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# Generation of squeezed vacuum on cesium D2 line down to kilohertz range*

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We report the experimental generation of a squeezed vacuum at frequencies ranging from 2.5 kHz to 200 kHz that is resonant on the cesium D2 line by using a below-threshold optical parametric oscillator (OPO). The OPO is based on a periodically-poled $KTiOPO_4$ (PPKTP) crystal that is pumped using a bow-tie four-mirror ring frequency doubler. The phase of the squeezed light is controlled using a quantum noise locking technique. At a pump power of 115 mW, maximum quadrature phase squeezing of 3.5 dB and anti-squeezing of 7.5 dB are detected using a home-made balanced homodyne detector. This squeezed vacuum at an atomic transition in the kilohertz range is an ideal quantum source for quantum metrology of enhancing measurement precision, especially for ultra-sensitive measurement of weak magnetic fields when using a Cs atomic magnetometer in the audio frequency range.

**Keywords:** quantum optics, squeezed vacuum states, optical parametric oscillators, low frequency

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## 1. Introduction

Squeezed light is an important source in many areas of continuous-variable quantum information science, including quantum communication,[1] precision measurement,[2–4] quantum storage and studies of the interactions between light and atoms.[5,6] Parametric down-conversion process in a subthreshold optical parametric oscillator (OPO) is often used to generate continuous wave (CW) squeezed light. As a result of the development of modern technologies such as high-quality nonlinear crystals, low-loss coatings and high-efficiency detectors, 15 dB of squeezing has been obtained with the ultimate goal of surpassing the standard quantum limit for high-sensitivity measurements at 1064 nm.[7] Unfortunately, the generation process and the measurement frequency range mainly focus on the radio-frequency range. Laser relaxation oscillation and other technical noise sources have typically limited squeezing to the megahertz range,[8] and thus CW squeezed sources at audio frequencies have rarely been reported to date. However, the development of various applications often requires signal measurements to be performed at low frequencies, which would require squeezed light to be produced in the low-frequency range. For example, stably controlled squeezed states with bandwidths ranging from kilohertz down to a few hertz or even lower will be required for gravitational wave detectors.[9] In the quantum communication field, squeezed light can be stored and released by the electromagnetically-induced transparency (EIT) of the atomic medium.[10] However, because of the narrow transparency windows that are available in EIT, squeezed light at low frequencies is again required.[11] In addition, high-sensitivity magnetic field measurements are an important requirement in the measurements of geomagnetic anomalies, spatial magnetic fields and biological magnetic fields, in which the sideband frequencies range from kilohertz to hertz levels or lower.[12–14] Therefore, shifting the spectrum of the squeezed vacuum states downwards into the acoustic band is highly important for use in quantum metrology and quantum optics experiments. In 2004, McKenzie *et al.* first realized a broadband continuous squeezed field in a frequency range of 280 Hz–100 kHz, and the phase of the squeezed vacuum was controlled using a quantum noise locking technique.[15] In 2007, Vahlbruch *et al.* observed squeezed states in a Fourier frequency band down to 1 Hz by using a frequency-shifted coherent light control method to lock the squeezed vacuum phase.[16] In 2012, Stefszky *et al.* successfully obtained more than 10 dB of squeezing at an analysis frequency of 10 Hz as a result of a series of technical improvements.[17] Unfortunately, these results were observed at 1064 nm and 1560 nm, which are in the wavelength ranges of gravitational wave detection and fiber telecommunication and far from those of the alkali metal atomic transitions. Nevertheless, squeezed light corresponding to the transitions of the alkali metal atoms, such as cesium (Cs) and rubidium (Rb), have great potential applications in fields including nonclassical spectroscopy, light–atom interactions, information

