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Experimental investigation about the influence of pump phase noise on phase-correlation of output optical fields from a non-degenerate parametric oscillator

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Abstract – The influence of the phase fluctuation of the pump laser on the phase correlation between the signal and idler modes of the output fields from a non-degenerate optical parametric oscillator operating above oscillation threshold was experimentally investigated. The noise spectra of the intensity-difference and the phase-sum of the entangled optical beams were measured with a pair of unbalanced fiber Mach-Zehnder interferometers specifically designed. The experimental results prove the previous theoretical prediction and are in reasonable agreement with the calculation based on semiclassical theory involving the phase fluctuation of pump laser.

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Optical parametric oscillators both degenerate (DOPO) and nondegenerate (NOPO) have been one of the most important entanglement sources in the quantum information of continuous variables (CV) [1]. As a useful tool in quantum optics for the generation of nonclassical states of light, the quantum fluctuation characteristics of the output fields from OPO have been extensively studied since the late 1980s. Firstly Reid and Drummond theoretically predicted that the signal and idler optical modes produced from NOPO operating above or below the oscillation threshold are in an entangled state with the quantum correlation of amplitude and phase quadratures [2–5]. In 1992, the CV entanglement of optical modes was experimentally demonstrated by Ou *et al.* with a NOPO below threshold [6]. Although the quantum correlation of amplitude quadratures between intense signal and idler from above-threshold NOPO (named twin beams) was measured experimentally and effectively applied by several groups [7–12], the phase correlation of the twin beams with nondegenerate frequencies was not observed for a long time. For measuring the phase correlation of twin beams using general homodyning detector, Laurat *et al.* 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 shot-noise-limit (SNL) [13]. Then, in 2005 CV entanglement of frequency-nondegenerate twin beams was experimentally measured by two groups with scanning a pair of tunable ring analysis cavities [14] or with two sets of unbalanced Mach-Zehnder (M-Z) interferometers [15], respectively. In 2006 the entangled twin beams with stable frequency difference was obtained by Pfister's group [16]. However, those experimentally measured phase-correlations were always smaller than that of the theoretical prediction. At the end of 1980s, Fabre *et al.* presented the expressions for calculating quantum correlations of amplitude and phase quadratures between twin beams [17], in which the pump laser was regarded as an ideal coherent state thus the influence of the pump excess phase noise on entanglement of twin beams was not considered. In fig. 3 of ref. [15] achieved by our group before, we compared the normalized noise power spectra of the intensity difference and the phase sum calculated from the expressions given in ref. [17] and the experimentally measured values, which showed that the measured value of the intensity difference perfectly agreed with that calculated theoretically but the measured phase correlation noise was higher by 0.08 than the calculated values. Earlier, Reid and Drummond theoretically proved that a correlation between signal and idler phase diffusion existed and hence that the sum-phase

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fluctuations are not affected by this noise [4]. To explain why the experimentally measured phase-correlation of twin beams were always less than the theoretical values, the influence of the excess phase noise of the pump laser was recently considered in the theoretical calculations [18–21]. All calculations show that the excess phase noise of the pump laser will reduce the phase correlation of twin beams and will not influence the intensity correlation. So far, to the best of our knowledge there is no experimental demonstration on this effect. In this paper we present the first experimental study on the influence of the excess pump phase noise to the phase-correlation of twin beams. For directly comparing with theory, we derived a formula of the intensity-difference (S_p) and the phase-sum (S_q) noise spectra between output signal and idler of NOPO with the semiclassical method used in ref. [17], but in our calculation the excess phase noise of the pump laser, $E(\omega)$, is involved:

$$S_p(\omega) = 1 - \eta \frac{TT'}{T'^2 + \omega^2\tau^2}, \quad (1)$$

$$S_q(\omega) = 1 - \eta' \frac{TT'}{T'^2\sigma^2 + \omega^2\tau^2} + \eta' \frac{2TT'(\sigma - 1)}{T'^2\sigma^2 + \omega^2\tau^2} E(\omega), \quad (2)$$

where η and η' are the transmission efficiency for the intensity and phase correlation measurement, respectively; $T' = T + \delta$, T is the transmission coefficient of the output mirror of the NOPO and δ is the extra intracavity loss in the NOPO; $\sigma = (P/P_0)^{1/2}$ is the pump parameter (P : the pump power, P_0 : the threshold pump power of the NOPO); ω is the analysis circular frequency in the range of radio frequency (rf); τ is the round-trip flying time of photons in the optical cavity. The detailed theoretical analyses on this subject have been presented in another publication of ours, ref. [22]. Equations (1) and (2) were deduced under the condition that the finesse of the NOPO cavity for the pump laser is much smaller than the finesse for the signal and idler beams as that used in ref. [17].

