allowed the phase of the vacuum to be locked in a downstream homodyne detector. The frequency of the squeezing reported here was limited from below by noise introduced inside the OPAs. We propose an extension to this work that should eliminate these technical issues and produce squeezing at much lower frequencies.

![Squeezed vacuum production via classical noise cancellation using two OPAs.](image)

FIG. 1: Squeezed vacuum production via classical noise cancellation using two OPAs.

Noise cancellation schemes have been proposed to enhance squeezing utilizing Kerr non-linearity in fibers [8] and second harmonic generation [9]. The scheme presented here is similar to that of [9] but uses optical parametric processes. A single laser beam is split on a 50/50 beam splitter and used to seed a pair of identical OPAs, each consisting of a \( \chi^{(2)} \) non-linear medium inside an optical resonator. The OPA output fields are then re-combined in phase on another 50/50 beam splitter as shown in Fig. 1. The phase of the seed field relative to a non-resonant second harmonic pump field dictates the seed amplification of each OPA. This phase is controlled to de-amplify the seed, resulting in amplitude squeezed output fields. In this configuration the overall non-linearity \( \Upsilon \) of each resonator, which is dependant on the crystal non-linearity and pump power, becomes real and negative. A treatment of optical parametric oscillation which uses the linearized formalism of quantum mechanics and the mean field approximation is given in [10]. Extending this to optical parametric amplification we obtain the fourier domain amplitude quadrature operators \( X_{\text{squez}}^+ \) for the fields exiting the OPA output couplers

\[
X_{\text{squez}}^+ = \frac{\sqrt{2} \gamma_{\text{oc}}}{i\omega - \Upsilon + \gamma} \left( \sqrt{2} \gamma_{\text{ic}} X_{\text{ic}}^+ + \sqrt{2} \gamma_{\text{l}} X_{\text{l}}^+ \right) + X_{\text{oc}}^+ \left( \frac{2 \gamma_{\text{oc}}}{i\omega - \Upsilon + \gamma} - 1 \right)
\]  

(1)

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$X_{ic,j}^+$ and $X_{oc,j}^+$ are the amplitude quadrature operators of the external fields incident on the input (ic) and output (oc) couplers of the OPAs; and the vacuum fields $X_{lj}^+$ result from loss inside each OPA. The two interacting modes considered here are distinguished by the subscripts $j \in \{1,2\}$ throughout the paper (see Fig. 1). $\gamma_{ic}$, $\gamma_{oc}$ and $\gamma$ are the decay rates respectively due to the input and output coupler transmitivity, and the intracavity loss; and $\gamma = \gamma_{ic} + \gamma_{oc} + \gamma_l$ is the overall resonator decay rate.

The amplitude quadrature operators for the output fields of a 50/50 beam splitter with one intense $X_{in,1}^+$ and one vacuum $X_{in,2}^+$ input field can be expressed as $X_{ic,j}^+ = (X_{in,1}^+ + X_{in,2}^+)/\sqrt{2}$ and $X_{ic,2}^+ = (X_{in,1}^+ - X_{in,2}^+)/\sqrt{2}$. Substituting these expressions as the seed fields in Eqs. (1) we obtain

$$X_{sqz,j}^+ = \frac{\sqrt{2} \gamma_{oc}}{i \omega - \frac{1}{2} + \gamma} \left( \sqrt{\gamma_{ic}} X_{in,1}^+ - (-1)^j X_{in,2}^+ \right) + \frac{2 \gamma_{oc}}{i \omega - \frac{1}{2} + \gamma_l} X_{lj}^+$$

$$+ X_{oc,j}^+ \left( \frac{2 \gamma_{oc}}{i \omega - \frac{1}{2} + \gamma} - 1 \right)$$

The interference of these beams in phase on a 50/50 beam splitter yields an intense squeezed beam, and a squeezed vacuum, which have amplitude quadrature operators $X_{out,1}^+$ and $X_{out,2}^+$ respectively, given by

$$X_{out,j}^+ = \frac{\sqrt{2} \gamma_{oc}}{i \omega - \frac{1}{2} + \gamma} \left( 2 \sqrt{\gamma_{ic}} X_{in,j}^+ + \sqrt{2} \gamma_l (X_{lj}^+ - (-1)^j X_{lj}^+) \right)$$

$$+ \frac{1}{\sqrt{2}} \left( \frac{2 \gamma_{oc}}{i \omega - \frac{1}{2} + \gamma} - 1 \right) (X_{oc,1}^+ - (-1)^j X_{oc,2}^+)$$

Note that interfering the beams with a $\pi/2$ phase shift would have produced an Einstein-Podolsky-Rosen entangled pair [11]. The amplitude noise variance spectra $V_{out,j}^+$ of the output beams can be calculated, $V = \langle X^2 \rangle - \langle X \rangle^2$. Seeding each OPA through its input coupler and assuming that the fields entering through the output coupler and through loss are uncorrelated vacuum we obtain

$$V_{out,j}^+ = \frac{4 \gamma_{oc} (\gamma_{ic} V_{in,j}^+ + \gamma_l) + \omega^2 + (2 \gamma_{oc} + \frac{1}{2} - \gamma)^2}{\omega^2 + (\frac{1}{2} - \gamma)^2}$$

These spectral noise distributions are identical to those that would be produced from two independent OPAs, one seeded with the intense input beam (X$_{in,1}^+$), and one with the vacuum field entering at the first beam splitter (X$_{in,2}^+$) (c.f. Eqs. (1)). Unlike the case for a single vacuum seeded OPA [12] however, the resonance frequency of each OPA can be conveniently locked to the frequency of the seed beam and the vacuum squeezed output can be produced with bright sidebands far outside the frequency range for squeezing. These sidebands are produced by applying anti-correlated phase modulation to the intracavity fields of the OPAs, and allow the quadrature of the squeezed vacuum to be locked in downstream applications.

