Observation of two-color continuous variable quantum correlation at 0.8 and 1.5 μm

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Quantum correlation between signal and idler beams at 0.8 and 1.5 μm was experimentally observed by using an above-threshold optical parametric oscillator based on a periodically poled $\mathrm{KTiOPO_4}$ crystal. The measured quantum noise reduction in the intensity difference of the twin beams was 2.5 dB. The system presented here is of interest for long-distance quantum information processing. © 2010 Optical Society of America

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Quantum states are the fundamental resources of quantum communication and quantum information processing. Alkaline atoms that absorb and emit at a wavelength of around 0.8 μm have been shown to be good media for storage of optical quantum states [1,2]. The presence of telecommunication optical fibers makes the wavelength of 1.5 μm suitable for the distribution of optical quantum states over long distances [3]. Thus, two-color optical quantum states at 0.8 and 1.5 μm are of interest for long-distance quantum information processing [4,5]. Polarization-entangled photons at 0.8 and 1.6 μm have been generated in quasi-phase-matched two- and single-crystal sources [6–8]. Quantum intensity correlation beams in an above-threshold nondegenerate optical parametric oscillator (NOPO) were first demonstrated by Heidmann *et al.* with a type II phase-matched crystal [9]. In this paper, two-color continuous variable (cv) twin beams at 0.8 and 1.5 μm were prepared experimentally by using a type I above-threshold NOPO [10–12]; 2.5 dB of quantum noise reduction in the intensity difference of the twin beams was observed.

Figure 1 shows the schematic diagram of the experimental setup. The laser source is a homemade 526.5 nm single-frequency continuous wave Nd:YLF/LBO laser with a maximum output power of 770 mW [13]. A faraday isolator was set in the input light of the NOPO to eliminate the backreflection. The NOPO cavity was formed by two cavity mirrors with 30 mm radii of curvature, which are separated by 64 mm. The beam waist of the pump beam is about 50 μm inside the nonlinear crystal. The input coupler was coated for high reflectivity at 0.8 and 1.5 μm and high transmission at 526.5 nm. The output coupler was coated for high reflectivity at 526.5 nm and partial transmission (about 3%) at 0.8 and 1.5 μm. A 20 mm long periodically poled $\mathrm{KTiOPO_4}$ (PPKTP, Raicol Crystals) crystal with a poling period of 9.68 μm was chosen as the nonlinear crystal for its relatively high nonlinear coefficient and room temperature operation. The crystal was oriented such that the pump, signal, and idler beams were all polarized parallel to the c axis and propagated along the a axis. Both end faces of the PPKTP crystal were antireflection coated at 526.5 nm, 0.8 μm, and 1.5 μm. The crystal was put in a temperature-controlled oven with an accuracy of 0.01 °C. In our current experiment, the temperature of the crystal oven was set to 40 °C and the measured wavelengths of the signal and idler beams were 802 and 1533 nm, respectively.

To observe the quantum correlation between the twin beams, a cavity servo-control system was utilized to lock the NOPO cavity. The typical threshold power of the NOPO was 13 mW. The signal and idler beams were separated by a dichroic beam splitter and detected by two homodyne detection systems, which were built from two ETX-500 (Epitaxx) and two FND-100Q (EG&G) photodiodes, respectively. A half-wave plate in front of a polarizing beam splitter acts as a 50/50 beam splitter. The photocurrent signals were recorded using a spectrum analyzer (N9010A, Agilent). For each beam (signal/idler), the noise power of the difference photocurrent signal corresponds to the quantum noise limit (QNL), and the noise power of the sum photocurrent signal corresponds to the intensity noise power. Thus, the difference of the sum (difference) photocurrent signal of each beam corresponds to the intensity difference noise power (the combined QNL) of the twin beams.