The measurement scheme and principle of the phase fluctuation using an unbalanced M-Z interferometer are the same as that presented by Glöckl *et al.* originally [23]. According to the requirement in ref. [23], for measuring the phase fluctuation of the input field of the interferometer the difference in length between the short and the long arms of the unbalanced interferometer (ΔL) should be equal to $c/(2fn)$, where f is the analysis frequency, c is the light velocity in vacuum and n is the refraction index of the transmission medium. As that shown in eqs. (1) and (2), the quantum fluctuation of the intensity difference and the phase sum decrease when the analysis circular frequency (ω) is lower for a given NOPO. It means that the quantum correlation of twin beams is higher at lower analysis frequency. For measuring the phase correlation of twin beams at the different analysis frequency conveniently, we constructed a pair of unbalanced fiber M-Z interferometers with totally equivalent elements. The length of the short arm of the interferometers is fixed at 2 m and that of

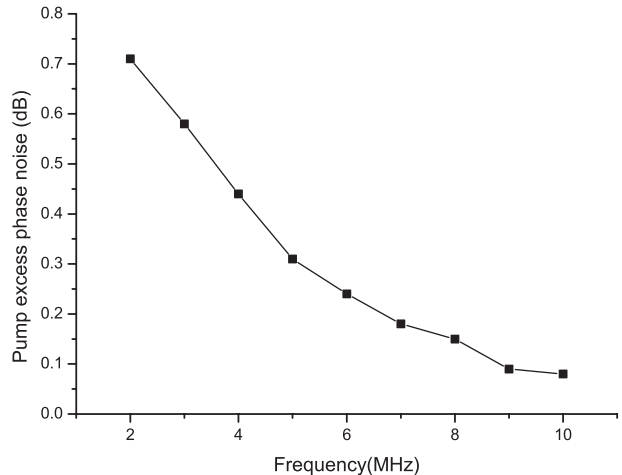


Fig. 1: The excess phase noises of the initial pump laser at different analysis frequencies.

the long arm can be selected among 50 m, 21 m and 12 m, which correspond to the requirement for the analysis frequencies of 2 MHz, 5 MHz and 10 MHz, respectively. The refraction index of the fiber equals 1.55. In order to study quantitatively the influence of the excess pump phase noise on the phase correlation of twin beams, a phase modulator is placed in the optical path of the pump laser before NOPO. The given modulation intensity stands for a certain excess white phase noise of pump laser.

Firstly, the phase noise of the pump laser is measured. For measuring the initial phase noises of the pump laser, an optical cavity was used, which projected phase quadrature fluctuations into easily measurable amplitude quadrature fluctuations [16,24,25]. The optical cavity used in the experiment was an one-ended empty Fabry-Pérot cavity consisting of two concave mirrors with 100 mm radius of curvature. The transmittance of the input-output mirror at the wavelength of pump laser (540 nm) was 2.1% and the other mirror was less than 0.01%. The input and output light beams were separated by a $\lambda/4$ -wave plate and a polarizing beam splitter placed before the input-output mirror of the optical cavity [25]. The phase noises of the initial pump laser without the additional excess noises measured at different analysis frequencies are shown in fig. 1. The phase noise decreases as the analysis frequencies increase from 2 MHz to 10 MHz. The highest noise at 2 MHz is about 0.7 dB above the SNL (zero line) and the lowest one at 10 MHz is less than 0.1 dB above the SNL. It means that the phase noise of the initial pump laser is not at the SNL, thus the investigation to the influence of the excess pump phase noise is significant.

Figure 2 is the schematic of the unbalanced M-Z fiber interferometer which consists of a polarizing beam splitter (PBS), two reflection mirrors (M_1 and M_2), and a 50/50 optical beam splitter (M_3). The short and long fibers with input and output fiber couplers (FC) constitute the short and long arms of the interferometer. The half-wave plates HWP_1 and HWP_2 are used for aligning the polarization