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storage and readout, quantum information networks, and ultra-precision measurements. In 2007, Takeno *et al*. observed 9 dB of vacuum squeezing at 860 nm, which was close to the Cs D2 line, at a measurement frequency of 1 MHz.[18] A major step forward was made by Burks *et al*., who focused on squeezed light generation at an atomic transition. They obtained 3 dB of squeezing at a frequency of 50 kHz at 852 nm.[19] In 2010, Wolfgramm *et al*. applied polarization-squeezed probe light to a hot unpolarized ensemble of Rb atoms, and improved the sensitivity of their magnetometer by 3.2 dB at a measurement frequency of 120 kHz.[20] In contrast, squeezed light on atomic lines is urgently needed of further developing the lower frequency direction. In this paper, we demonstrate a system that produces vacuum squeezed light on the Cs D2 line, in which a frequency doubler is used as a pump source of an OPO based on $KTiOPO_4$ (PPKTP). Using a subthreshold parametric down-conversion process, the squeezed vacuum is obtained experimentally at frequencies ranging from 2.5 kHz to 200 kHz. The phase of the squeezed vacuum on the homodyne detector is controlled using a quantum noise locking technique that operates without a carrier.[21] The maximum squeezing level is 3.5 dB below the standard quantum level (SQL), while the corresponding anti-squeezing is 7.5 dB above the SQL.

## 2. Experiment

A schematic diagram of the experimental setup is shown in the following Fig. 1.

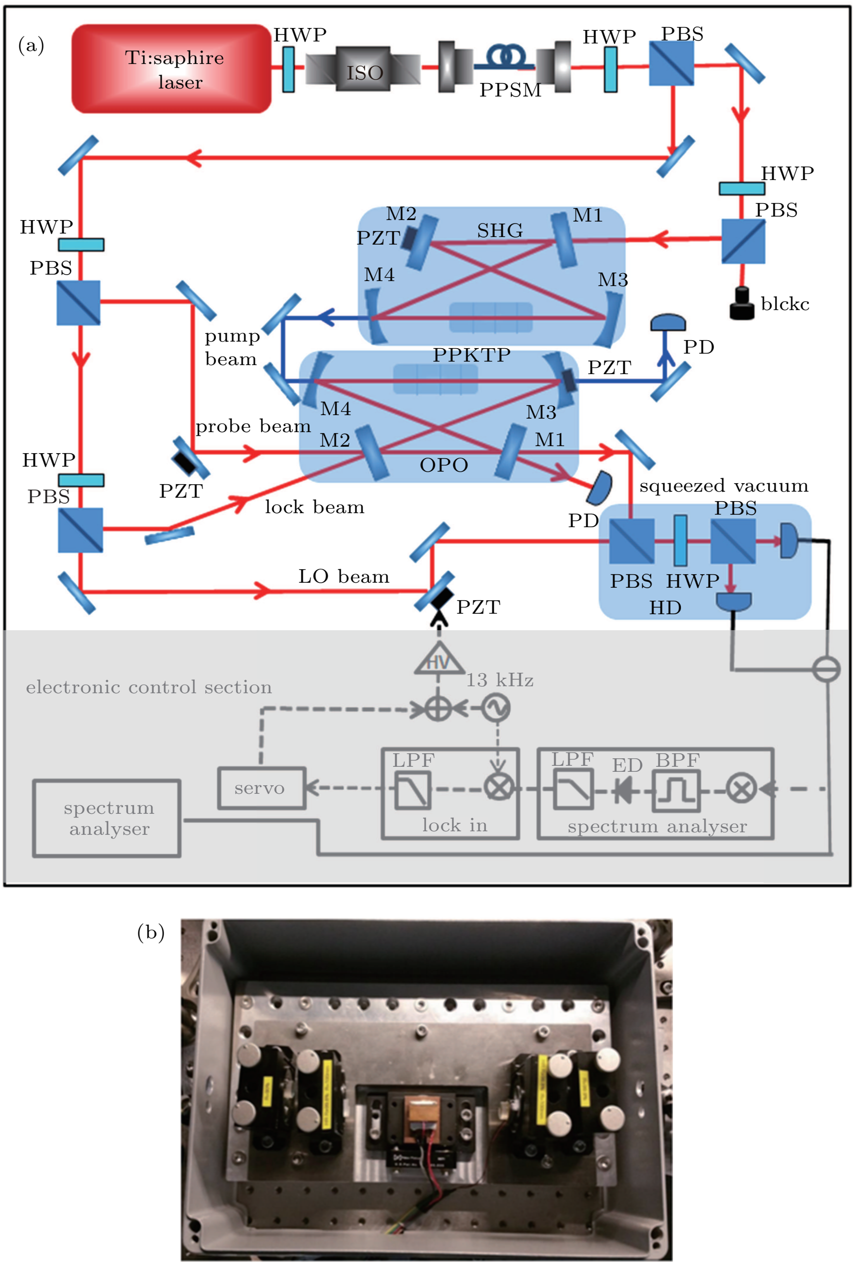


**Fig. 1.** (color online) (a) Schematic diagram of the experimental setup. ISO: Faraday isolator; PPSM: polarization-preserving single-mode fiber; HWP: half-wave plate; PBS: polarization beam splitter; PD: photodetector. The dash lines indicate the control electronics for the phase of the homodyne detection process. BPF: band-pass filter; ED: envelope detector; LPF: low-pass filter; HV: high-voltage amplifier. (b) Photograph of the OPO and its housing.

