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Experimental generation of bright two-mode quadrature squeezed light from a narrow-band nondegenerate optical parametric amplifier

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The bright Einsten-Podolsky-Rosen (EPR) beams with the quantum correlations between the quadrature-phase amplitudes of the spatially separated signal and idler beams have been experimentally generated from a cw nondegenerate optical parametric amplifier injected by seed waves with degenerate frequency but orthogonal polarization. The correlation degree of 0.853 ± 0.004 between the quadrature-phase amplitudes of the output entangled beams is directly inferred from the measured quadrature-phase squeezing of the output vacuum squeezed-state light field formed from superposition of the original signal and idler modes. Our theoretical calculation and experimental measurements provide a reliable method to confirm the quadrature phase-squeezing and EPR correlation of bright light field.

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In the end of the 1980s, Reid and Drummond pointed out the possibility of demonstrating the Einstein-Podolsky-Rosen (EPR) paradox [1] via quadrature-phase measurements performed on the two output beams of a nondegenerate optical parametric amplifier (NOPA) [2,3] and then they discussed the correlation in nondegenerate optical parametric oscillator (NOPO) below the threshold of oscillation [4]. For the first time the EPR paradox was demonstrated experimentally for continuous variables by employing a NOPO below the threshold, that can be considered as a NOPA with input of the vacuum state and appreciable gain over a limited bandwidth, in 1992 [5]. The studying interest on the EPR beams is being extensively excited by the successful teleportation experiment of continuous quantum variables [6]. In this experiment, the entangled EPR beams, that were generated by combining two independent squeezed vacuum fields produced from a subthreshold degenerate optical parametric oscillator (DOPO) at a 50/50 beam splitter, play a key role for transforming quantum information. A teleportation scheme with bright squeezed light has been proposed theoretically [7]. Although high intensity correlated twin beams, the intensity difference fluctuation between that is below the standard quantum limit (SQL), have been generated from NOPOs above the threshold by several groups [8–10] and have been applied to the subshot-noise measurements [10,11] and the quantum nondemolition measurement with a nonunity gain of signal [12]; unfortunately the frequencies of twin beams from NOPOs above the threshold are nondegenerate and not easy to be controlled to degenerate, so only the intensity correlation has been realized. Schneider *et al.* generated the bright quadrature-amplitude squeezed light with the degenerate optical parametric amplifier (DOPA) in the case of parametric deamplification [13]. However, the bright EPR beams cannot be produced from a DOPA due to that the degenerate signal and idler modes cannot be separated. So far, the bright quadrature-phase squeezed-light and bright EPR beams have not been realized experimentally. The principal difficulty for these experiments is to control the frequency degeneration of signal and idler modes with perpendicular polarization and complete doubly resonating of two nondegenerate subharmonic modes in a cavity. By injecting frequency-degenerate seed waves into the NOPO below its oscillation threshold (named as narrow-band NOPA) and locking the cavity on the frequency of seed waves, we obtained the bright twin beams with rigorously degenerate frequency and orthogonal polarization, for the first time, to our knowledge. To ensure stable phase squeezing of the NOPA output we actively lock the injected subharmonic signal and harmonic pump field in phase to achieve maximum parametric amplification. The quadrature amplitude squeezing of output vacuum mode formed from superposition of the original signal and idler modes (named superposed mode) is experimentally measured. The phase squeezing of the superposed bright output modes and the quantum correlation between the quadrature phase amplitudes of output bright signal and idler modes are directly inferred. For the bright phase squeezing we are not able to measure it with self-homodyne detection such as for bright amplitude squeezing in Ref. [13], while a local oscillator beam that should be far more intense than the detected signal must be utilized [14]. Usually the intensity of the local beam is ten times that of the signal intensity at least; therefore in the case of ~1 mW bright phase-squeezing light the local beam over 10 mW has to be used. We cannot find the photodiode of high-quantum efficiency for squeezing detection that can operate at such a high-power level. We think that this is the reason why the bright phase squeezing and EPR correlation between bright beams have not been detected experimentally up to now. Our theoretical calculation confirmed certain relations of the variances between the output vacuum field and bright light beams, hence it is reasonable to infer the bright phase squeezing and EPR correlation from the measured phase-sensitive squeezing of output vacuum field. Our calculation and experiment presented an indirect and undoubted path to demonstrate the quantum correlation between bright EPR beams and bright phase squeezing. The technical difficulty of having no appropriate detector was bypassed elegantly and simply. We demonstrate that the frequency-degenerate twin beams from NOPA are the EPR beams that can provide the quantum entanglement required for teleportation of the quantum state, quantum communication, quantum computing, quantum information processing, and experimentally investigating quantum mechanics.