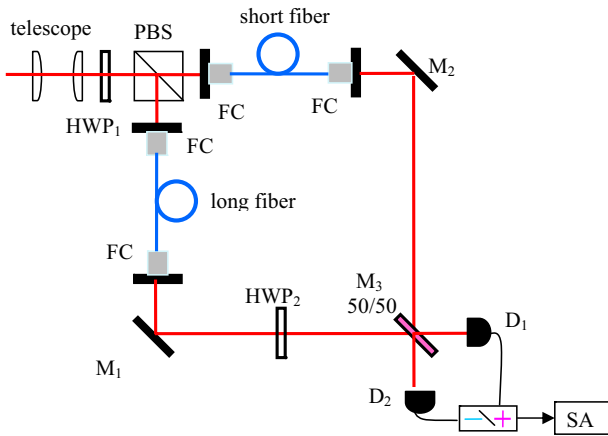


Fig. 2: Schematic of the fiber M-Z interferometer. PBS: polarization beam splitter; FC: fiber coupler; HWP₁₋₂: half-wave plate; telescope: lenses combination; M₁₋₂: mirror with high reflectivity; M₃: 50/50 beam splitter; D₁₋₂: photo-detector; +/-: positive and negative power combiners; SA: spectrum analyzer.

direction of light relative to PBS and that between two arms, respectively. The output optical fields from M₃ are detected by a balanced detection system consisting of high-efficiency photodiodes (D₁ and D₂). The sum and difference of the photocurrents detected by D₁ and D₂ can be achieved with the positive and negative power combiners (+/-), respectively. If aligning the polarization of input light with HWP₁ to make total input light pass only through the short fiber, in this case, M₃, D₁ and D₂ play a role of general balanced detector, thus the sum and difference photocurrents give the amplitude noise level and the SNL of the input light, respectively [15,23]. By splitting the input light equally to the two arms of the interferometer and adjusting the phase difference between the two optical beams passing through the short and long arms to $\pi/2$, the difference photocurrent corresponds to the phase noise level of the input light and the sum photocurrent stands for the SNL [15,23]. The measured losses of both short and long arms are about 22% which mainly come from the losses of the fiber couplers. The loss in the fiber can be neglected, thus the losses in two arms are almost equivalent.

The experimental system is shown in fig. 3. The pump laser at 540 nm wavelength is produced from a homemade CV-frequency-doubled and frequency-stabilized Nd:YAP/KTP laser (Nd:YAP-Nd-doped YAlO₃ perovskite, KTP-potassium titanyl phosphate) [26]. The semi-monolithic NOPO consists of an α -cut type-II phase-matching KTP crystal and an output coupler which is a concave mirror of 50 mm curvature with high reflectivity at 540 nm and the transmission coefficient of 3.2% at 1080 nm. The front face of KTP is coated to be used as the input coupler of the NOPO with the reflectivity of 39% at 540 nm and high reflectivity at 1080 nm. The other face is coated with the antireflective

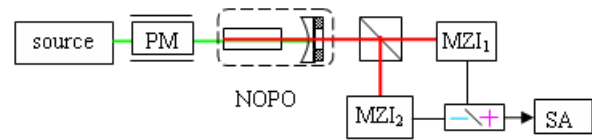


Fig. 3: Experimental set-up. PM: phase modulator; MZI₁₋₂: M-Z interferometer; +/-: positive and negative power combiner; SA: spectrum analyzer.

film at both wavelengths at 540 nm and 1080 nm to reduce the intracavity loss. The output coupler is mounted on 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 150, and the total intracavity extra loss is about 1%. The twin beams with cross-polarized directions are produced in the NOPO through a nonlinear optical process of frequency down-conversion. The output signal and idler beams are separated by the polarizing beam splitter (PBS), and then each of them is directed into an unbalanced M-Z interferometer (MZI₁ and MZI₂). The difference and the sum photocurrents are analyzed and recorded by the spectrum analyzer (SA). In the system, two of the three spectrum analyzers are used in MZI₁ and MZI₂, and the other one for the final measurements of the photocurrent combinations [15].

During all measurements the pump power of the NOPO is kept at 194 mW, which is 64 mW higher than the oscillation threshold power of ≈ 130 mW. Although the phase correlation should be better for the pump power close to the threshold according to the theoretical calculation [2,7], we found in experiments that the NOPO with lower finesse of the pump laser could operate stably only when a higher pump power was used. The highly unstable output from the NOPO was observed 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 low finesse of the pump laser owing to its flat resonance peak, thus mode competition and mode hopping 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 pump power of 194 mW the detected output power of the twin beams is about 20 mW.