Figure 2 is the measured intensity difference noise spectrum at the pump power of 34 mW. The powers of the 1.5 μm signal and 0.8 μm idler are 6.8 and 10 mW, respectively. A maximum of 2.5 dB intensity difference squeezing was observed at a frequency of around 2 MHz. The inferred squeezing was 3.2 dB by subtracting the electronic dark noise of the detectors (8 dB below the QNL). The observed squeezing degraded at high analysis frequencies, and the bandwidth of the squeezing spectrum is limited by the linewidth of the optical parametric oscillator cavity which is 12 MHz in our experiment. The intensity difference noise spectrum of the twin beams from a NOPO above threshold can be given by [14,15]

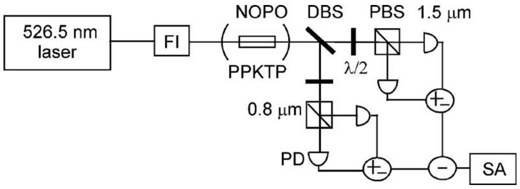

Fig. 1. Schematic diagram of the experimental setup: FI, Faraday isolator; DBS, dichroic beam splitter; PD, photodetectors; PBS, polarizing beam splitter; SA, spectrum analyzer.

$$R(f) = 1 - \eta_D \eta_{\mathrm{OC}} \frac{1}{1 + (f/f_c)^2}, \tag{1}$$

where $R(f)$ is the noise power normalized to the QNL, η_D is the detection efficiency, η_{OC} is the escape efficiency, and f_c is the cavity linewidth. By using the experimental parameters, $\eta_D = 0.76$, $\eta_{\mathrm{OC}} = 0.75$, $f_c = 12$ MHz, $f = 2$ MHz, the theoretical prediction from Eq. (1) is $R(f) = 3.5$ dB, which is in good agreement with the experimental value of 3.2 dB. The squeezing was also investigated for different pump power levels from 28 to 40 mW, and the observed squeezing spectrum was almost the same. That is consistent with the theoretical prediction of Eq. (1). The above analysis suggests that the nonperfect optical detection efficiency and escape efficiency are the main limitations in our experiment. Further experiments will be carried out to optimize these parameters to achieve a higher squeezing level. It should be noted that an above-threshold NOPO could produce entangled twin beams [16,17]. To observe the entanglement between the twin beams in our experiment, the quantum phase correlation properties of the twin beams should be measured. Currently, two analysis cavities for measuring the phase correlation are being built.

In conclusion, intensity quantum correlation between signal and idler beams at 0.8 and 1.5 μm was experimentally observed by using an above-threshold NOPO based on a PPKTP crystal. The two-color cv nonclassical quantum state presented here has potential applications in long-distance quantum information processing. For example, the signal beam can be tuned to 795 nm by adjusting the temperature of the PPKTP crystal and used to excite rubidium atoms which serve as a local quantum memory, and the idler beam at 1.5 μm is suited to low-loss fiber-optic transmission.

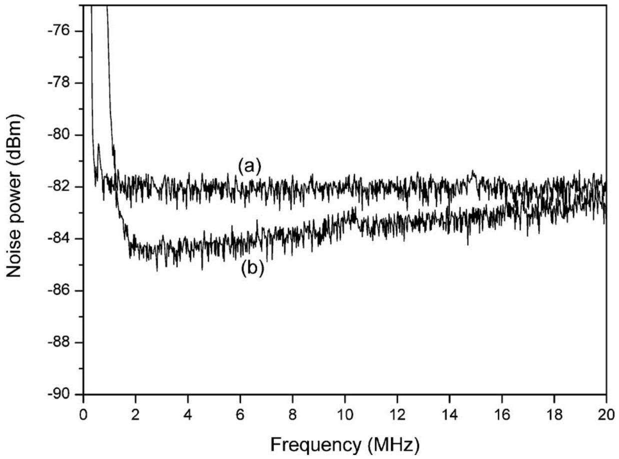

Fig. 2. The observed intensity noise spectrum of the signal and idler beams. (a) is the combined QNL of the signal and idler beams; (b) is the intensity difference noise between the signal and idler beams. The settings of the spectrum analyzer: resolution bandwidth is 100 kHz and video bandwidth is 100 Hz.

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