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In this paper we simply present the theoretical analyses about the quantum fluctuation and correlation of output signal and idler beams from NOPA at first, then describe the experimental scheme and give the experimental results.

Ou *et al.* calculated the noise spectra and the degree of the correlation for the output fields from a NOPA below the threshold only with the incoming vacuum noise in detail [15]. We extended the theoretical calculations to the NOPA with the injected seed waves recently [16]. The two superposed modes from NOPA are expressed as

$$d_{+}=\frac{1}{\sqrt{2}}(a_1+a_2),\quad d_{-}=\frac{1}{\sqrt{2}}(a_1-a_2), \tag{1}$$

where a_1 and a_2 stand for the original signal and idler modes. In the case of NOPA, the d_+ mode is the bright coherent squeezed states and the d_- mode is the vacuum squeezed state if the quantity of injected seed waves in a_1 and a_2 are equal and the losses of a_1 and a_2 are balanced; that just is the common pursuit in designing experimental systems and not difficult to meet. In Ref. [16] we calculated the output variances of two quadrature-phase amplitudes $\mathrm{V}(\delta X_{+}^{out},\Omega)$ and $\mathrm{V}(\delta Y_{+}^{out},\Omega)$ for the d_+ modes [see Eqs. (12a) and (12b) in Ref. [16]]; with totally the same method we can also calculate the variances $\mathrm{V}(\delta X_{-}^{out},\Omega)$ and $\mathrm{V}(\delta Y_{-}^{out},\Omega)$ for the d_- mode. If neglecting the noise of the pump field, that is very low at the detection frequency (3 MHz), the calculated results show:

$$\begin{aligned}\mathrm{V}(\delta X_{-}^{out},\Omega)&=\mathrm{V}(\delta Y_{+}^{out},\Omega),\\ \mathrm{V}(\delta Y_{-}^{out},\Omega)&=\mathrm{V}(\delta X_{+}^{out},\Omega).\end{aligned} \tag{2}$$

It means that the variance of the amplitude component of the quadrature-phase amplitudes of the d_- mode is equal to that of the phase component of the d_+ mode and vice versa. Therefore, if the variances of one of the superposed modes has been measured then the variance of the other ones are naturally determined. Due to the above-mentioned technical difficulty in the detection of the phase-sensitive quantum fluctuation for the bright field above 1 mW, we detect the quadrature squeezing of the d_- mode to infer that of the d_+ mode.

It has been well-demonstrated in Ref. [15] that the quadrature-phase amplitudes $X^{(1)}=\frac{1}{2}(a_1+a_1^{\dagger})$ and $Y^{(1)}=\frac{1}{2}i(a_1-a_1^{\dagger})$ of signal modes a_1 and that of idler mode a_2, $X^{(2)}=\frac{1}{2}(a_2+a_2^{\dagger})$ and $Y^{(2)}=\frac{1}{2}i(a_2-a_2^{\dagger})$ are quantum correlated and anticorrelated respectively, i.e., the spectrum variances $\mathrm{V}[(X^{(1)}-X^{(2)}),\Omega]$ and $\mathrm{V}[(Y^{(1)}+Y^{(2)}),\Omega]$ are both smaller than the SQL normalized to 1. From the fluctuation dynamic equations of NOPA with the injected seed waves [Eqs. (4b) and (4c) in Ref. [16]] we can easily demonstrate:

$$\begin{aligned}\mathrm{V}[(X^{(1)}-X^{(2)}),\Omega]=\mathrm{V}[(Y^{(1)}+Y^{(2)}),\Omega]&=2\mathrm{V}(\delta Y_{+}^{\mathrm{out}},\Omega)\\ &=2\mathrm{V}(\delta X_{-}^{\mathrm{out}},\Omega)\end{aligned} \tag{3}$$

which is the same with the Eq. (24) in Ref. [15] derived from the NOPA without the injection except vacuum noise. Thus the degree of correlation between output signal and idler beams can be obtained via the fluctuation spectrum of the quadrature-phase amplitude of output superposed mode d_-. In fact, the correlation in quadrature-phase amplitudes of the two output beams manifests itself as a reduction in fluctuations of the signal and idler quadrature phase amplitude difference. If the fluctuations are below the vacuum fluctuation of one of the beams they are the EPR beams [3]. Since the SQL of the signal beam should be 3 dB less than that of the two beams in the case of balance [10], when the squeezing is more than 3 dB below the SQL of total output, the EPR correlation will be demonstrated.

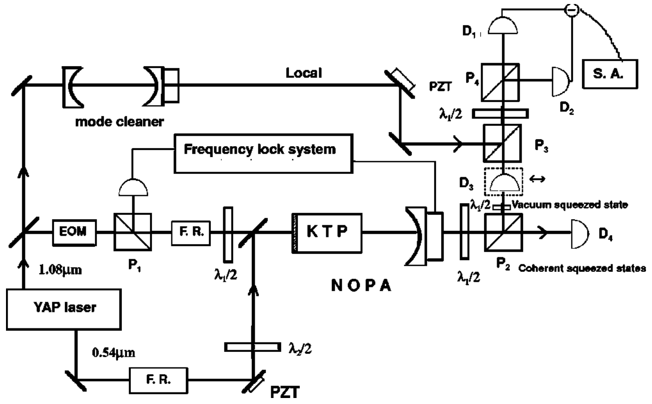

FIG. 1. The experimental setup.

The schematic of the experimental setup is shown in Fig. 1. A home-made intracavity frequency-doubled and frequency-stabilized cw ring Nd:YAP (yttrium-aluminum-perovskite) laser [17] serves as the light source of the pump wave (the second-harmonic wave at 0.54 μm) and the seed wave (the fundamental wave at 1.08 μm) for NOPA. The NOPA with semimonolithic configuration consists of an α-cut type II potassiam titanyl phosphate (KTP) crystal (10 mm long), the front face of which was coated to be used as the input coupler (the transmission $>95\%$ at 0.54 μm and $\sim 0.5\%$ at 1.08 μm) and the other face was coated with the dual-band antireflection at both 1.08 and 0.54 μm, as well as a concave mirror of 50-mm-curvature radius, which is used as the output coupler of EPR beams at 1.08 μm (the transmission of $\sim 5\%$ at 1.08 μm and high reflectivity at 0.54 μm). The output coupler is mounted on a piezoelectric transducer to lock actively the cavity length on resonance with injected seed wave by means of the FM sideband technique. The measured finesse, the free spectral range, and the linewidth of the cavity at 1.08 μm are 90, 2.6 GHz, and 28 MHz, respectively. Total intracavity losses of $\sim 1.3\%$ are estimated. The Faraday rotators (FR), the half-wave plates ($\lambda_1/2$ for 1.08 μm, $\lambda_2/2$ for 0.54 μm) and the polarized beam splitters (P_1–P_4) are used for optical isolation, polarization orientation, and splitting polarized beams. The photodiodes D_1, D_2 (ETX500 InGaAs) and the polarized beam splitter P_4 construct a balanced homodyne detector. The squeezed vacuum from NOPA and the local beam at 1.08 μm from the mode cleaner are mixed at P_3 and then are injected in P_4 at 45° polarization relative to that of P_4. The NOPA is pumped by the harmonic wave of 380 mW at