The system is mainly composed of (i) a second harmonic generator (SHG), (ii) an OPO, and (iii) a homodyne detection (HD). A CW Ti:sapphire laser is locked onto the D2 transition of the Cs atoms. The 852-nm laser beam is then divided into four parts. Approximately 400 mW of the fundamental wave light is used for SHG to produce 180 mW of the pump field at 426 nm that allows the OPO to generate a squeezed vacuum.[22] A small fraction of the beam is used as a local beam (LO) for the HD. The remaining two parts of the beam are used as a cavity length locking beam and the probe beam for the OPO cavity, respectively. To avoid the interference between the locking beam and the probe beam (see Fig. 1), the locking beam is injected through a high-reflectivity mirror and propagates in the opposite direction to the pump beam. However, a small fraction of the locking beam still circulates backwards as a result of reflection from the crystal surfaces. This problem is solved by reducing the locking beam power to the lowest possible level. Our OPO cavity is a single resonant four-mirror ring cavity in which only the fundamental wave is resonant, and a 1 mm×2 mm×20 mm type-I PPKTP crystal is used as a nonlinear crystal. The OPO is composed of two planar mirrors, M1 and M2, and two concave-convex mirrors, M3 and M4, that have the same radius of curvature of 100 mm. M3 and M4 are high-reflectivity mirrors at 852 nm and are anti-reflective at 426 nm. We choose 10% transmission for the coupler mirror (M1) and bond a piezoelectric (PZT) element to mirror M3, which is then used to lock the cavity length. The total cavity length is approximately 638 mm and the distance between M3 and M4 is 118 mm, which results in a beam waist of 39.4 μm at the center of the crystals. To reduce the acoustic noise and other vibration-related noise, we fabricate a solid OPO by using the Newport-9814 Stability Series Top Actuated Mirror Mount, which is built on a whole piece of low expansion Invar Alloy material board and is then placed into a metal sheath for spatial isolation (see Fig. 1(b)). Squeezed light is then produced when the crystal temperature is stabilized at its phase-matching temperature by using a temperature controller and the OPO cavity length is tuned on resonance. Finally, we use a home-made low-frequency low-noise balanced homodyne detector[23] to complete the squeezing measurements.

In Fig. 1(a), the AC signal of the HD output is divided into two parts. One part, serving as the detection signal for the quantum noise locking, enters into the spectrum analyzer (HP-8590D). The other part is sent to another low frequency spectrum analyzer (Aligent, 4396B) to analyze the quantum noise power. The dash lines show the electronics used for HD phase control. The error signal from the HD system is generated by modulating the LO beam phase and subsequently demodulating the difference photocurrent noise power from the homodyne detector. The noise power is detected using a spectrum analyzer (HP-8590D, with zero span at 1 MHz, a resolution bandwidth (RBW) of 100 kHz and a video bandwidth (VBW) of 30 kHz) and is demodulated using a lock-in amplifier (Stanford Research Systems (SRS)-SR830). After filtering, the error signal is finally fed back to the PZT.

## 3. Results and discussion

Firstly, we study the classical performance of the OPO as a phase-sensitive amplifier. For that purpose, a weak probe beam is injected into the OPO through high-reflectivity mirror M2, and by slowly scanning the injection phase, the amplification $G$ is measured through output coupler mirror M1. The measured parametric gain $G$ versus pump power characteristic is shown in Fig. 2. In this figure, the red solid circles indicate the experimental data, and the red curve represents the theoretical calculation result based on the following relation:[24]

$$G=\frac{1}{\left(1-\sqrt{P_2/P_{2,t}}\right)^2}, \tag{1}$$

where $P_2$ is the pump power, and the oscillation threshold $P_{2,t}$ of the OPO cavity is given by

$$P_{2,t}=\frac{(T+L)^2}{4E_{\rm NL}}. \tag{2}$$

In this experiment, the output coupler transmission is $T=10\%$. The single pass conversion coefficient is measured to be $E_{\rm NL}=2\%\ {\rm W}^{-1}$, and the intracavity loss is $L=2.56\%$. Using these experimental parameters, the threshold $P_{2,t}$ is inferred to be approximately 197 mW.

