Transfer of intensity quantum correlation with twin beams

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We demonstrate experimentally a protocol of transferring nonclassical quantum properties using two pairs of quantum-correlated twin beams in the continuous variable regime. The intensity quantum correlation from one twin beam is transferred to two initially independent idler beams with the help of a displacement transformation. It makes two originally independent beams exhibit an intensity quantum correlation of 0.8 dB below shot-noise level. © 2007 Optical Society of America

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The transfer of a quantum state from one subsystem to another subsystem is a prerequisite for quantum communication. One can transfer a quantum state either by the method of teleportation or through quantum networking. The basic idea behind a quantum network is to transfer a quantum state from one node to another node with the help of a carrier (a quantum channel) such that it arrives intact [1]. Quantum teleportation is a popular example of the transfer of quantum states. The initial unknown state of a quantum system can be transferred to another system with the assistance of the entanglement [2–6]. Recently, the quantum network has been developed extensively by transferring and operating a quantum state between different subsystems [7–9]. In the continuous variable regime, the quantum teleportation of squeezed state [10] and entanglement swapping [11] have been demonstrated experimentally. It is significant for the development of quantum repeater and quantum network. However, they all are measurement and transfer of both quadrature amplitude and quadrature phase of light fields simultaneously. It demands that all the light beams in different subsystems are frequency degenerate and classically coherent for measuring the fluctuations of two quadrature components with a balanced homodyne detection system. Thus the experiment process is very complex.

Unlike the measurement of two quadrature components, only the field intensities are measured for the intensity quantum-correlated twin beam generated by a nondegenerate optical parametric oscillator (NOPO). Although this does not involve the transfer of quantum state for the present protocol, the transferred result has shown nonclassical characteristics.

Since the first reported experimental demonstration of the twin beam [12], its application has been studied extensively both in optical measurement beyond the standard quantum limit [13–15] and quantum key distribution [16–18].

A conditional protocol of transferring quantum correlation in the continuous variable (CV) regime was recently demonstrated [19]. A post-selection, proposed originally in the discrete-variable system, was used. To the best of our knowledge, the unconditional intensity quantum correlation transfer of CVs has not been experimentally accomplished so far. Thus it is still a challenge to realize unconditional quantum-correlation transfer without post-selection. In the present Letter, we will report the experimental realization of intensity quantum-correlation transfer.

The correlation transfer scheme is shown schematically in Fig. 1. Two independent NOPOs produce two pairs of twin beams; each pair of twin beams consists of a signal beam (B1 or B3) and an idler beam (B2 or B4) that are intensity quantum correlated and called quantum-correlated twin beams. Both signal beams B1 (from NOPO1) and B3 (from NOPO2) are detected, respectively (D1, D2), and the photocurrent fluctuations are subtracted to drive the amplitude modulator (AM) for the purpose of displacing the idler beam B4 (with a reference beam and a 99/1 beam split, which can change beam B4 perfectly into B2 in ideal conditions) from NOPO2. G is the system gain of the feedback loop. Considering the general conditions that the light powers and the intensity

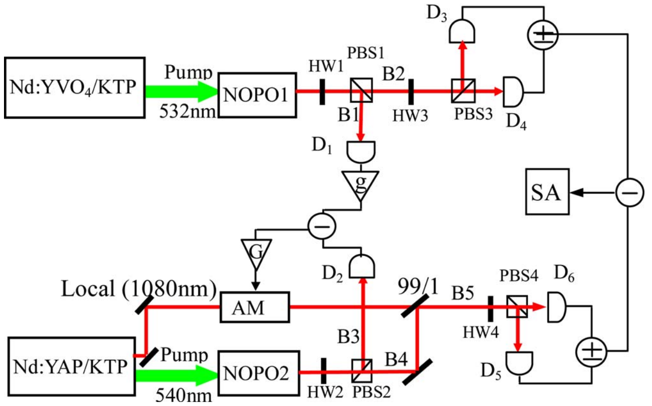

Fig. 1. (Color online) Schematic of experimental setup. NOPO1, NOPO2, nondegenerate optical parametric oscillators; Nd:YVO$_4$/KTP, Nd:YAP/KTP, laser source; HW1–HW4, half-wave plates; PBS1–PBS4, polarizing beam splitters; D$_{1-4}$, photodiode detectors; B1–B5, beams 1–5; AM, amplitude modulator; SA, spectrum analyzer; G, system gain of feedback loop; g, gain factor to balance the currents from D1, D2.

quantum correlations of two twin beams are different, we introduce another gain factor g in one way (hereafter detector D1) to balance the currents from D1 and D2. The amplitude fluctuations of beam B4 after modulation at Fourier frequency Ω become

$$\delta p_5(\Omega) = \delta p_4(\Omega) + G(\Omega)[g(\Omega)\delta p_1(\Omega) - \delta p_3(\Omega)], \quad (1)$$

where $\delta p_1 - \delta p_5$ are the amplitude fluctuations of beams B1–B5, respectively, i.e., the fluctuation of the quadrature component that is in phase with the mean field [20]. $G(\Omega)$ and $g(\Omega)$ are the system transfer functions for mediating the fluctuations transfer, and they correspond to gain G and g, respectively.

