

## Conditional transfer of quantum correlation in the intensity of twin beams

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A conditional protocol of transferring quantum correlations in a continuous variable regime was experimentally demonstrated. The quantum correlation in two pairs of twin beams, each characterized by intensity-difference squeezing of  $7.0 \pm 0.3$  dB, was transferred to two initially independent idler beams. The quantum-correlation transfer resulted in intensity-difference squeezing of  $4.0 \pm 0.2$  dB between two idler beams. The dependence of the preparation probability and transfer fidelity on the selection bandwidth was also studied.

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The ability to transfer quantum properties from one system to another is a prerequisite for quantum communications. A well-known example is the quantum-state transfer between atoms and photons. Unitary interactions between atoms and photons, such as strong-coupling cavity QED [1] and electromagnetically induced transparency [2], have been employed to transfer an initial quantum state from one subsystem to another subsystem. Quantum frequency conversion is another example, in which the quantum properties of an optical wavelength are transferred to another [3]. A more popular example is quantum teleportation [4]. The initial unknown state of a quantum system can be transferred to another with the assistance of entanglement. All of these protocols are unconditional and demand a lot of effort for experimental realization. Here we demonstrate a simpler protocol, in which quantum correlation of twin beams is conditionally transferred from one pair to another pair by post-selection.

Differing from squeezed states on quadrature amplitudes, the intensity difference noise between signal and idler beams of twin beams is below the shot noise limit; therefore, only the field intensities need to be measured rather than the quadrature amplitudes. Since the first experimental demonstration of twin beams, their generation and application have been studied extensively [5]. Recent investigations have focused on characterizing twin beams in the time domain [6] and conditional preparation of a sub-Poissonian state based on post-selection of twin beams [7]. A more exciting achievement is that ultrastable twin beams have been produced at a precise frequency degeneracy from a nondegenerate optical parametric oscillator (NOPO) operating above its threshold through the use of a new nonlinear crystal and an active phase-lock system [8]. The entanglement state can also be generated by using a self-phase-locked OPO [9]. These reports indicate that the quantum correlation between the two beams of twin beams can be as a testbed for verifying the foundations of the quantum theory in quantum optics and quantum information fields.

Conditional-state preparation, or post-selection, was originally proposed for use in a discrete-variable system. It was widely and successfully used to prepare a single-photon state from quantum-correlated photons (“twin photons”) generated via parametric down-conversion [10]. Quantum correlation between two photons—a signal and a trigger—is the prereq-

uisite for such a general procedure. When a single-photon detector, located in one of the emission channels, registers a single photon, the correlated twin-photon state collapses into a single photon in a well-defined spatiotemporal mode traveling along the other emission channel. This technique has been used in many experiments since it was originally proposed. State collapse is obviously not restricted to the case of photon counting, so it may be interesting to extend this technique to a continuous-variable regime. Continuous detection conditioned by a photon counting event has been implemented in various schemes, such as generation of a “degaussification” state [11], tests of quantum nonlocality [12], entanglement purification [13], and generation of a Schrödinger-cat state. In a cavity QED experiment, conditional measurements of atomic states have also led to the experimental generation of optical states with a well-defined phase [14]. On the other hand, Lvovsky *et al.* [10] prepared a bit of quantum information encoded in a discrete basis conditioned on observation of a continuous observable [15]. The conditional preparation of a nonclassical state of light was also experimentally demonstrated in continuous-variable regime [9,16]. So far, discrete- and continuous-variable quantum information science has developed with some overlap between these two domains. To the best of our knowledge, no scheme has been suggested to transfer quantum properties by the technique of conditional preparation in the continuous variables. This is the purpose of the present paper, in which the degree of quantum correlation  $4.0 \pm 0.2$  dB below the shot-noise limit for the intensity difference resulting from two pairs of twin beams exhibiting 7.0 dB, is transferred using the simple conditional preparation technique.