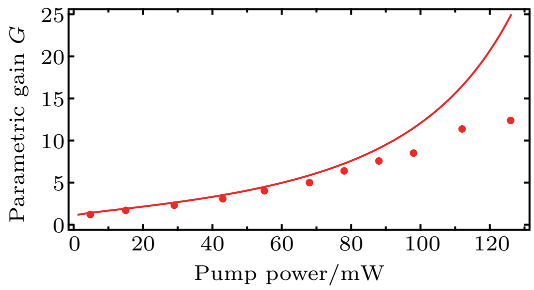


**Fig. 2.** (color online) Parametric gain versus pump power, where solid line represents the theoretical simulation results and solid circles denote experimental results.

In the below-threshold OPO, the anticipated noise variances of the squeezed (Sq) and anti-squeezed (Asq) quadratures are given as follows:[25]

$$V_{\rm Asq,Sq}=1\pm\eta_{\rm det}\eta_{\rm esc}\frac{4x}{(1\mp x)^2+\Omega^2}, \tag{3}$$

where $x=\sqrt{P_2/P_{2,t}}$ is the normalized nonlinear interaction strength; $\eta_{\rm det}$ is the detection efficiency of the HD and given by $\eta_{\rm det}=\eta_{\rm tr}\times\eta_{\rm vis}^2\times\eta_{\rm qu}$, with $\eta_{\rm tr}$ being the propagation efficiency, $\eta_{\rm vis}^2$ being the interference efficiency, and $\eta_{\rm qu}$ being the quantum efficiency of the photodiodes; $\eta_{\rm esc}$ is the escape efficiency of the cavity, which is defined as $\eta_{\rm esc}=T/(T+L)$;

$\Omega = 2\pi f/k$ is the normalized measurement frequency, with $f$ being the measurement frequency. Using the cavity round-trip length $l_{cav}$ and the speed of light $c$ the cavity decay rate can be defined as $k = c(T+L)/l_{cav}$.

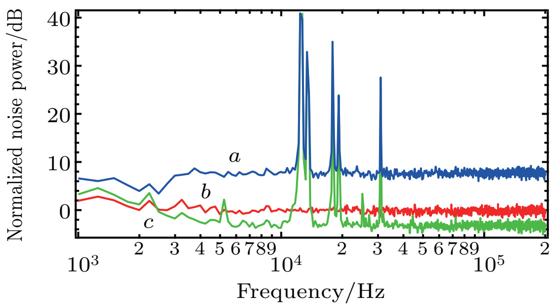


**Fig. 3.** (color online) Measured noise spectra for (curve *a*) anti-squeezed light, (curve *b*) the SQL, (curve *c*) squeezed light after correction of the electronic noise (15 dB below the SQL) of the HD system. RBW = 100 Hz, VBW = 10 Hz. Sweep time = 19.6 s. All traces are averaged over 10 times.

The normalized noise power spectrum in a range from 1 kHz–200 kHz is shown in Fig. 3 at a pump power of approximately 115 mW. The standard vacuum noise reference is recorded here using LO power of 1.0 mW and a blocked probe beam port. Trace *a* shows the noise power of the anti-squeezed light, and trace *b* is the SQL. The measurement results for the squeezed light are shown as trace *c*. These results show that squeezing is eventually obtained down to 2.5 kHz. There are some spurious noise signals on both the anti-squeezing and squeezing spectra around the frequencies of 13 kHz, 19 kHz, and 31 kHz, which are caused by modulation signal of the phase of the squeezed vacuum relative to the LO beam, the OPO cavity length and the SHG cavity length, respectively, as used in dither-lock techniques.[26] When the measurement frequency is higher than 30 kHz, a stable squeezing of approximately 3.5 dB is observed. To obtain squeezing at lower frequencies, we must carefully shield the LO- or ambient-light-induced scattered photons to prevent it from coupling to the OPO cavity.[15,27]

