We experimentally demonstrate that the quantum entanglement between amplitude and phase quadratures of optical modes produced from a non-degenerate optical parametric amplifier (NOPA) can be enhanced and manipulated phase-sensitively by means of another NOPA. When both NOPAs operate at de-amplification, the entanglement degree is increased at the cavity resonance of the second NOPA. When the first NOPA operates at de-amplification and the second one at amplification, the spectral features of the correlation variances are significantly changed. The experimental results are in good agreement with the theoretical expectation.

FIG. 1: (Color online) Experimental setup. Laser, Nd:YAP/KTP laser source; HW, λ/2 wave plate; PBS, polarizing beam splitter; BS1-2, 50/50 beam splitter; D1-4, ETX500 InGaAs photodiode detectors; +/−, positive/negative power combiner; MC, mode cleaner; M0-6, different mirrors (see text for detail); PZT, piezo electric transducer; SA, spectrum analyzer.
for NOPA1 (NOPA2) are 51 mm (557 mm) and 165 (153), respectively. The output signal and idler beams ($b_1$ and $b_2$) from NOPA2 are separated by a polarizing-beam-splitter (PBS) and then they are respectively sent to two balanced homodyne detectors for simultaneously measuring the noise power spectra of their quadrature components. The measured noise power are combined by a positive or negative power combiner (+/-) and then the combined correlation variances of amplitude or phase quadratures between $b_1$ and $b_2$ are detected by a spectrum analyzer (SA).

At first, we achieved the double resonance of injected sub-harmonic coherent signal and idler in NOPA1 using FM sideband technique $[3]$. Then the relative phase between the pump field and the injected signal field is locked to $\pi$, that is to enforce the NOPA1 operating at de-amplification $[3]$. When a block was inserted between M3 and M4 and the pump light of NOPA2 was turned off, the output light by NOPA1 was not coupled into NOPA2 and almost totally was reflected by M3 to PBS. In this case the quadrature correlation variances of the EPR beams produced by NOPA1 were measured. The measured correlation variances spectra of the amplitude sum, $\langle \delta^2(\hat{X}_{a_1} + \hat{X}_{a_2}) \rangle$, and the phase difference, $\langle \delta^2(\hat{Y}_{a_1} - \hat{Y}_{a_2}) \rangle$, both were $2.4 \pm 0.1 \text{ dB}$ below the corresponding shot noise limit (SNL) at the analysis frequency of $\Omega = 3.0 \text{ MHz}$, where $\hat{X}_{a_1}$ and $\hat{X}_{a_2}$ ($\hat{Y}_{a_1}$ and $\hat{Y}_{a_2}$) are the amplitude (phase) quadratures of output modes $a_1$ and $a_2$ by NOPA1, respectively. It means that the EPR entangled optical field with the amplitude anti-correlation and the phase correlation were obtained. During the experiment the pump power and intensity of the injected signal for NOPA1 are kept at 120 mW (below the oscillation threshold of 200 mW) and 10 mw before the input coupler, respectively. The power of the output EPR entangled beams is about 52 $\mu$W.

Removing the block between M3 and M4 as well as turning on the pump light of NOPA2, the EPR beams by NOPA1 were injected into NOPA2. When NOPA2 was operated at de-amplification also, the output signal and idler modes by NOPA2 were still entangled with the anti-correlation of amplitude quadratures ($\langle \delta^2(\hat{X}_{b_1} + \hat{X}_{b_2}) \rangle < \text{SNL}$) and the correlation of phase quadratures ($\langle \delta^2(\hat{Y}_{b_1} - \hat{Y}_{b_2}) \rangle < \text{SNL}$) like the entanglement features of the injected signals, where $\hat{X}_{b_1}$ and $\hat{X}_{b_2}$ ($\hat{Y}_{b_1}$ and $\hat{Y}_{b_2}$) are the amplitude (phase) quadratures of output modes $b_1$ and $b_2$ by NOPA2, respectively. The correlation variance spectra of $\langle \delta^2(\hat{X}_{b_1} + \hat{X}_{b_2}) \rangle$ and $\langle \delta^2(\hat{Y}_{b_1} - \hat{Y}_{b_2}) \rangle$ versus the cavity detuning measured by scanning the length of optical cavity of NOPA2 are shown in Fig.2(a) and (b), respectively. Under the resonance with zero detuning ($\Delta = 0$), both variance of the amplitude sum (Fig.2(a) trace iii) and the phase difference (Fig.2(b) trace iii) are about $3.0 \text{ dB}$ below the SNL (trace i). If locking the cavity length to the resonance point a stable correlation variance of $3.0 \pm 0.1 \text{ dB}$ below the SNL is obtained (trace iv). In this case the entanglement degree of the output fields by NOPA2 are enhanced about $0.6 \text{ dB}$ with respect to that of the injected entangled states. Trace ii in Fig.2(a) and (b) are the correlation variance spectra of amplitude sum (a) and phase difference (b) calculated by Eq.(25) in Ref.[12] with the actual parameters of the experimented system, respectively. Deviating from the resonance with a small detuning the correlation noises increase rapidly to two maximums of $2.0 \text{ dB}$ above the SNL at $\Delta = \pm 4.9 \text{ MHz}$ and then decrease to the initial correlation degree of the injected EPR beams ($\sim 2.4 \text{ dB}$ below the SNL) at far detuning.

