Experimental demonstration of quantum entanglement between frequency-nondegenerate optical twin beams

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The quantum entanglement of amplitude and phase quadratures between two intense optical beams with a total intensity of 22 mW and a frequency difference of 1 nm, which are produced from an optical parametric oscillator operating above threshold, is experimentally demonstrated with two sets of unbalanced Mach–Zehnder interferometers. The measured quantum correlations of intensity and phase are in reasonable agreement with the results calculated based on a semiclassical analysis of the noise characteristics given by Fabre *et al.* [J. Phys. (France) **50**, 1209 (1989)]. © 2006 Optical Society of America

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In recent years quantum information with continuous variables has been extensively investigated.[1] The existence of entanglement between amplitude and phase quadratures of intense signal and idler modes (named twin beams) produced from an optical parametric oscillator (OPO) operating above threshold was theoretically predicted by Reid and Drummond[2] in 1988 and then was successively analyzed with detailed theoretical calculations.[3–6] In particular, Fabre *et al.* presented useful expressions for calculating quantum correlations of amplitude and phase components between output twin beams from a nondegenerate OPO (NOPO) above threshold by means of a semiclassical analysis of noise characteristics.[4] The noise spectra of the intensity difference $S_I(f)$ and the phase sum $S_P(f)$ of twin beams are expressed, respectively, by

$$S_I(f) = S_0\left[1 - \frac{\eta\xi}{1 + (f/B)^2}\right], \tag{1}$$

$$S_P(f) = S_0\left[1 - \frac{\eta\xi}{\sigma^2 + (f/B)^2}\right], \tag{2}$$

where f is the noise frequency, S_0 is the shot-noise limit (SNL), B and ξ $[=T/(T+\delta)]$ are the cavity bandwidth and the output coupling efficiency, respectively, of the NOPO (T is the transmission coefficient of the output coupling mirror and δ is extra intracavity loss), η is the detection efficiency, and $\sigma(=\sqrt{P/P_0})$ is the pump parameter (P is the pump power and P_0 is the threshold pump power of the NOPO). The intensity difference quantum correlations of twin beams were measured experimentally with self-homodyne detectors by several groups of scientists and were effectively applied.[7–12] However, phase correlation of the twin beams was not observed for a long time owing to technical difficulty in measuring the phase noise of twin beams with nondegenerate frequencies. Until recently Laurat *et al.*[11] forced the NOPO to oscillate in a strict frequency-degenerate situation by inserting a $\lambda/4$ plate inside the NOPO and observed a 3 dB phase-sum variance above the SNL.[13] Later, 0.8 dB phase correlation below the SNL ($\Delta^2\hat{q}_+=0.82$) between twin beams with different frequencies from a NOPO for a pump power of ~4% above threshold was measured by Villar *et al.* by scanning a pair of tunable ring analysis cavities.[14] At almost the same time, we were also devoting our efforts to measuring the quantum entanglement of twin beams from a NOPO above threshold. The measurement scheme used by us is basically the same as that described by Glöckl *et al.*,[15] who performed sub-shot-noise measurement of the phase quadratures of intense pulsed light.[16] Because the phase correlation will be significantly affected by the phase fluctuation of the pump laser,[6] and as the condition for deducing Eqs. (1) and (2) of Ref. 4 requires a finesse of the NOPO cavity for the pump laser that is much lower than that for the twin beams, in our design the ratio of the cavity finesses for the pump and the twin beams is 16:164, which is much smaller than those in Refs. 13 and 14. Because of the lower finesse, the resonant peak of the pump laser in the cavity is relatively flat, and thus the threshold power is higher (~120 mW).

First, using a pair of Mach–Zehnder (M-Z) interferometers with unbalanced arm lengths, we detected the amplitude and phase noise of signal and idler output fields from a NOPO above threshold at an analysis frequency of 20 MHz. Then the quantum correlations were defined by the noise levels of the intensity difference and the phase sum of the photocurrents measured by two unbalanced interferometers. For an unbalanced M-Z interferometer, when the relative optical phase shift (φ) between two optical fields that pass through the short arm of length L and through the long arm of length $L + \Delta L$ is adjusted to $\varphi=\pi/2+2k\pi$ (k an integer), and at the same time the phase shift (θ) of the spectral component of rf fluctuations at a sideband frequency ($\Omega=2\pi f$) is controlled to $\theta=\pi$, the fluctuations of the sum and the difference photocurrents of two output fields from the M-Z interferometer in frequency space are proportional to the vacuum noise level and the spectral

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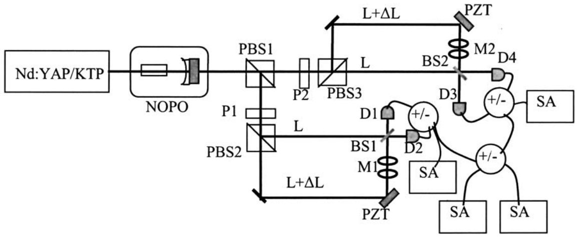

Fig. 1. Schematic of the experimental setup: Nd:YAP/KTP, laser source; +/−, positive–negative power combiner; D1–D4 ETX500 InGaAs photodiode detectors; SA's, spectrum analyzers, other abbreviations defined in text.

component of the phase quadrature of the initial fields, respectively.[15] Therefore, to measure the phase fluctuation of the input field, one should take the difference in length ΔL between the short and the long arms as $\Delta L = c\pi/\Omega$ (c is the speed of light) to meet the condition $\theta = \Omega \Delta L/c = \pi$.