The experimental setup is outlined in Fig. 1. Two independent quantum-correlated twin beams at 1064 nm were produced by two triply resonant NOPO’s. The NOPO’s were pumped by a diode-pumped cw frequency-doubled Nd:YAG laser. To increase mechanical stability and reduce extra loss, both the OPO1 and OPO2 have a semimonolithic configuration. Each of them consists of a 10-mm-long KTP crystal and concave mirror with a curvature of 20 mm. The input coupler is directly coated on one facet of the KTP crystal. The reflectivity of the input coupler is 90% for the pump (532 nm) and high reflectivity for the signal and idler beams (1064 nm). The output coupler is high reflectivity for the

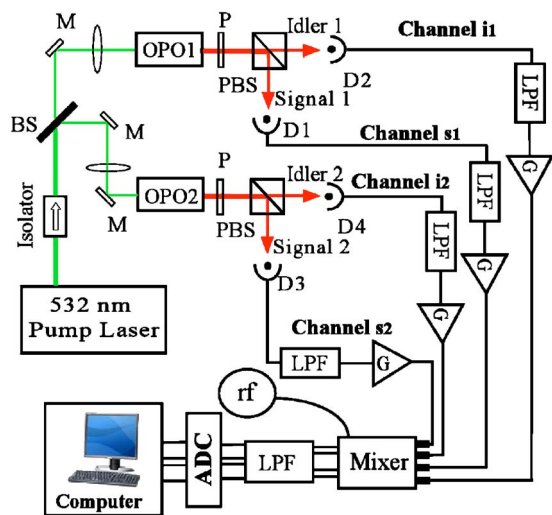


FIG. 1. (Color online) Schematic of experimental setup. OPO, optical parametric oscillator; M, mirror; P, half-wave plate; PBS, polarizing beam splitter; BS, beam splitter; D, photodiodes; LPF, low-pass filter; and G, low-noise electronic amplifier.

pump and its transmission is 5% for the infrared. OPO lengths are actively locked on the pump resonance. For this purpose, the piezoelectric transducer (PZT), on which the output coupler is mounted, is dithered at 100 kHz and the pump light leaking from the cavity is monitored by a photodiode. The error signal was derived by mixing the photocurrent and another 100-kHz rf signal. The error signal is fed back to the PZT after passing through a homemade proportional-integral controller. This kept the cavity length to the triply resonant frequency. At exact triple resonance, the oscillation threshold is less than 10 mW. In particular, at a pump power of 30 mW an output power of 16 mW was obtained. The pump power of the OPO's was adjusted so that the two output twin beams were of equal intensity. The configuration and operating principles of the NOPO's have been described in detail previously [6,19]. Both produce twin beams of 7.0 dB of intensity-difference squeezing at 3.5 MHz as the photocurrent difference measured using a spectrum analyzer. The two pairs of orthogonally polarized twin beams from OPO1 and OPO2 were divided using two polarizing beam splitters (PBS's). The output of the PBS's were directly detected using four balanced high-quantum-efficiency photodiodes. A half-wave plate was inserted before the polarizing beam splitters. It was used to rotate the polarization of the twin beams, which enabled us to measure the shot-noise level [5]. When the polarization of twin beams are rotated by an angle of 0° to the PBS axis, we record the quantum correlation between twin signal and idler beams of twin beams. However, when it is rotated by an angle of 45°, we can record the shot-noise level. To reconfirm the shot-noise level, a coherent light with the same power of the twin beams was input to the other ports of PBS1 and PBS2 (not shown in Fig. 1).

The detection and implementation of the quantum-correlation transfer system was done in the time domain, not in the frequency domain. We accessed the full quantum characterization of the twin beams at a given Fourier frequency

$\Omega$ . Each photocurrent detected by the photodiodes (D1–D4) was amplified by a low-noise 46-dB-gain amplifier after it passed through a 21.4-MHz low-pass filter. The photocurrent was then mixed with an electrical local oscillator of frequency  $\Omega$ . The near-dc region down-converted the frequency output of the mixer was further amplified and filtered using a 100-kHz low-pass filter to prevent the signal from being averaged over a large frequency range. It was then digitized at a sample rate of 200 kHz using a 12-bit, 4-channel acquisition card. To establish the quantum correlation between the two idler lights of two twin beams (channel i1 and channel i2), we simultaneously measured the intensity of the two signal lights of the twin beams. Upon measurement, the two idler beams of the twin beams will collapse into an eigenstate of this observable [7]. When the measurement results of two signal beams have the same values, the two idler states will collapse into the same state. In other words, as we demonstrate below, quantum correlation can be established between the two initially independent idler beams of the two pairs of twin beams if we post-select the events based on the measured results of two signal beams of the two pairs of twin beams (channels s1 and s2).