0.54 μm, that is controlled just below the oscillation threshold of 400 mW, and the polarization of that is along the *b* axis of the KTP crystal. Due to the large transmission (>95%) of input coupler at 0.54 μm, the pump field only passes the cavity twice without resonating. After the seed beam at 1.08 μm polarized at 45° relative to the *b* axis of the KTP crystal is injected into the cavity, it is decomposed to signal and idler seed waves with identical intensity and the orthogonal polarizations along the *b* and *c* axes, respectively, which correspond to the vertical and horizontal polarization. The temperature of KTP crystal placed in a special designed oven is actively controlled around the temperature for achieving type II noncritical phase matching (63 °C) with a broad full width of about 30 °C [18]. An electronic feedback circuit is employed to stabilize actively the temperature of crystal to a few mK.

To obtain the frequency-degenerate and balanced signal and idler output both the *b*- and *c*-polarized waves at 1.08 μm must resonate simultaneously in a cavity. By fine tuning the crystal temperature the birefringence between signal and idler waves in KTP is compensated and the simultaneous resonance in the cavity is reached. The process of adjusting temperature to meet double resonance can be monitored with an oscilloscope during scanning the length of cavity. Once the double resonance is completed the NOPA is locked on the frequency of the injected seed wave via a standard FM-sideband technique [19]. In the case of double resonance, the signal and idler modes are in phase so the bright superposed mode is at 45° polarization with respect to the *b* axis. The polarization of output bright field is rotated 45° to the horizontal direction by a half-wave plate of 22.5 °C relative to the *b* axis just behind NOPA, then the output field passes P_2 and is detected by D_4. If without double resonance, there is no certain phase relation between the output signal and idler modes due to the dispersion effect of two orthogonal polarized modes in crystal, so the output field is similar to a natural light with isotropic polarization, then detectors D_3 and D_4 placed on two output ports of P_2, should receive the identical intensity of light.

Figure 2 is the recorded traces on the oscilloscope during scanning the length of cavity, the upper trace for D_4 and the lower one for D_3. Before the double resonance is met, both traces are in the same very low-voltage level (almost zero), due to the absence of resonant gain and the low transmission (0.5%) of input coupler at 1.08 μm (although the power of injected seed wave before the cavity is about 10 mW). Once the double resonance is completed, all output light is received by D_4 (high peak on upper trace) and nothing by D_3; because of that the scale in Fig. 2 for D_4 (lower) is double that of D_3 (5 mV). These results demonstrate that the output signal and idler modes are frequency degenerate and in phase. Here, we suggested a simple method to check the frequency degeneracy of two subharmonic modes.

To investigate the quantum correlation of the quadrature-phase amplitudes between signal and idler output, the detector D_3 is moved off and the output squeezed vacuum field is detected by the balanced-homodyne detector. Figure 3 shows the phase dependence of the quantum noise in the vacuum squeezed state $[d_-=(1/\sqrt{2})(a_1-a_2)]$ produced from the projection of the output signal and idler fields along the direction at $-45°$ relative to the signal beam polarization (*b* axis). The quadrature-phase amplitude squeezing up to 3.7 ± 0.2 dB is measured under the conditions of propagation efficiency $\sim$4%, detector quantum efficiency $\sim$90% (D_1 and D_2) (corresponding total detection efficiency $\sim$86%) and the homodyne efficiency between two arms $\sim$97%. Blocking the output of NOPA, the noise level of SQL (''0'' line) is obtained. From the other output port of P_2, the bright coherent squeezed state light of $\sim$1 mW is observed. It has been demonstrated in Eq. (2) that the maximum quadrature phase squeezing of the bright output should be also 3.7$\pm$0.2 dB. From Eq. (3) we can directly

