Generation of a squeezed state at 1.55 μm with periodically poled $LiNbO_3$*

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We report on the generation of a squeezing vacuum at 1.55 μm using an optical parametric amplifier based on periodically poled $LiNbO_3$. Using three specifically designed narrow linewidth mode cleaners as the spatial mode and noise filter of the laser at 1.55 μm and 775 nm, the squeezed vacuum of up to 3.0 dB below the shot noise level at 1.55 μm is experimentally obtained. This system is compatible with standard telecommunication optical fibers, and will be useful for continuous variable long-distance quantum communication and distributed quantum computing.

Keywords: squeezed states, telecommunication wavelength of 1.55 μm, optical parametric amplifier

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1. Introduction

Continuous variable (CV) quantum states of light at a wavelength of 1.5 μm have recently been focused on by researchers.[1−3] The squeezed states of light at this wavelength can be transmitted with the lowest decoherence characteristics in traditional silica-based telecommunication glass fibers due to the fact that its optical loss is as low as 0.2 dB/km.[4] Moreover, the sensitivity of the interferometer can be improved a lot when the detector is driven by light at a wavelength of 1.5 μm.[5,6]

In previous years squeezed light around 1.5 μm has been generated in the pulsed laser regime[7−9] because there is no good quality continuous-wave (cw) laser at 1.5 μm for quantum experiments. In 2008, a 2.4-dB cw squeezed vacuum state at 1.5 μm was reported using an Er-doped fiber amplifier seeded by a single-frequency laser diode.[1] After that, a 5.3-dB cw squeezed vacuum state was generated using a fiber laser at 1550 nm based on a periodically poled potassium titanyl phosphate (PPKTP) crystal.[2] However the fiber laser exhibits large excess noise above shot noise level (SNL)[10], and it can reduce the quantum characteristics of the nonclassical states of light in a quantum optical experiment. So far, an optical parametric amplifier (OPA) has been verified to be the most successful technique to generate cw quantum states of light (squeezed states of light or entangled states of light) with a high quality[11,12]

In the present paper, we report on the generation of a cw vacuum squeezed state at 1.55 μm using an OPA containing a periodically poled lithium niobate (PPLN) crystal. The pump source of the OPA is the output from the external cavity enhanced second-harmonic generation (SHG), injected by a cw single frequency fiber laser. With the help of three narrow linewidth mode cleaners (MC) as the spatial mode and noise filter of the laser at 1.55 μm and 775 nm, a squeezed vacuum of up to 3.0 dB below the SNL at 1.55 μm was experimentally observed.

2. Experimental setup

A schematic diagram of the experimental setup is shown in Fig. 1. A commercially erbium fiber laser (NP Photonic Inc.) provided about 2.0 W of cw single-frequency radiation at 1.55 μm. An optical isolator (OI) was used to eliminate the back-reflection light. Half wave plates (HWP) were used to control the polarization of the laser beam. The laser beam was sent

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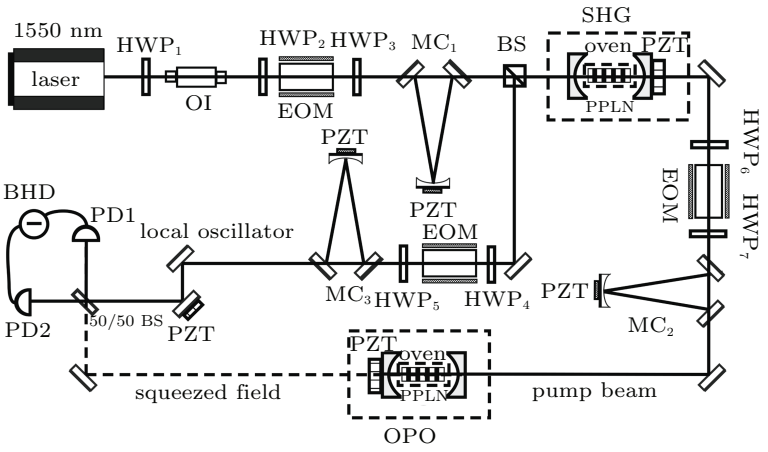


