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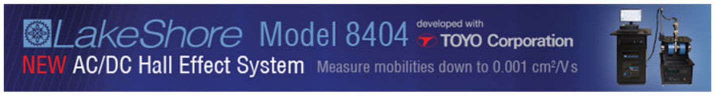

APPLIED PHYSICS LETTERS **100**, 091112 (2012)

Robust generation of bright two-color entangled optical beams from a phase-insensitive optical parametric amplifier

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Bright two-color continuous variable (CV) entangled optical beams at 0.8 and 1.5 μm are generated by utilizing a phase-insensitive optical parametric amplifier with only 1.5 μm signal field injected. Without locking the relative phase between the signal and pump fields, the amplitude quadrature difference squeezing of 3.30 dB and phase quadrature sum squeezing of 3.35 dB are observed, which satisfy the entanglement criterion. The demonstrated scheme here eliminates the necessity of precise phase control between the signal and pump fields and enables robust generation of two-color CV entangled states. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3690876]

Quantum entanglement[1] plays a key role in a variety of quantum communication tasks, such as quantum teleportation, quantum dense coding, quantum cryptography, and quantum repeater, etc.[2–4] Thanks to the well-established quantum entanglement sources, the past two decades have witnessed a rapid development of quantum communication.[4] It is known that the distribution of quantum states over long distances (for instance, over optical fibers or free space) will be limited by photon loss and this bottleneck can be overcome by implementing quantum repeater protocol, which can create long-distance entanglement from shorter-distance entanglement via entanglement swapping.[5,6] In above cases, stable and compact sources of entangled fields at non-degenerate (different) frequencies will be needed for transferring quantum information between different nodes via quantum channels.

Recently, two-color[7–13] and even three-color[14] continuous variable (CV) quantum entangled states have been observed in experiment by using various kinds of intracavity second-order nonlinear processes. Among them, phase-sensitive optical parametric amplifier (OPA) is an efficient way to prepare highly squeezed and balanced two-mode entangled states but does not allow a practical homodyne measurement of the quantum states due to the absence of appropriate local oscillators (LO). The combined OPA and optical parametric oscillator (OPO) scheme overcomes the limitations and paves the way for preparing and detecting high quality two-color CV entanglement of light fields with any expected frequencies.[13] However, current OPA schemes which are used to generate CV entangled states focus on phase-sensitive regime where accurate control of the relative phase between the pump and seed fields is necessary, i.e., the relative phase must be stabilized in order to maintain maximum parametric amplification or deamplification. In this case, the entanglement sources will be disturbed inevitably by various vibrations from the surrounding environment, even though a sophisticated servo system is employed. This raises a natural question: can the OPA schemes work reasonably well while eliminate the necessity of the phase locking? Actually, this question has been answered by Coutinho dos Santos *et al.*,[15] and it was proposed that OPAs with reasonably low levels of injected signal field (without idler field injected) allow for demonstrations of quantum entanglement and the Einstein-Podolsky-Rosen paradox. Because only the signal field is used as the injected field, the OPA is essentially phase insensitive. In this Letter, we present an experimental robust generation of bright two-color CV entangled beams by utilizing a phase-insensitive OPA with only signal injected. The observed quantum correlations for amplitude quadrature difference and phase quadrature sum are 3.30 dB and 3.35 dB, respectively, at analysis frequency of 1.37 MHz, which satisfy the entanglement criterion of Duan *et al.*[16]

In Ref. 15, the authors analyzed the effect of injected signal field on the classical and quantum properties of the nondegenerate OPO, through perturbation approach starting from the full equations of motion in the positive-P representation. For a perfect cavity with no intracavity linear losses, the external squeezing spectra for the combined quadratures can be given by[15]

$$V^{out}_{y_+}(\Omega) = \langle \Delta^2(\hat{Y}_1+\hat{Y}_2)\rangle = 1 - \frac{2x_{0s}(\Omega^2+D^2-E^2)}{\Omega^2(\Omega^2+C^2+D^2+2E^2)+(CD-E^2)^2}, \tag{1}$$

$$V^{out}_{x_-}(\Omega) = \langle \Delta^2(\hat{X}_1+\hat{X}_2)\rangle = 1 - \frac{2x_{0s}(\Omega^2+A^2-E^2)}{\Omega^2(\Omega^2+A^2+B^2+2E^2)+(AB-E^2)^2}, \tag{2}$$

where

$$\begin{aligned}
&A = 1 - x_{0s}/2 + (x_{1s}+x_{2s})^2/4,\\
&B = 1 + x_{0s}/2 + (x_{1s}-x_{2s})^2/4,\\
&C = 1 + x_{0s}/2 + (x_{1s}+x_{2s})^2/4,\\
&D = 1 - x_{0s}/2 + (x_{1s}-x_{2s})^2/4,\ E = (x_{1s}^2 - x_{2s}^2)/4,\\
&x_{0s} = 2\mu_0\{1 - 2\mu_1^2/[(1-\mu_0^2)^2 + 2\mu_1^2]\},\\
&x_{1s} = 8\mu_1/(4 - x_{0s}^2),\ x_{2s} = 4\mu_1 x_{0s}/(4 - x_{0s}^2),\\
&\mu_0 = \sqrt{P_p/P_{th}},\ \mu_1 = \sqrt{\omega_p P_s/(2\omega_s P_{th})},
\end{aligned} \tag{3}$$