The intensity noise spectrum of each beam is related to the amplitude fluctuation through

$$S_i(\Omega) = \langle \delta p_i(-\Omega)\delta p_i(\Omega)\rangle, \qquad i = 1-5, \quad (2)$$

where S_i can be normalized to its shot-noise level (SNL). It means that S_i will be equal to 1 when δp_i is vacuum fluctuation or a coherent state. The quantum correlation of the twin beam can be expressed by the normalized noise spectrum of intensity difference between the twin beam [20]:

$$S_{1-2}(\Omega) = \frac{1}{2}\langle[\delta p_1(-\Omega) - \delta p_2(-\Omega)][\delta p_1(\Omega) - \delta p_2(\Omega)]\rangle, \quad (3)$$

$$S_{3-4}(\Omega) = \frac{1}{2}\langle[\delta p_3(-\Omega) - \delta p_4(-\Omega)][\delta p_3(\Omega) - \delta p_4(\Omega)]\rangle. \quad (4)$$

At optimum case, the intensity difference noise spectrum $S_{5-2}(\Omega)$ at frequency Ω will reach its minimum value:

$$S_{5-2}^{opt}(\Omega) = S_{1-2}(\Omega)\left(1 - \frac{S_{1-2}(\Omega)}{2S_A(\Omega)}\right) + S_{4-3}(\Omega)\left(1 - \frac{S_{4-3}(\Omega)}{2S_B(\Omega)}\right), \quad (5)$$

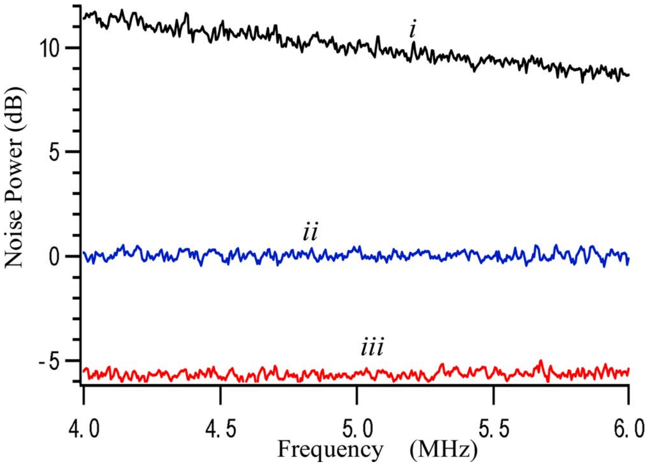

Fig. 2. (Color online) Experimental normalized noise spectrum of intensity difference from NOPO2. Curve *i*, single-beam noise power spectrum; curve *ii*, SNL ($\theta = 22.5°$); and curve *iii*, correlated intensity difference noise spectrum ($\theta = 0°$) of the twin beam from NOPO.

where $S_{1-2}(\Omega)$ and $S_{4-3}(\Omega)$ are two twin beams intensity difference noise spectra, respectively. They both are less than 1 for quantum-correlated twin beams. S_A and S_B are the intensity noise spectra of single beams from the NOPOs output; it is reasonable to assume that the B1 and B2 noise spectra are the same (S_A) and that B3 and B4 are the same (S_B), respectively. If $S_{5-2}^{opt} < 1$, beams B2 and B5 are intensity quantum correlated. In general, S_A and S_B are much greater (~ 10 dB) than the SNL at measurement frequency. The noise spectrum is decided mainly by operation state of the OPO (including the ratio between pump power and OPO threshold, off-resonance of phase, and relaxation oscillation of OPO) [21]. Taking this condition into account, Eq. (5) can be expressed approximately as [22]

$$S_{5-2}^{opt}(\Omega) \approx S_{1-2}(\Omega) + S_{4-3}(\Omega). \quad (6)$$

From the above equation, it is clear that the last result depends mainly on the intensity quantum-correlation level of the quantum-correlated twin beam from both NOPOs. For the two same NOPOs, there will be a quantum correlation between beams B5 and B2 only if there is an average of at least 3 dB of quantum correlation in each twin beam. If there are no quantum correlations in the two twin beams, $S_{5-2}(\Omega)$ will be 3 dB larger than SNL.