The experimental system for the entanglement measurements is depicted in Fig. 1. The NOPO consists of a 10 mm long α-cut type II $KTiOPO_4$ (potassium titanyl phosphate, KTP) crystal and a concave mirror of 30 mm curvature. The front face of KTP is coated to be used as the input coupler of the pump laser at 540 nm, which is produced from a homemade frequency-doubled and frequency-stabilized Nd:YAP/KTP [Nd-doped $YAlO_3$ (perovskite) KTP] laser.[17] The concave mirror, with a transmission of 3.2% at 1080 nm wavelength, is the output coupler of the twin beams. The mirror is mounted upon a piezoelectric transducer (PZT) for actively locking the cavity length of the NOPO on resonance with the pump laser. The measured cavity finesse for 1080 nm is ~164, and the total intracavity extra loss is ~0.6%; thus the output coupling efficiency ξ is 84%. First the twin beams with cross-polarized directions are separated by polarizing beam splitter PBS1, and then each of them is directed into an unbalanced M-Z interferometer. The 50/50 beam splitters, BS1 and BS2, are the output mirrors of the two interferometers. The output optical fields are detected by a balanced detection system consisting of high-efficiency photodiodes D1 and D2 (D3 and D4). The input beam splitter of the interferometer is made from polarizing beam splitter PBS2 (PBS3) and λ/2 wave plate P1 (P2). By rotating the polarization orientation of P1 (P2) we can conveniently switch between phase and amplitude measurements.[15] In our system, the difference in length of two arms, ΔL, is 7.5 m, which matches the analysis frequency of 20 MHz to make $\theta = \pi$. The difference in the dc photocurrents D1 and D2 (D3 and D4) serves as the error signal and is fed back onto the piezoelectric transducer mounted on one of the mirrors of the interferometer to stabilize the relative optical phase between the two arms at $\varphi = \pi/2 + 2k\pi$. A set of optical lenses M1 (M2) in the interferometer is used for mode matching two beams, one from the short and one from the long arm, on BS1 (BS2). The variances of the output photocurrent fluctuations of two interferometers were recorded by a pair of spectrum analyzers, and then the correlation variances of amplitude and phase quadratures between the twin beams were denoted by the difference and the sum of the corresponding photocurrents from each interferometer. For demonstrating the quantum entanglement of twin beams, pump power P of the NOPO is kept at 230 mW, which is 110 mW higher than the oscillation threshold power ($P_0 = 120$ mW) during all the measurements. Although the phase correlation should be better for the pump power close to the threshold [Eq. (2)], we found that the NOPO with lower finesse for the pump laser could operate stably only when a higher pump power, at approximately twice the threshold, was used, and the output was highly unstable, when the pump power approached the threshold. We believe that the reason for these results is that the multiple modes can oscillate simultaneously in the NOPO with the low finesse of the pump laser owing to its flat resonance peak, thus mode competition and mode hoping must induce instability. When the pump power is increased, once the oscillation of a twin-beam mode dominates in the NOPO, the output will be stable. Under the operating condition, the detected output power of the twin beams is 22 mW, which experimentally has produced the most intense entangled beams to our knowledge. The measured wavelengths of the

