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Generation of a squeezing vacuum at a telecommunication wavelength with periodically poled $LiNbO_3$

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A continuous-wave squeezed vacuum at a telecommunication wavelength was reported. Using an Er-doped fiber amplifier seeded by a single-frequency laser diode as the pump laser source, via a frequency doubler and an optical parametric oscillator based on periodically poled $LiNbO_3$, the squeezed vacuum of 2.4 ± 0.1 dB below the shot noise limit at 1560 nm was observed (the inferred initial squeezing is about 6.4 ± 0.5 dB). This system is compatible with standard telecommunication optical fiber, and will be useful for long-distance quantum communication and distributed quantum computing. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2938053]

Squeezed states have great potential in high-precision quantum measurements and continuous variable (CV) quantum information.[1] For fiber-optic-based long-distance quantum communication, squeezed states at telecommunication wavelength are particularly useful. However, the experimental generation of continuous-wave (cw) squeezed states at telecommunication wavelength is less well studied. By utilizing pulsed lasers, 4.1 dB amplitude squeezing[2] at 1505 nm, 1.7 dB squeezed vacuum[3] at 1550 nm, and 3.2 dB quadrature squeezing[4] at 1535 nm were observed experimentally. Subthreshold optical parametric oscillator (OPO) is a reliable tool to generate cw quadrature squeezed states.[5] Recently, the squeezed light with 10 dB quantum noise reduction has been produced from a type I degenerate OPO.[6] Periodically poled $LiNbO_3$ (PPLN) crystal is one of the excellent nonlinear crystals for the frequency conversion at near-infrared and midinfrared wavelength and has shown good performances in the frequency doubling of 1.5 μm laser.[7–9] In this letter, we present a generation system of the cw squeezed vacuum at the telecommunication wavelength, in which an Er-doped fiber amplifier (EDFA) seeded by a single-frequency laser diode and a frequency doubler are used for the pump source of an OPO based on PPLN. Through a subthreshold parametric frequency downconversion process in the OPO, the squeezed vacuum of 2.4 ± 0.1 dB below the shot noise limit (SNL) at 1560 nm was experimentally measured.

A schematic diagram of the experimental setup is shown in Fig. 1. Differing from the usual generation systems of the cw squeezed states of light, the laser source used by us is an EDFA (Model EAD-2K-C-LP) seeded by a single frequency laser diode (TOPTICA DL100), with the maximum output power of 2 W and the operating spectral range from 1550 to 1563 nm. By means of the optical feedback of a confocal Fabry–Pérot cavity,[10,11] the line width of laser source was reduced from 1 MHz to 200 kHz, meanwhile, its excess phase and amplitude noises were suppressed by 15 and 12 dB, which are still 28 and 10 dB higher than that of the SNL, respectively.

A −40 dB Faraday isolator (FI) was set in the input light of the frequency doubler to eliminate the back reflection of the pump laser. A small portion of the pump laser was used for the local oscillation of the balanced homodyne detector (HD) and another small portion for the probe beam of the OPO. The retained large power of 1.3 W was sent in to the frequency doubler to produce the cw single-frequency laser at 780 nm via the second-harmonic-generation (SHG) process.[9] The frequency doubler was a single-ended linear cavity in which only the fundamental wave was resonantly enhanced and a PPLN crystal was used as the nonlinear crystal for implementing frequency upconversion. After optimizing the transmission of the input coupler (that is 13%) and improving the mode matching efficiency (that is 98%), 700 mW single-frequency laser at 780 nm was obtained with the frequency doubling efficiency of 73%. Figure 2 shows the dependences of the output power of the 780 nm laser and the second-harmonic (SH) conversion efficiency on the power of the incident fundamental laser on the frequency doubler.

The generated single-frequency 780 nm laser was utilized to pump the OPO which consists of a PPLN crystal and two planoconcave spherical mirrors with the radius of curvature of 30 mm. The effective cavity length of the OPO was 55 mm and the beam waist radius of the fundamental wave in the crystal was about 50 μm. The OPO was designed to make the degenerate downconversion field at 1560 nm resonate in the optical cavity and the pump field at 780 only double pass. The output coupler of the OPO was partial transmission at 1560 nm ($T=6\%$) and high reflective at 780 nm ($R>99.7\%$). The input coupler of the OPO was

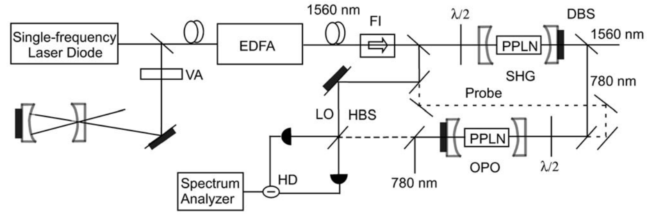

FIG. 1. Schematic diagram of experimental setup. VA: variable attenuator, FI: Faraday isolator, SHG: second harmonic generation, DBS, dichroic beam splitter, LO: local oscillator, HBS: 50/50 beam splitter, HD: balanced homodyne detector.