In the experiment, at first the amplitude and phase noise spectra of the signal and idler modes are measured by MZI₁ and MZI₂, respectively. Then, the quantum correlations of twin beams are defined by the noise levels of the intensity difference and the phase sum of the photocurrents measured by the two interferometers. Figures 4(a), (b) and (c) are the measured quantum correlation variances of the signal and idler beams at 2 MHz, 5 MHz and 10 MHz, respectively, in which three different lengths (50 m, 21 m and 12 m) of the long arms of two interferometers are used, respectively, to meet the

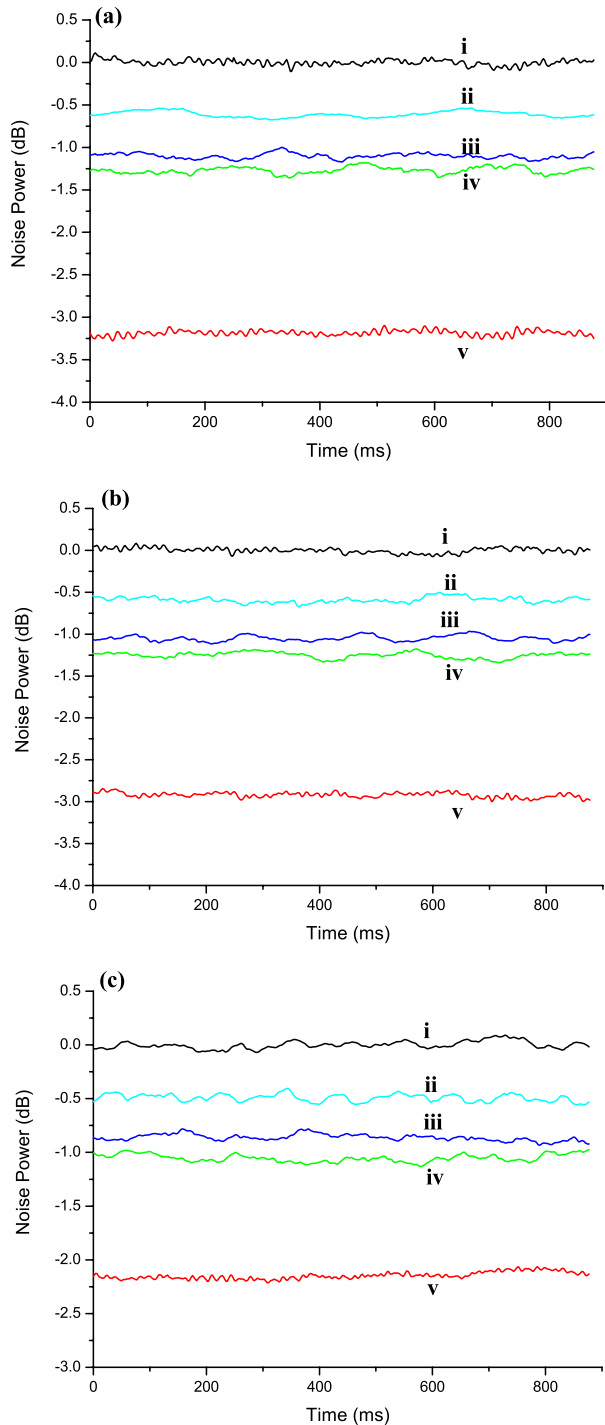


Fig. 4: Noise spectrum of quantum correlations at 2 MHz (a), 5 MHz (b) and 10 MHz (c). i: SNL; ii: the phase correlation noise power with 1.00 excess phase noise; iii: the phase correlation noise power with 0.33 excess phase noise; iv: the noise power of the phase correlation; v: the noise power of the intensity difference.

requirement of the phase correlation measurement at three different analysis frequencies as mentioned before. In the three figures, trace i, v and iv correspond to the SNL of the twin beams, the noise powers of the intensity-difference and the phase-sum under the situation without adding

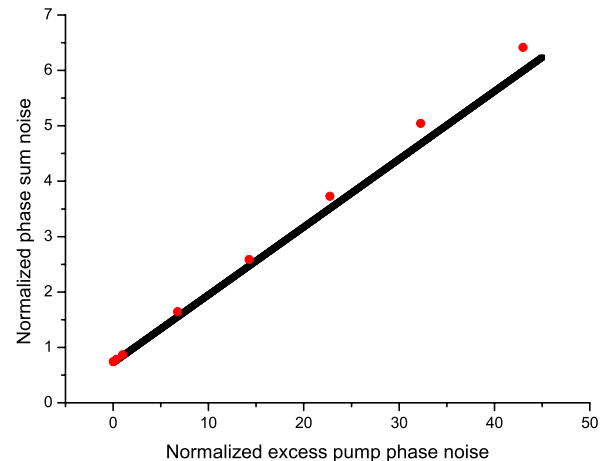


Fig. 5: Phase sum noise at 2 MHz *vs.* excess pump phase noise. The values of horizontal and vertical axes are relative to SNL. The straight line is the theoretical curve corresponding to eq. (2) calculated with the experimental parameters. The dots are experimentally measured data points.