Fig. 1. Schematic diagram of the experimental setup. OI: optical isolator; EOM: electro–optical modulator; HWPs: half wave plate; MCs: mode cleaners; BS: beam splitter; PDs: photo diode; BHD: balanced homodyne detector; PZT: piezo–electric transducer.

through a ring MC1 cavity with a finesse of 180 and a linewidth of 2.0 MHz as a preliminary spatial mode and noise filter. An electro–optical modulator (EOM) with a radio frequency (RF) of 35 MHz was employed to lock the MC1 cavity using the Pound–Drever–Hall (PDH) technique[13] The main portion of output from MC1 was injected into the external enhanced SHG cavity to obtain a high-power low-noise cw laser at 775 nm that acted as the pump source of the OPA. The residual light was used separately as the signal beam of an OPA and the local oscillator (LO) of the balanced homodyne detector.

The external enhanced SHG cavity was a linear cavity composed of two curvature mirrors with a radius of 30 mm and a PPLN crystal. The input coupler had a partial reflection for the fundamental beam ($T_{1.55\ \mu m} \sim 6.0\%$) and a high reflection (HR) for second-harmonic (SH) ($R_{775\ nm} > 99.7\%$), and the output coupler had HR for fundamental ($R_{1.55\ \mu m} > 99.7\%$) and partial reflection for SH ($T_{775\ nm} \sim 10.0\%$). The length of the SHG cavity was 63 mm, resulting in a cavity waist of 69 μm for the fundamental beam. The PPLN crystal had a dimension of 1 mm (thickness) × 10 mm (width) × 20 mm (length) with a poled period of 18.6 μm and both ends were antireflectively coated at 1.55 μm and 775 nm, and the temperature was controlled by a temperature controller with an accuracy of 0.01 °C (Model YG-2009B). The measured mode match of the TEM_{00} mode of the fundamental beam to the external SHG cavity was 96% in the absence of a MC1 cavity and it is 99% in the presence of a MC1 cavity. When the PPLN crystal was at a controlled temperature of 130 °C, 560 mW of SH power was obtained via 730-mW pumping power with 76% SH conversion efficiency. There was a 3% improvement of SH conversion efficiency owing to the spatial filtering of MC1. The MC2 with a linewidth of 1.0 MHz and MC3 with a linewidth of 16 MHz were used as the spatial mode and noise filters for the 775-nm beam, LO and signal beam at 1.55 μm (the signal beam was omitted in Fig. 1), and locked using the PDH technique with RF 65 MHz and 82 MHz respectively.

The OPA had the same structure and crystal parameters as the external enhanced SHG cavity. The input coupler had a high transmission for pump ($T_{775\ nm} > 9.0\%$) and an HR for down-conversion ($R_{1.55\ \mu m} > 99.7\%$) and the output coupler had a partial reflection for down-conversion ($T_{1.55\ \mu m} \sim 6.0\%$) and an HR for pump ($R_{775\ nm} > 99.7\%$). The length of the OPA cavity was 63 mm, resulting in a cavity waist of 49 μm for the pump. The signal beam was used for aligning the OPA and measuring the classical parametric gain. The down-conversion output from the OPA was separated from the residual pump field by a dichroic beam splitter. The squeezed state was observed by a balanced homodyne detection system based on a pair of photodiodes (ETX-500 Epitaxx). The measured bandwidth of the detectors was approximately 30 MHz, and the observed common noise rejection was 30 dB at an analysis frequency of 2 MHz to 30 MHz.