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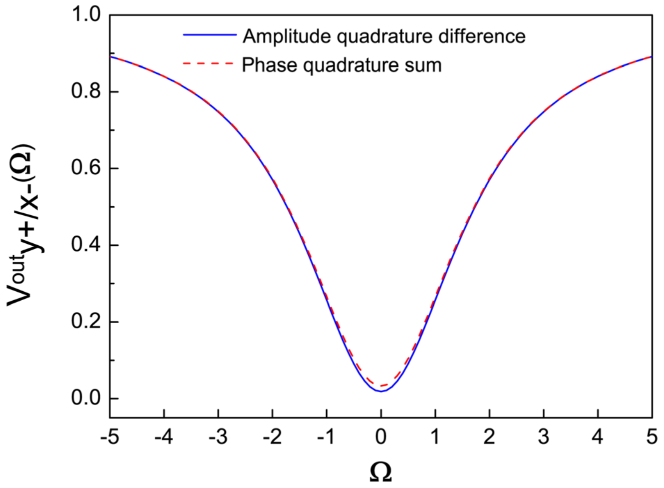

FIG. 1. (Color online) Theoretical quantum correlation spectra of amplitude quadrature difference (blue solid curve) and phase quadrature sum (red dashed curve). Frequencies (Ω) are expressed in units of the cavity damping rate for down-converted fields.

where $\hat{X}_j,\hat{Y}_j(i = 1, 2)$ are amplitude and phase quadratures, respectively, P_p, P_s, and P_{th} are the pump, injected signal, and threshold power, respectively, ω_p and ω_s represent the angular frequencies at the pump and signal frequencies.

By using our experimental parameters: $\mu_0 = 0.77$ and $\mu_1 = 0.028$, the calculated quantum correlation spectra of the combined quadratures as a function of normalized analysis frequency Ω (in units of the OPA cavity damping rate for down-converted fields) are shown in Fig. 1. The results show that high degree of quantum entanglement should be observed in our experiment. Here, one needs to keep in mind that the intensity of the injected signal is required to be much less than that of the pump field to ensure a high degree of quantum entanglement. This is due to the fact that the degree of the quantum entanglement is proportional to the parametric gain of the OPA, for strong injected signal, the pump field will be depleted inevitably, and this will reduce the parametric gain.

The experimental setup is sketched in Fig. 2. The pump laser derived from a homemade 526.5 nm laser was separated into two portions by a beam splitter (BS), which then pumped a ring nonlinear resonator from two opposite directions. The ring entangler is in a bow tie configuration consisting of two spherical mirrors with 60-mm radii of curvature and two plane mirrors. Both the spherical mirrors were coated for high reflectivity at 0.8 and 1.5 μm (>99.8%) and high transmission at 526.5 nm (98%). The output coupler was coated for partial transmission (~6%) at 0.8 and 1.5 μm. A 20-mm-long periodically poled $KTiOPO_4$ (PPKTP) was used as the nonlinear medium. In the forward direction, the pump power was set above (1.2 times) the oscillation threshold (97 mW) and the nonlinear resonator operated as an above-threshold OPO. The generated intense twin beams were mainly acted as LO for homodyne detection. In the backward direction, the entangler was pumped below (0.6 times) the threshold. A small fraction of the intense down-converted fields in the forward OPO was picked out by an uncoated plane mirror and then directed to a dichroic beam splitter (DBS, coated for high transmission at 1.5 μm and high reflectivity at 0.8 μm) and a plane mirror (coated for high reflection at 1.5 μm). Thus, only the 1.5 μm signal field was injected into the backward OPA to act as the seed field.

To confirm the signal-injected OPA is phase insensitive, the OPA cavity was held on resonance with a single signal-idler mode pair via a dither-locking method and then the relative phase between the signal and the pump fields was scanned. The measured intensity of the output signal field remained almost the same during the phase scanning (as shown in Fig. 3, the variation of the relative phase is around 2.8π). This phenomenon clearly verifies the phase-insensitive characteristic of the signal-injected OPA and differs from that of phase-sensitive OPAs where classical parametric amplification and deamplification should be observed. Compared with the situation where the pump field was absent, the intensity of the output signal field can be amplified about 6 times when the pump field was used. It was