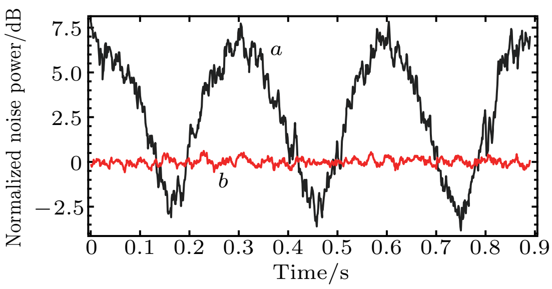


**Fig. 4.** (color online) Plots of squeezing at 35 kHz versus time, where (curve *a*) black line represents the normalized quantum noise power of the squeezed vacuum at the Cs D2 line when the LO phase is scanning, while (curve *b*) red line refers to the normalized SQL with RBW = 1 kHz and VBW = 300 Hz.

We perform quantum noise measurements of the SQL and the squeezed and antisqueezed noise powers while scanning the LO phase as a function of time at a frequency of 35 kHz with RBW = 1 kHz and VBW = 300 Hz. The results are shown in Fig. 4. Trace *a* shows the quantum noise power of the squeezed beam, and trace *b* represents the normalized SQL. The 3.5 dB below SQL is measured directly, and the corresponding anti-squeezing is 7.5 dB. This noise reduction can be explained based on Eq. (3) by using the experimental parameters. A number of factors limit the observed squeezing in practice, and these factors are listed in Table 1 below.

**Table 1.** Factors limiting squeezing from the OPO and the detection system.

| Factors | Value |
|---|---|
| Normalized nonlinear interaction strength (finite OPO gain) | 0.982 |
| Finite frequency of measurement | 0.999 |
| OPO escape efficiency | 0.796 |
| Propagation efficiency from OPO to detectors | 0.957 |
| Homodyne efficiency on 50/50 beamsplitter | $(0.965)^2$ |
| Quantum efficiency of detector | 0.95 |
| Total | 0.661 |

In accordance with Eq. (3), under the conditions of measurement frequency of zero hertz, pump power at the OPO threshold and an ideal measurement efficiency, the quantum noise $V_{Sq}$ approaches to zero, which corresponds to a complete quantum noise reduction. In the actual experiment, at the finite OPO gain $x = 0.76$, the noise reduction can still reach as high as 0.982; at the finite measurement frequency $f = 35$ kHz, the normalized frequency $\Omega = 0.0037$, the quantum noise $V_{Sq}$ also goes nearly down to zero corresponding to a quantum noise reduction of 0.999. Addition of all the limiting factors gives a 66.1% quantum noise reduction, which corresponds to 4.7 dB of squeezing to be observed, and is higher than the experimental result. It should be noted here that due to the serious light-absorption-induced thermal effect in PPKTP, which occurs at this particular wavelength,[28] the OPO intracavity losses increase under pumped conditions.[18,24] Pump light absorption also induces thermal lensing, thermal stress and thermally-induced phase mismatch. In fact, we have verified that the measured losses increase to 3.51% after illumination with a pump light power of 115 mW for 60 s. The pump parameters and the escape efficiency decrease and the expected squeezing also decreases to approximately 4 dB, which is in reasonable agreement with the observed level of 3.5 dB from Fig. 4. The analysis above suggests that the optical loss of the OPO is a major limiting factor that prevents higher levels of squeezing from being achieved in our experiments. We therefore intend to improve the system as follows: 1) we will carefully reduce the intracavity losses as far as possible through using the high quality optical components, while also reducing the pump-induced losses via a moderate increase in the size of the cavity mode waist; 2) we will also improve the overall detection efficiency.

## 4. Conclusions

In this work, we demonstrate the squeezed light generation on the cesium D2 line by degenerate parametric down-conversion in a symmetrical bow-tie ring subthreshold OPO cavity. Adopting a quantum noise locking technique without a carrier, squeezing of 3.5 dB is observed directly and this squeezing is preserved for frequencies down to 2.5 kHz. Squeezing at such low frequencies is measured using a home-made balanced homodyne detection system. At present, the squeezing is limited by the intracavity losses of the OPO and the detection efficiency. The generation of this squeezed light at such a low frequency on the atomic transition is an important step towards applications of squeezed light such as ultra-sensitive measurements beyond the SQL, precision control of optical systems, quantum memories and further investigation of nonclassical light-matter interactions.

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