In theory none of the laser noise is carried through onto $V_{out,2}^+$. In reality however, the two OPAs will not be identical and this will cause classical noise from the intense input beam to couple into the vacuum output. By varying the input beam splitter ratio it is possible to completely compensate for these differences over some frequency range. For example balancing the intensity of the seed beams such that the intensity of the (ideally) squeezed vacuum output of the system ($X_{out,2}^+$) is minimized suppresses the classical noise from the seed beam ($X_{in,1}^+$) at $\omega = 0$. Since the denominators in eqs. (3) are slowly varying with $\omega$ while $\omega \ll \gamma - \frac{1}{2}$ the classical noise is also suppressed throughout this frequency range. The suppression is only limited by inefficiencies in the mode-matching between the OPA output beams.

The experimental setup used to generate a locked squeezed vacuum is shown in Fig. 2. Two amplitude squeezed beams were produced in a pair of spatially separated optical parametric amplifiers (OPAs). The OPAs were optical resonators constructed from hemilithic MgO:LiNbO$_3$ crystals and output couplers. The reflectivities of the output couplers were 96% and 6% for the fundamental (1064 nm) and the second harmonic (532 nm) laser modes, respectively. The OPAs were pumped with single-mode 532 nm light generated by a 1.5 W Nd:YAG non-planar ring laser and frequency doubled in a second harmonic generator (SHG) [13]. Each OPA was seeded with 1064 nm light after spectral filtering in a mode-cleaner. An intracavity phase modulation on this seed enabled control of the length of the OPAs. The coherent amplitude of the output of each OPA experienced an amplification dependent on the phase difference between pump and seed ($\phi_{sh}$). A phase modulation on the second harmonic pump generated an error signal that was used to lock to maximum deamplification. In this regime each OPA produced an amplitude squeezed beam. The seed power to the OPAs was adjusted so that these two beams were of equal intensity. We combined both beams on a 50/50 beam splitter and observed a visibility between them of 98.6 %. One output of this beam splitter was used
FIG. 2: Schematic diagram of the experiment. BS: beam splitter, DC: dichroic, MC: mode-cleaner, $\lambda/2$: half-wave plate $\phi_{sh}$ actively controlled phase shift on second harmonic beam.

to lock the relative phase of the input beams producing either an intense (1.2 mW), or a weak (0.9 $\mu$W) squeezed beam at the other output. This beam was analyzed in a homodyne detector that was locked so that the phase modulation from the OPAs was not observed. Since the OPA outputs were amplitude squeezed, this setup naturally provided a measurement of the maximally squeezed quadrature independent of the relative phase of the squeezed beams incident on the 50/50 beam splitter. A homodyne visibility of 96% was observed for the intense squeezed beam. The majority of the power of the weak squeezed beam came from the residual unmode-matched part of the input beams and had a non-Gaussian transverse modeshape, consequently the homodyne visibility observed for this beam was only 28%. The squeezed vacuum however, arose from the mode-matched part of this beam and therefore had the same homodyne visibility as the intense squeezed beam. The low visibility of the residual power caused the classical noise that it carried to be poorly detected. This effect and the 50/50 beam splitter visibility together led to a predicted optical supression of approximately 29 dB. The classical noise from the homodyne local oscillator was electronically suppressed by 64 dB and was insignificant for our measurements.

Fig. 3 shows the observed squeezing traces for intense and vacuum squeezed beams. Both the OPA resonators and the homodyne detector were phase locked. The intense squeezed beam was degraded by the resonant relaxation oscillation of the laser and squeezing was only observed above 1.9 MHz. The squeezed vacuum however was observed to be squeezed from 220 kHz to the end of our measurement range at 2.1 MHz, excluding frequencies between 640 kHz and 870 kHz where our optical suppression was not high enough to suppress the laser relaxation oscillation. The signal at 810 kHz was the beat between the SHG and OPA locking frequencies. The low frequency degradation observed in our squeezed vacuum was caused by uncorrelated acoustic and locking noise introduced within the OPAs. Further improvement to the squeezing spectra could only be achieved by either reducing this noise, or by classically correlating it. Employing a ring OPA as shown in Fig. 4 accomplishes the second of these alternatives. A squeezed output is
produced by each of the two directional modes in the OPA. In this configuration the noise introduced in the resonator is common mode and cancels on the vacuum output of a 50/50 beam splitter.

![Diagram of proposed scheme to cancel classical noise. OC: output coupler, BS: beam splitter, NC: non-linear crystal.]

The noise cancellation techniques described in this paper is compatible with existing techniques such as spectrally filtering the OPA seeds in a high finesse mode-cleaner, or using a servo controlled laser intensity noise eater.

In conclusion, we have produced a locked continuous wave squeezed vacuum with a pair of OPAs. By phase modulating the OPAs we produced phase sidebands that act as a phase reference allowing the quadrature of the squeezing to be locked in downstream applications. We used these sidebands to lock a homodyne detector and measured stably locked vacuum squeezing down to 220 kHz. We propose an alternative OPA configuration that should allow the production of vacuum squeezing at significantly lower frequencies.

The authors acknowledge the Alexander von Humboldt foundation for support of R. Schnabel; the Australian Research Council for financial support; and Dr. D. Shaddock for insightful discussion.

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