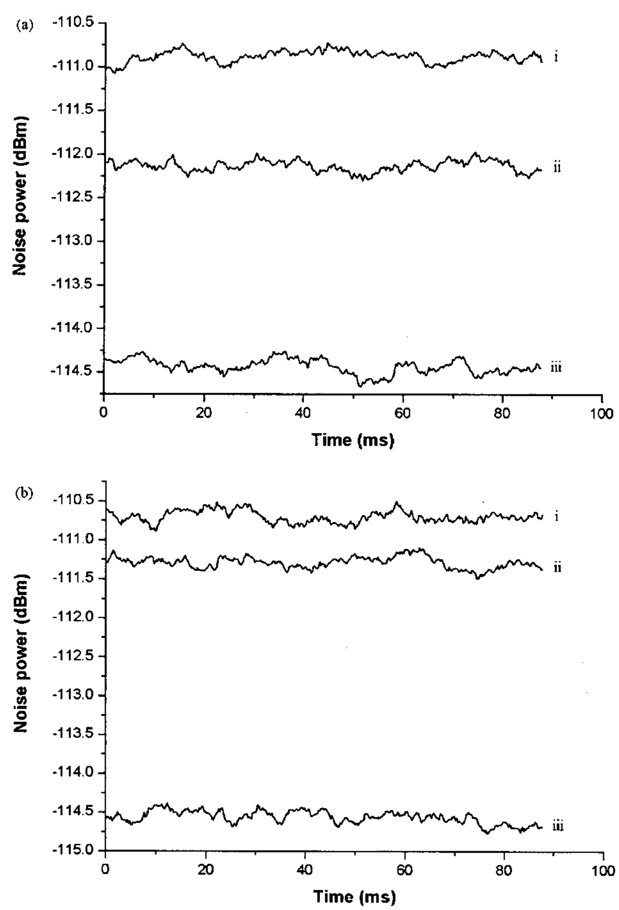

Fig. 2. (a) Amplitude and (b) phase correlation noise powers of twin beams at 20 MHz. i, SNL; ii, correlation noise; iii, electronics noise limit. Measurement parameters of the spectrum analyzer: resolution bandwidth, 10 kHz; video bandwidth, 30 Hz.

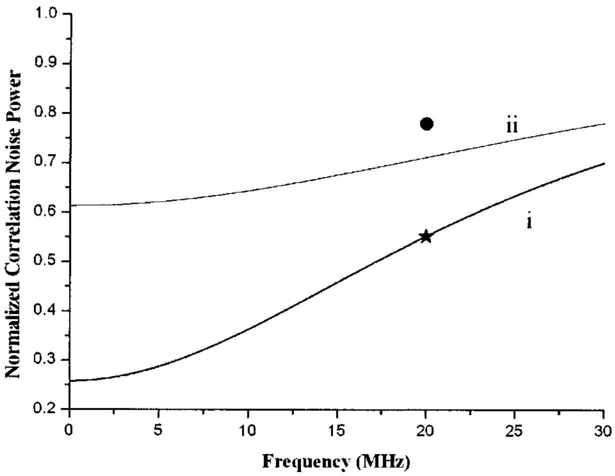

Fig. 3. Normalized noise power spectra of i, amplitude difference and ii, phase sum calculated from theoretical analysis. Star and filled circle, experimental values for amplitude (0.55, corresponding to 2.58 dB below the SNL) and phase (0.78, corresponding to 1.05 dB below the SNL) correlation, respectively.

signal and the idler beams are 1080.215 and 1079.130 nm, respectively ($\Delta\lambda = 1.085$ nm).

The differences between the two amplitude noise powers and the sum of the two phase noise powers are given in Fig. 2(a), trace ii and Fig. 2(b), trace ii, respectively. The correlation variances of the intensity difference and the phase sum between the twin beams are below the SNLs of twin beams [traces i in Figs. 2(a) and 2(b)] of 1.25 ± 0.06 and 0.60 ± 0.07 dB, respectively. After accounting for the influences of the electronics noise of ~3.9 dB below the SNL the correlations of amplitude and phase quadratures should be ~2.58 and ~1.05 dB, respectively, below the SNL. The sum of the correlation variances of the amplitude (X) and the phase (Y) quadratures of the twin beams is

$$\left\langle \delta\left(\frac{X_1 - X_2}{\sqrt{2}}\right)^2 \right\rangle + \left\langle \delta\left(\frac{Y_1 + Y_2}{\sqrt{2}}\right)^2 \right\rangle = 1.332,$$

which is less than the SNL normalized to 1 for each combination of quadratures (the SNL of both twin beams is 2).[14] Thus the quantum entanglement between the signal and the idler optical beams with nondegenerate frequencies generated from a NOPO above threshold is experimentally proved in accordance with the inseparability criterion proposed by Duan *et al.*[18]

Figure 3 gives the normalized noise power spectra of the intensity difference (trace i) and the phase sum (trace ii) calculated from Eqs. (1) and (2) by use of the parameters of the real experimental system ($\xi = 0.84$, $B = 24.7$ MHz, $\sigma = 1.38$, $\eta = 0.88$). The normalized correlation variances measured at 20 MHz (Fig. 2) are marked in Fig. 3 by a star for amplitude and by a filled circle for phase. The experimental values are in reasonable agreement with the calculated results. The measured phase correlation noise is higher by 0.08 than that of the theoretical calculation because the imperfect mode-matching efficiency between the two beams from the short and long arms of the interferometer and the influence of the phase fluctuation of the pump field are not involved in Eq. (2). The measured mode-matching efficiency is ~90%, which introduces extra noise of ~0.03 in the phase quadratures.[19] The remaining excessive noise of ~0.05 may come from the pump fluctuation, perhaps.

In conclusion, we have experimentally demonstrated the quantum entanglement of frequency-nondegenerate twin beams produced from a continuous wave NOPO operating above threshold by use of a pair of unbalanced M-Z interferometers. The twin beams with high mean intensities of 22 mW can easily be manipulated and utilized; therefore the scheme presented can be conveniently applied in future quantum communication with continuous variables.

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