3. Experimental results and discussion

The mode cleaners are employed for improving the characteristics of the laser beam.[14] The improved spatial mode of the pump beam contributes to better

mode matching to the SHG and OPA cavities, and to the next step for enhancing nonlinear conversion efficiencies in SHG and OPA processes. In addition, the MC reduces the intensity noise of the laser beam, which is more important for quantum optical experiment. When the MC1 is locked using the PDH technique, the intensity noises of the laser before MC1 and after MC1 are measured using a self-balanced detection system[15] and recorded by a spectrum analyzer (N9010A, Agilent) with a bandwidth resolution of 100 kHz, a video bandwidth of 100 Hz, and a sweep time of 1.5 s. The intensity noise of the fiber laser before MC1 is more than 20 dB above the SNL from the analysis frequency of 2 MHz to 20 MHz, and it reaches the SNL at an analysis frequency of 15 MHz after MC1. The SNL is calibrated by a thermal white light source. The power transmission of the MC1 is 60%. The noise characteristics of the output from MC1 is not suitable for the quantum experiment, but the filter of the MC1 will be the base of the second filter. The intensity noises of the laser before MC2 (the output of SHG) and after MC2 (the pump of OPA) are also measured using the same system when MC2 is locked. The intensity noise power spectrum is shown in Fig. 2, the sum signal gives the intensity noise power of the 775-nm laser (curves *b* and *c*) and the difference signal gives the SNL (curve *a*). It can be seen that the intensity noise of the pump of the OPA reaches the SNL at an analysis frequency of 4 MHz (curve *b* in Fig. 2), owing to the MC acting as a noise eater, but the intensity noise of the output of SHG (curve *c* in Fig. 2) exhibits a large excess noise above the SNL until the analysis frequency of 15 MHz. The electronic noise level of the self-balanced detector is 10 dB below the SNL (not shown in Fig. 2).

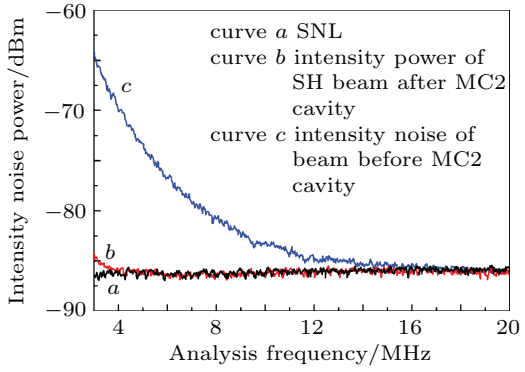


Fig. 2. (colour online) Measured intensity noise power spectra of the 775-nm laser before and after the MC2 cavity.

When the MC3 is locked, and the intensity noise of the laser after MC3 (that is the LO and signal beam at 1.55 μm) is measured and recorded by the same system. Figure 3 shows the intensity noise power spectrum. Curves *a* and *b* in Fig. 3 give the SNL and the intensity noise power of the 1.55-μm laser. It can be seen that the intensity noise of the LO and signal beam at 1.55 μm reaches the SNL at an analysis frequency of 5 MHz.

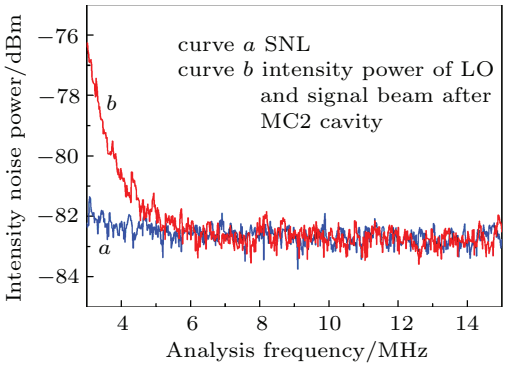


Fig. 3. (colour online) Measured intensity noise power spectra of a 1.55-μm laser after the MC3 cavity.

The OPA is pumped by the output of SHG, which is spatially and noise filtered by MC2. The measured pump threshold of OPO is 46 mW. A signal beam at 1.55 μm (omitted in Fig. 1), which is spatially and noise filtered by MC3 is used to measure the classical parametric gain of the OPA. The measured classical parametric gain is 80 at a pump power of 38 mW. In squeezing experiments, the interference contrast between the LO and the squeezed field on the 50/50 homodyne beam splitter (BS) is crucial. To adjust the visibility we inject the signal beam through the HR back side of the OPA. This signal beam matches the OPA TEM_{00} mode. The light that was transmitted is propagated in the mode congruent to the mode to be squeezed and could be used to overlap with the LO on the homodyne beam splitter. A fringe visibility of 99% is obtained.