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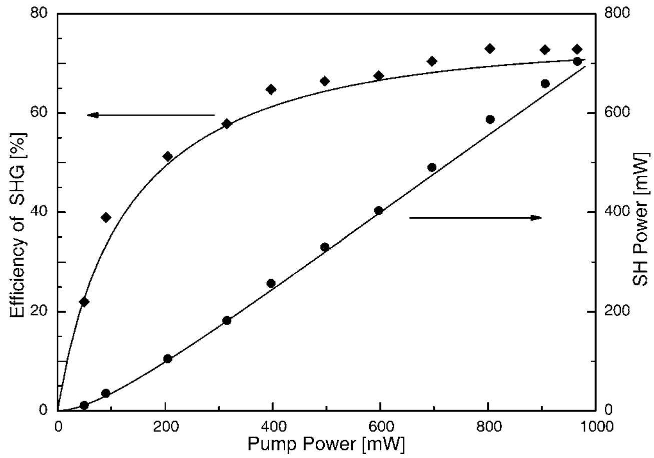

FIG. 2. Dependences of the output power of the 780 nm laser and the conversion efficiency of SHG on the power of the incident fundamental laser. The solid lines are theoretical predictions.

high reflectivity at 1560 nm ($R > 99.7\%$) and high transmission at 780 nm ($T > 90\%$). The PPLN crystal was coated with antireflectivity at both 1560 and 780 nm and with the dimension of 1 mm (thickness), 10 mm (width), and 20 mm (length). The PPLN comprises six quasiphase-matching (QPM) poled periods from 18 to 19 μm. In the present experiment, the 18.6 μm period is utilized at the QPM temperature of 120 °C. The crystal was mounted inside a specially designed oven with temperature control accuracy of 0.01 °C. The 780 nm pump laser was carefully mode matched into OPO and the measured OPO pump threshold power for generating frequency down-conversion was 55 mW.

The probe beam was used for aligning the resonant cavity as well as measuring the intracavity loss and the classical parametric gain. The measured intracavity loss was 0.012 and the line width of the OPO resonator was 15 MHz. The classical parametric gain of 200 was observed under pump power of 50 mW which is below the OPO oscillation threshold. The output squeezed light from the OPO and the residual pump field are separated via a dichroic beam splitter (DBS). Then, the squeezed light and the local oscillator (LO) are combined at a half-beam splitter (HBS) and are detected by two photodiodes with the quantum efficiency of 85%. The HBS and the two photodiodes construct a HD to detect the noise of the amplitude and phase quadrature of the squeezed light. The electronic noise level of the HD is 15.0 dB below the SNL. To check the balance of the homodyne detector, we used an electro-optic modulator to impart an amplitude modulation onto the probe beam. The observed common noise rejection at analysis frequency of 5 MHz is 30 dB.

Figure 3 shows the quadrature quantum noise levels of the squeezed light at the pump power of 50 mW measured with a spectrum analyzer as the LO phase was scanned. Trace a in Fig. 3 corresponds to the SNL which was measured by blocking the squeezed vacuum (the SNL was also calibrated by a thermal white-light source). When the squeezed vacuum was injected, the quantum fluctuations depending on the quadrature phase were recorded (trace b). The measured squeezed noise level was 2.4 ± 0.1 dB below the SNL. The OPO squeezing spectrum from 2 to 30 MHz is shown in Fig. 4 as the LO phase was locked. Trace a in Fig. 4 shows SNL and the squeezing spectrum is shown in trace b. At least 2 dB of squeezing can be measured from 2 to 10 MHz, and at higher frequencies the squeezing degraded due to the linewidth of the OPO cavity.

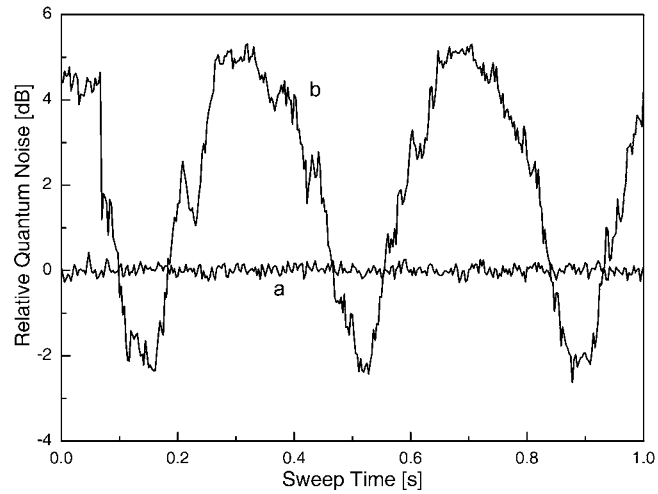

FIG. 3. Measured quadrature quantum noise of the squeezed vacuum generation. (a) SNL (b) Quantum noise of the squeezed vacuum as the LO phase was scanned. The settings of the spectrum analyzer: zero-span mode at 5 MHz, resolution bandwidth is 30 kHz and video bandwidth is 300 Hz.