In the experiments, we first locked both OPO1 and OPO2 on the pump resonance. The OPO's operated stably for more than half an hour without mode hopping. The generated twin beams were measured using a spectrum analyzer in the frequency domain [5] or by mixing the photocurrent with a sinusoidal local oscillator in the time domain [6,7]. Both measurement results indicated a quantum correlation of  $7.0 \pm 0.3$  dB between the signal and idler beams, which were output from both OPO1 or OPO2. Transfer of the quantum correlation between the two idler beams of two pairs of the twin beams was then performed. For each input state, which corresponded to coherent light and twin beams rotated by 45° and 0°, two successive acquisitions (300 000 points for each channel) were acquired, one under conditional selection and the other under unconditional selection.

It is well known that twin beams can be characterized by their joint photon number distribution [17,18]. In the ideal case of a system with no losses, the joint photon number distribution is  $p(n_s, n_i) = 0$ , when  $n_s \neq n_i$ ; however,  $p(n_s, n_i) \neq 0$ , when  $n_s = n_i$ . This means that the idler beam of twin beams will collapse into a perfect  $N$ -photon Fock state when an  $N$ -photon state is detected at the signal beam. Now, supposing a system consists of two pairs of twin beams—in other words, it has joint photon number distributions  $p_1(n_{s1}, n_{i1})$  and  $p_2(n_{s2}, n_{i2})$ —which have the above-mentioned characteristics; the two idler beams will simultaneously collapse into an  $N$ -photon state when  $N$ -photon states are detected at two signal beams of two pairs of twin beams at the same time: i.e.,  $n_{s1} = n_{s2} = N$ . Therefore, the quantum correlation between the two idler beams will be automatically established and the photon number distribution  $p_3(n_{i1}, n_{i2})$  between them will have the above-mentioned characteristics of twin beams. This shows that quantum correlation can be transferred from the system  $(n_{s1(2)}, n_{i1(2)})$  to the system  $(n_{i1}, n_{i2})$ .

In a real experiment, the correlation between the signal and idler beams, which are generated by an OPO, is not

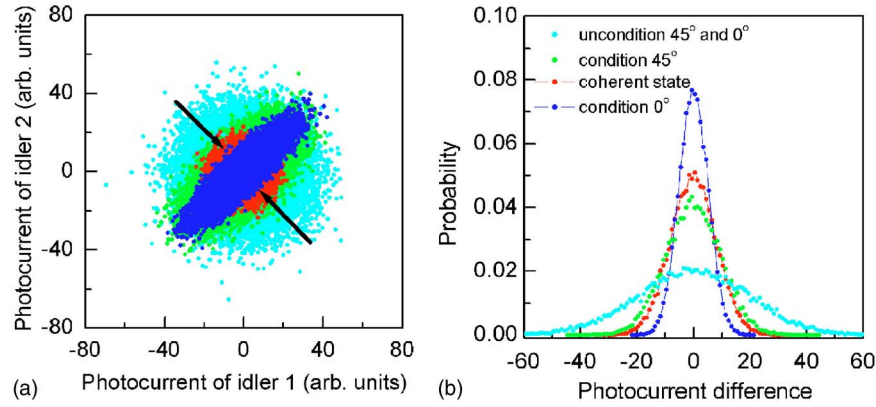


FIG. 2. (Color online) Experimental results: (a) correlation between two idler intensity fluctuations (only 20 000 shown). Cyan points correspond to unconditioned results with input state of twin beams rotated by  $45^\circ$  and  $0^\circ$ ; green points correspond to conditioned results with input state of twin beams rotated by  $45^\circ$ , indicate experimentally measured shot-noise level; red points correspond to conditioned and unconditioned results with input state of the coherent state, indicate the reconfirmed shot-noise level; and blue points correspond to conditioned results of input state with twin beams rotated by  $0^\circ$ , the narrowing distribution of the points indicates the successfully transferred quantum correlation. (b) The conditioned and unconditioned photocurrent difference probabilities with various input states. Selection bandwidth equals  $0.03\delta$ .

perfect, and the Fourier components of the signal and idler intensity quantum fluctuations are correlated only when they lie inside the cavity bandwidth. The imperfect correlation and less-than-unity detection efficiency results in the correlation being characterized by the limited intensity-difference squeezing. In other words, the measured photon number difference fluctuation distribution  $p(n_s - n_i)$  between the signal and idler of twin beams will be narrower than that of two uncorrelated beams [6]. The instantaneous values of the signal and idler photocurrents therefore play a role in the occurrence of counts in a photon counting regime. The conditional preparation is that we select the idler photocurrent only during time intervals when the signal photocurrent satisfies the post-selection conditions (see also [7,20]).