The schematic of the experimental setup is shown in Fig. 1. Two homemade intracavity frequency-doubled and frequency-stabilized cw ring lasers (Nd:YVO$_4$ and Nd:YAP) serve as the light source (at 532 and 540 nm). The downconverted modes generated by NOPO1 (NOPO2) are separated by polarizing

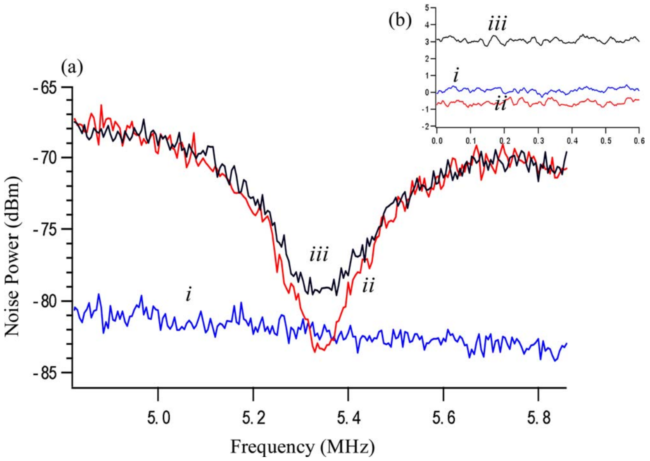

Fig. 3. (Color online) Experimental transferred results. Curve *i*, SNL; curve *ii*, intensity difference noise spectrum between beams B2 and B5 with two quantum-correlated twin beams ($\theta = 0°$); curve *iii*, intensity difference noise spectrum with two quantum-uncorrelated twin beams ($\theta = 22.5°$). (a) Measuring from 4.8 to 6 MHz. (b) Measuring at 5.34 MHz and normalized to shot noise.

beam splitter PBS1 (PBS2) into a signal light B1 (B3) and an idler light B2 (B4). Arms B2 and B4 are measured, respectively, with self-balanced detector systems. It is easy to calibrate the SNL for beams B2 and B4, respectively [23].

The experimentally measured normalized noise spectrum from NOPO2 is shown in Fig. 2. Curve *i* is the single-beam noise power spectrum. Curve *ii* shows the SNL, which is measured with half-wave plate HW1 angle $\theta=22.5°$, and curve *iii* is the intensity difference noise spectrum ($\theta=0°$) of the twin beam from NOPO. The measurement results indicate a quantum correlation of 5.4±0.1 dB from 4 to 6 MHz. The measured correlation is 2.8±0.1 dB for NOPO1. It corresponds to $S_{1-2}=0.52$ and $S_{4-3}=0.29$. The quantum correlation of the twin beams from NOPO2 is better than NOPO1 mainly because of the limited bandwidth of OPO mirrors. The wavelength difference of the twin beam from NOPO1 (1039 and 1089 nm) is much bigger than NOPO2, which operates at near-wavelength degeneration.

The transferred results compared with SNL from 4.8 to 6 MHz are shown in Fig. 3(a). The two balanced detectors are used in two arms to calibrate the SNL of beams B2 and B5, respectively. Curve *i* is the total SNL, which is the summation of the SNL of beam B2 (D3–D4 in Fig. 1) and beam B5 (D5–D6 in Fig. 1). Curve *ii* is the intensity difference noise spectrum between beams B2 and B5 with the condition of quantum correlation transferring ($\theta=0°$ for HW1 and HW2). It is clear that the maximum noise reduction is 0.8 dB (83%) below SNL at a frequency of 5.3 MHz, showing that the transfer of intensity quantum correlation is accomplished successfully. Curve *iii* is the intensity difference noise spectrum with two pairs of quantum-uncorrelated twin beams, where the signal and idler modes of two NOPOs are mixed by PBS1 and PBS2 ($\theta=22.5°$), respectively, *viz*. $S_{1-2}=S_{4-3}=1$, and the minimum noise value of curve *iii* is just 3 dB more than SNL; it is consistent with Eq. (6). The normalized transferred results at 5.3 MHz are shown in Fig. 3(b) in the time domain.

In conclusion, we have experimentally realized the intensity quantum correlation transfer of multilight beams. An intensity difference noise reduction of 17% was observed between the two initially independent beams. The protocol can be used for beams of any wavelength, and there is no limitation of coherence.

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