excess phase noise on the pump laser, respectively. When the excess pump phase noise is increased to 0.33 or 1.00 with a phase modulator, the phase correlation noise power increases from iv to iii (0.33) or ii (1.00). As that predicted by theory [17–21], the intensity-correlation v is not affected by the excess phase noise of the pump laser. All amplitude and phase correlation variances measured at the three analysis frequencies are lower than the SNL even with the excess pump phase noise of 1.00, thus the quantum entanglement of twin beams within the certain range of the excess pump noise is experimentally proved. To demonstrate the linear dependence of the phase correlation of twin beams on the excess pump phase noise as described in eq. (2), we measured the phase sum noises of twin beams under seven different excess pump phase noises. The measured results at the analysis frequency 2 MHz are shown in fig. 5. The lowest point corresponds to the phase noise of the initial pump laser (the transverse coordinate 0.17, corresponding to 0.7 dB above the SNL). The other points are the experimental results after adding a white noise by means of a phase modulator. It is obvious that when the excess pump noise is larger than 2.0 (correspond to 3.0 dB), the phase sum noise of the twin beams is higher than the normalized SNL (1 on the longitudinal coordinate). The results perhaps can explain why the phase correlation of twin beams in some experiments was not observed [13].

Figure 6 shows the normalized noise power spectra of the intensity difference and the phase sum of twin beams calculated from eqs. (1) and (2) by use of our parameters of our real experimental systems ($\tau = 39.5$ ns, $\sigma = 1.22$, $\eta = 0.9 * 0.78$ and $\eta' = 0.9 * 0.78 * 0.78$ coming from the fiber coupling efficiency of 78% and the detection efficiency of 90%). Since the input optical beam of MZI passes through two fibers (short and long arms) in the measurement of the phase noise, we have $\eta' = 0.9 * 0.78 * 0.78$, but

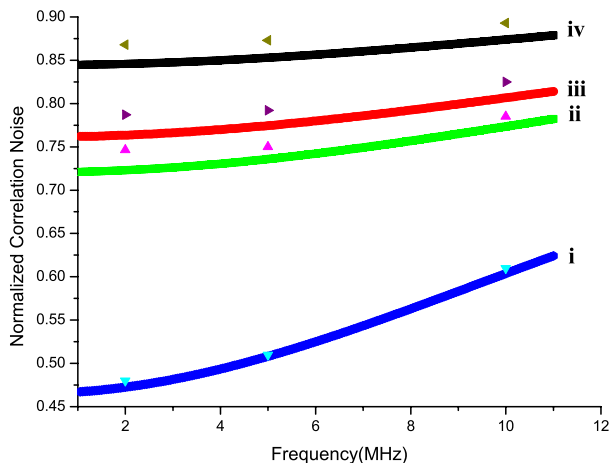


Fig. 6: Normalized correlation noise. Trace i (\blacktriangledown) corresponds to the theoretical (experimental) values of the intensity-difference. Trace ii (\blacktriangle), trace iii (\blacktriangleright) and trace iv (\blacktriangleleft) correspond to the theoretical (experimental) values of the phase sum with $E = 0, 0.33, 1.00$, respectively.

it only transmits through the short arm for the measurement of the intensity-difference, thus $\eta = 0.9 * 0.78$. Trace i corresponds to the intensity difference spectrum. Trace ii, iii, iv corresponds to the phase sum spectra with the pump excess noise $E = 0, 0.33, 1.00$ respectively. The symbols $\blacktriangledown, \blacktriangle, \blacktriangleright$ and \blacktriangleleft are the experimental measured values corresponding to the intensity difference and the phase sum with $E = 0, 0.33$ and 1.00 , respectively. The experimental analysis frequencies are 2 MHz, 5 MHz and 10 MHz. We can see that the experimental measurements are in reasonable agreement with that theoretically calculated. Still, the experimentally measured values of the phase sum noise ($\blacktriangle, \blacktriangleright, \blacktriangleleft$) are a little higher than that of theory (ii, iii, iv). We consider that is because the possibly spurious phase-noise of the pump laser produced inside the NOPO has not been considered in eq. (2). A detailed theoretical analysis on the problem has been presented in another publication of ours (see ref. [22]).

In conclusion, we experimentally demonstrated the dependence of the phase correlation of twin beams from NOPO operating above threshold on the excess phase noise of the pump laser. The experimental measurements agree with the theoretical predictions resulting from the semiclassical method quite well. The intense frequency-nondegenerate entangled light beams probably are appropriate to be used for quantum key distribution of optical continuous variables, since the local oscillations for homodyne detection are not needed, and also for distributing quantum information between different parts of the electromagnetic spectrum by means of teleportation.

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