The post-selection process is performed as follows: we first compare the results of measuring the intensity of the two signal beams ( $I_{s1}, I_{s2}$ ). The intensity values of the two idler beams ( $I_{i1}, I_{i2}$ ) are kept only if the difference between intensity values ( $I_{s1} - I_{s2}$ ) have a value of zero (within a band  $\Delta I$  smaller than the photocurrent standard deviation), which means we measured the same state at two signal beams. As we will show, this selection provides quantum-correlation transfer using two pairs of twin beams.

Figure 2 sums up the measurements obtained at a local frequency of  $\Omega = 3.5$  MHz. Figure 2(a) shows the actual recording. Each point corresponds to one simultaneous measurement of the photocurrent fluctuations of two idler beams of two pairs of twin beams. The direction of arrows indicates the correlation between two beams. It is also shown that the recorded photocurrent, when the polarization of twin beams are rotated an angle of  $45^\circ$ , can be as the shot-noise level. As the OPO was pumped above its threshold, the idler and signal beams produced intensity fluctuations, which were much larger than the shot-noise level [6,7]. As expected for twin beams rotated by  $0^\circ$ , a quantum correlation between the two idler beams was established when we post-selected the events based on the measured result of the two signal beams of the two pairs of twin beams. To quantify the amount of

measured quantum correlation between the two idler beams, we determined the variances of the stored data in the photocurrent difference of twin beams normalized to that of coherent state. We calculated the noise variance in the difference between the photocurrent fluctuation of the two idler beams. It reached a value of  $4.0 \pm 0.2$  dB below the shot-noise level [6]. To show the quantum character of the measured distribution, we give the probability distribution in Fig. 2(b). A histogram or probability distribution can be constructed from the data in Fig. 2(a). In the case of conditional and unconditional selection, the probability distributions of photocurrent difference between the channels  $i1$  and  $i2$  corresponding to the coherent state, twin beams rotated by  $45^\circ$  and  $0^\circ$  as input states, are plotted on Fig. 2(b). They were obtained by binning up the data in Fig. 2(a) according to the value of the photocurrent differences between two channels with a bin size much smaller than that of the standard deviation  $\delta$  of a coherent state with the same power [6,7]. The measured dis-

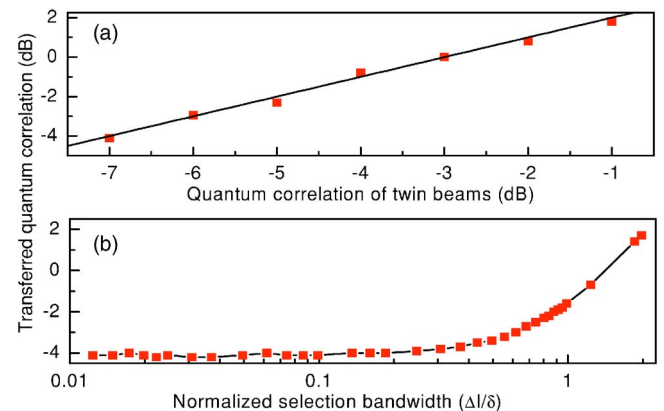


FIG. 3. (Color online) Measured transferred quantum correlation as a function of different values of the correlation of twin beams (a) and selection bandwidth on the trigger light normalized to  $\delta$  (b). In (a), the selection bandwidth is taken to equal  $0.03\delta$ . Squares: experimental data.