However, if NOPA2 is operated at amplification by locking relative phase between the pump field and the injected EPR beam in phase and NOPA1 still at de-amplification, the...
correlation features of quadratures between the output modes $b_1$ and $b_2$ will be significantly changed. In this case the noise powers of $\langle \delta^2(\hat{X}_{b_1} + \hat{X}_{b_2}) \rangle$ and $\langle \delta^2(\hat{Y}_{b_1} - \hat{Y}_{b_2}) \rangle$ are not squeezed. In contrast with the correlation features of the injected EPR beams with $\langle \delta^2(\hat{X}_{a_1} + \hat{X}_{a_2}) \rangle < SNL$ and $\langle \delta^2(\hat{Y}_{a_1} - \hat{Y}_{a_2}) \rangle < SNL$, the correlation variances of the output fields by NOPA2, $\langle \delta^2(\hat{X}_{b_1} - \hat{X}_{b_2}) \rangle$ and $\langle \delta^2(\hat{Y}_{b_1} + \hat{Y}_{b_2}) \rangle$, become the quantum correlated with noise powers below the SNL at the cavity resonance and near resonance. Fig.3(a) and (b) are the noise power spectra of $\langle \delta^2(\hat{X}_{b_1} - \hat{X}_{b_2}) \rangle$ and $\langle \delta^2(\hat{Y}_{b_1} + \hat{Y}_{b_2}) \rangle$ versus the cavity detuning of NOPA2 at $\Omega = 3.0 MHz$, respectively. Trace i is the SNL; trace ii and iii are the noise power spectra calculated by Eq.(25) in Ref.[12] and experimentally measured, respectively; trace iv is the noise spectra measured when the cavity of NOPA2 is locked at the resonance. Both correlation variances of amplitude difference (a) and phase sum (b) at the cavity resonance are 0.4 dB below the SNL and the minimal variances of 1.4 dB below the SNL appear at small detuning of $\Delta = \pm 3.5 MHz$. Then, the variances increase to much higher than the SNL at far detuning where the parametric interaction in NOPA2 no longer exist and thus $\langle \hat{X}_{b_1} - \hat{X}_{b_2} \rangle$ and $\langle \hat{Y}_{b_1} + \hat{Y}_{b_2} \rangle$ return to anti-squeezing components of the initially injected modes $a_1$ and $a_2$.

When NOPA1 and NOPA2 are operated at the same regime (Fig.2) the identical parametric interaction in NOPA2 will enhance the entanglement of the injected signal field. However, if NOPA1 and NOPA2 are operated at the opposite regime (Fig.3), the quantum correlations produced by the nonlinear process in NOPA2 have the opposite features with the correlations of the injected signal field at the resonance and the near resonance. Thus the amplitude anti-correlation and the phase correlation of the injected field are changed to the amplitude correlation and the phase anti-correlation of the output field due to the parametric amplification process in NOPA2. The shoulders appearing in the spectral shapes just outside the resonant point are caused by the interference between the pump field and the subharmonic seed field in NOPA2 in cooperation with the absorptive and dispersive responses of an optical cavity[13]. Comparing trace ii and iii in Figs.(2) and (3), we can see that theoretically calculated and experimentally measured correlation variance spectra are in good agreement except at the dips of the minimal variances. At these dips the calculated variances are smaller than measured values, that is perhaps because some extra instability appears at the suddenly changing points of the correlation variances which have not be involved in the theoretical equations.

For conclusion, we experimentally realized the entanglement enhancement and phase-sensitive manipulation of CV optical entangled states based on using NOPAs. The experiment provides a simple scheme to increase and manipulate CV quantum correlations of optical modes without the need for the difficult technique of single photon detection.[14].

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