Taking into account the imperfect detection efficiency (η) of 55.2% (including the detector quantum efficiency of 85%, the homodyne efficiency of 97%, and the optical propagation efficiency of 68.5%), the inferred squeezing of the output light from the OPO should be 6.4 ± 0.5 dB below the SNL ($V_{sq} = V_{sq,meas} - 1 + \eta / \eta$, see Ref. 12). Our analysis suggests that the nonperfect optical propagation efficiency was the main limitation in our experiment. If the optical propagation efficiency is improved by using high quality optical elements, more than 3 dB noise suppression can be measured.

The total uncertainty can be calculated to be 1.9 by multiplying the squeezing of 2.4 dB by antisqueezing of 5.2 dB, so the generated state is not a minimum uncertainty state. This is due to the linear loss (OPO escape efficiency, etc.), fluctuations of the OPO cavity length, and phase fluctuations between the LO and the squeezed beam.[13] The Einstein–

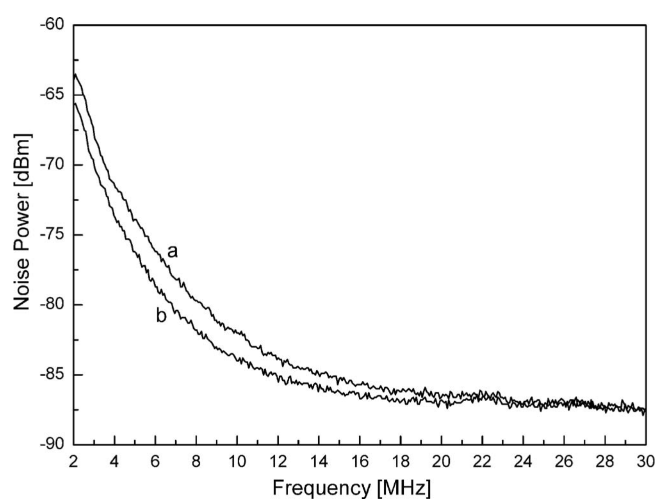

FIG. 4. Measured quantum noise spectrum: (a) SNL and (b) squeezing spectrum as the LO phase was locked. The settings of the spectrum analyzer: resolution bandwidth is 30 kHz and video bandwidth is 300 Hz, and the sweep time is 1 s.

Podolsky–Rosen (EPR) entangled state can be generated straightforwardly by combing two squeezing states at a 50/50 beam splitter, and the entanglement can be evaluated to be $\langle \Delta^2(\hat{X}_1 - \hat{X}_2) \rangle / 2 - \langle \Delta^2(\hat{Y}_1 - \hat{Y}_2) \rangle / 2 = 1.15 < 2$ by using the inseparability criterion[14] and our experimental parameters. Here, $\hat{X}_j, \hat{Y}_j (j = 1,2)$ are amplitude quadratures and phase quadratures of the EPR beams 1 and 2, respectively.

It should be mentioned that although the excess amplitude and phase noises in the pump laser were quite large, they did not strongly influence the generation of the squeezed vacuum in our experiment. We consider that the physical reason is that in the subthreshold optical parametric process, only few pump noises are transferred into the down-conversion field, thus there is no more effect on the squeezed level. The property degrades the requirement to the pump laser in the generation system of the squeezed vacuum, which is preferred by the practical application.

In conclusion, 2.4 ± 0.1 dB squeezed vacuum at 1560 nm was produced from a subthreshold cw pumped OPO with a PPLN crystal. It has been well demonstrated that the EPR entangled state for CV can be obtained by a simply linear optical transformation of two squeezed vacuum fields which have been applied in a variety of CV quantum communication system.[1] Unfortunately, the wavelengths (such as 1064 and 1080 nm[15,16]) of EPR entangled states in the most achieved experiments are not in the telecommunication range. In telecommunication single mode fibers, the loss of 1064 nm wavelength (1.5 dB/km) is 7.5 times of that of 1560 nm (0.2 dB/km), so the presented system will be useful for developing practical quantum telecommunication.

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