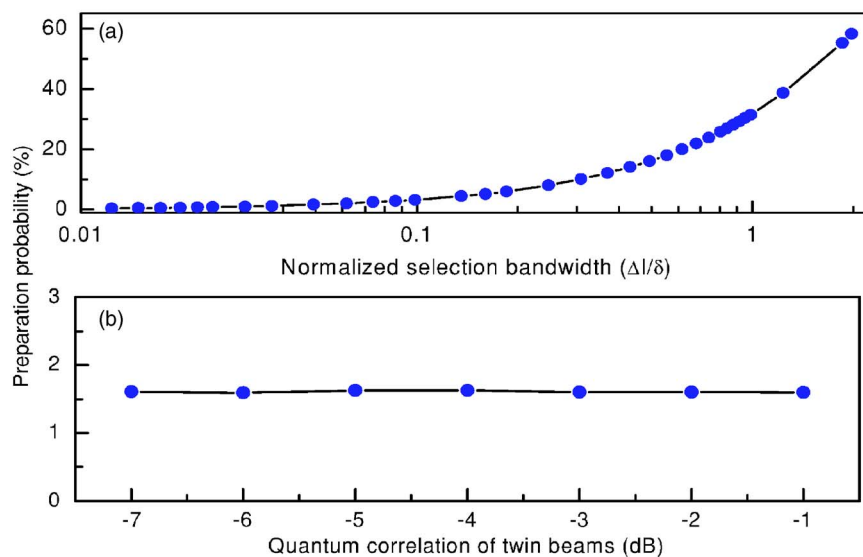


FIG. 4. (Color online) Preparation probability for different normalized selection bandwidths (a) and different values of the correlation of twin beams (b). In (b), the selection bandwidth is taken to equal  $0.03\delta$ . Circles: experimental data.

tribution of photocurrents difference between two idler beams is narrower than that of two coherent states, indicating the realization of quantum-correlation transfer between the two pairs of twin beams.

Just as the same as the case of conditional preparation of a sub-Poissonian state from twin beams [7,9], the transfer fidelity and preparation probability strongly depend on the selection bandwidth ( $\Delta I$ ). The success rate can be improved by increasing the selection bandwidth at the expense of a decrease in the transferred quantum correlation degree (transfer fidelity). In Fig. 3, we give the measured transferred quantum correlation in the conditionally produced transfer as a function of different amounts of quantum correlations of the twin beams [Fig. 3(a)], which can be varied by inserting losses on the OPO beams or rotating the half-wave plate (P), and the selection bandwidth normalized to  $\delta$  [Fig. 3(b)]. All the measured results show that quantum correlation between two idler beams of two independent twin beams was established when the quantum correlation of the twin beams was larger than 3 dB. The fidelity of the transferred quantum correlation was degraded by 3 dB from the initial quantum correlation of twin beams [7]. In the range where  $\Delta I/\delta$  is very small, the quantum correlation transfer is almost constant until the normalized selection bandwidth reaches the order of 0.1. In Fig. 4, we give the preparation probability for different normalized selection bandwidths [Fig. 4(a)] and different amounts of quantum correlation of the twin beams [Fig. 4(b)]. We note that the preparation probability in our experiment is different from that in the experiment of sub-Poissonian-state generation from twin beams [7], because we

selected events based on the classical coincidence between the two original twin beams differing from events which are kept only if signal and idler photocurrent values simultaneously fall inside a narrow band around the preselected mean value in Ref. [7]. In other words, events of idler intensity values around various mean values are selected in our experiment; however, events of idler intensity values around an unitary mean value were selected in a sub-Poissonian-state generation experiment. Due to the post-selection based on the classical coincidence between two independent twin beams, the preparation probability is insensitive to noise reduction of the twin beams.

In conclusion, we achieved a conditional quantum correlation transfer using two pairs of quantum-correlated twin beams initially produced from two OPO's. We studied the influence of the selection bandwidth and noise reduction in the twin beams on the transfer fidelity and preparation probability. This experiment showed that the nonclassical features were transferred using the method of conditional measurement even in a continuous-variable regime. When two OPO's operating at different wavelength ranges are employed, our simple protocol could be used to transfer the quantum correlation between two pairs of twin beams having different wavelengths. The transfer is obviously not restricted to the case of two pairs of twin beams. Using three or more pairs of twin-beam sources, it would be possible to generate multipartite beams with quantum correlation. The experimental protocol described here should thus contribute to the future quantum information and communications in the continuous-variable regime.

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