When the OPA is operated below the threshold with a pump power of 38 mW and the signal is blocked, the noise power of the down-conversion output from the OPA is measured by the balanced homodyne detection system and recorded by a spectrum analyzer (N9010A, Agilent) at an analysis frequency of 5 MHz. The recorded noise power spectrum is depicted in Fig. 4. Trace *a* corresponds to the SNL which is measured by blocking the squeezing vacuum. Traces *b* and *c* are the recorded squeezing and anti-squeezing output when the homodyne phase angle is locked. Trace *d* is the quadrature quantum noise converted from squeezing to anti-squeezing by linearly scanning the LO phase. The power of the LO

is 10 mW, the electronic dark noise of the homodyne detector is 20 dB below the vacuum noise and is not subtracted from the data. The measured squeezed noise is (3.0 ± 0.2) dB below the SNL and the anti-squeezed noise is (9.8 ± 0.2) dB above the SNL.

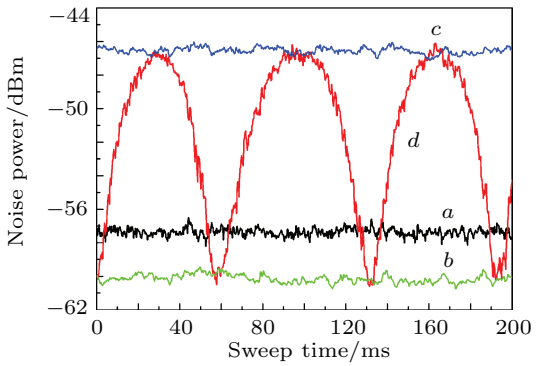


Fig. 4. (colour online) Noise powers of the squeezed light at an analysis frequency of 5 MHz. The spectrum analyzer parameters: the resolution bandwidth 300 kHz and the video bandwidth 300 Hz. Trace a denotes the shot noise level; Traces b and c are squeezing and anti-squeezing curves, respectively; Trace d represents the measured quadrature quantum noise converted from anti-squeezing to squeezing by linearly sweeping the LO phase.

Our measurement is limited by optical losses and the detection efficiency. There is an imperfect detection efficiency of 63% (including the detector quantum efficiency of 90%, the homodyne efficiency of 99%, the approximate escape efficiency of the OPA cavity of 90%, and the optical propagation efficiency of 84%). So the total loss of 37% reduces the squeezing once it is generated. In addition, the fluctuations of the cavity lock-in and phase lock-in systems are important restricting factors for improving the squeezed field. We expect that a much higher squeezing level could be observed by optimizing the optical system, searching for a better photodiode and reducing the lock-in fluctuation.

4. Conclusions

In this paper, we demonstrate a (3.0 ± 0.2) dB squeezed vacuum at a telecommunication wavelength of 1.55 μm generated from a subthreshold cw pumped OPA with a PPLN crystal. The specifically designed narrow linewidth MC cavities are employed for filtering the spatial mode and reducing the extra noise fluctuation of the pump fields. Squeezed vacuum states can be used to enhance the sensitivity of the detection of gravitational waves, which is already realized by operating at 1064 nm.[16,17] In the future, people may consider silicon as a test mass material and use the laser at 1.55 μm to reduce the thermal noise for a higher signal-to-noise ratio. Furthermore, the EPR entangled states for CV at 1.55 μm can be obtained by a simple linear optical transformation of two squeezed vacuum fields, which are used in a variety of CV quantum communication and computing systems. At present, some entangled states are still not produced except for so-called vacuum-class entanglement at 1.55 μm by mixing a squeezed mode with a vacuum mode.[18]

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