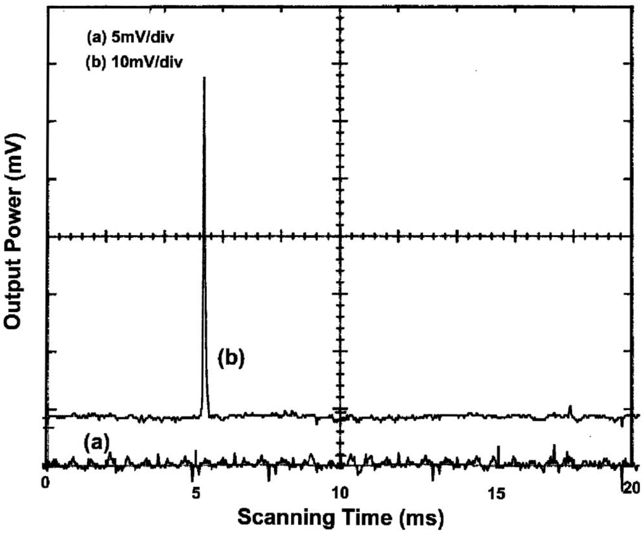

FIG. 2. The output powers received by the detectors D_4 (upper trace) and D_3 (lower trace) during scanning the length of cavity. Scanning speed $\sim$50 Hz.

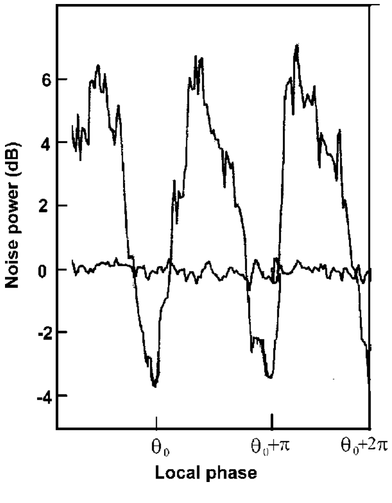

FIG. 3. The phase dependence of the quantum noise in the vacuum squeezed state from NOPA. The ''0'' line stands for the shot-noise limit, analysis frequency $\Omega/2\pi=3$ MHz. The resolution bandwidth and the video bandwidth in this measurement is 300 kHz and 300 Hz, respectively.

infer the quantum correlation between the output signal and idler beams $V((Y^{(1)}+Y^{(2)}),\Omega)=V((X^{(1)}-X^{(2)}),\Omega)=0.853\pm0.004$ which is less than the SQL and meets the requirement of EPR correlation. Rotating back the half-wave plate behind NOPA from 22.5° to 0° relative to the b axis of the KTP crystal, the quantum correlated signal and idler beams will be separated by the polarized beam splitter P_2. In this case the spatially separated bright EPR beams will be available. The noise reduction of ~3.7 dB in the intensity difference between the output signal and idler beam has also been measured by a self-homodyne detector, that directly proves the quantum correlation of intensity. Since the measurement method is totally the same with that for twin beams produced from OPO's above threshold and has been well discussed in the published papers [8–10], we do not pay more attention to it here. But if one has been convinced that the intensity correlated twin beams are frequency degenerate and in phase, the quadrature-phase amplitude squeezing can be inferred from the measured intensity difference squeezing between signal and idler beams with the equalities of Eqs. (2) and (3) as well. The result provides another simple way to infer bright EPR correlation and phase squeezing.

In conclusion, we have experimentally generated bright EPR beams with a NOPA injected by the seed waves. The correlation between the quadrature-phase amplitudes of two output EPR beams is inferred from the measured quadrature amplitude squeezing of the output superposed-vacuum mode (d_-). The presented way of inferring the phase squeezing and EPR correlation of the bright field from the measurement for the squeezed vacuum field, resolves the technical difficulty in these types of experiments. The bright EPR beams are the frequency-degenerate twin beams with both intensity and phase quantum correlation, which can be utilized in subshot-noise precision measurement, quantum communication, teleportation of quantum state, and so on. In our system, the cavity length is slaved to the injected seed wave, thus the stability of operation of NOPA is better than NOPO without the injection, which is favorable for practical applications.

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