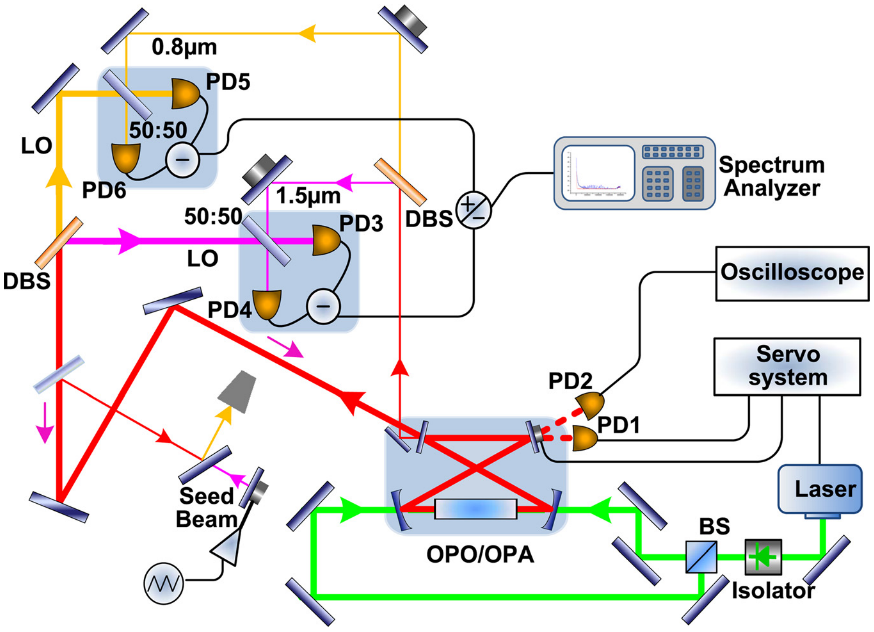

FIG. 2. (Color online) Schematic diagram of the experimental setup. BS: beam splitter; DBS: dichroic beam splitter; PD: photodiode; PID: proportional-integral-derivative controller; LO: local oscillator.

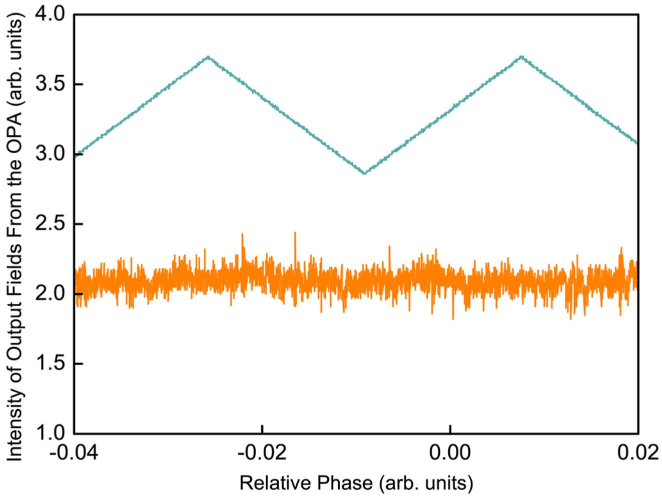

FIG. 3. (Color online) The measured intensity of the output signal field when the relative phase between the signal and pump fields was scanned by using a triangle wave voltage signal.

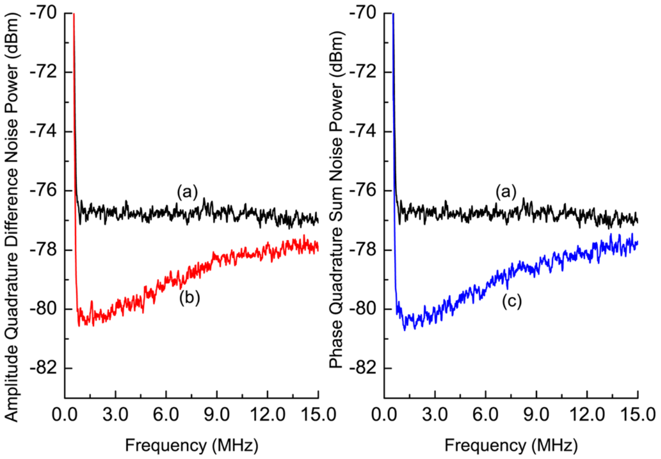

FIG. 4. (Color online) Measured quadrature noise spectra between the 0.8 and 1.5 μm down-converted fields. (a) Shot noise level; (b) Amplitude quadrature difference noise spectrum; (c) Phase quadrature sum noise spectrum. The settings of the spectrum analyzer: resolution bandwidth is 300 kHz and video bandwidth is 100 Hz.

found that the signal field can be amplified stably for a long term even though the relative phase between the signal and the pump fields was not actively controlled.

Without locking the relative phase between the signal and pump fields, the emitted down-converted fields from two directions were separated, respectively, by DBSs, and each beam was directed to a 50:50 BS for homodyne detection. We achieved a fringe visibility of 95% between the signal and LO beams. Amplitude quadrature difference and phase quadrature sum noise power spectra between down-converted fields at 0.8 and 1.5 μm were recorded by using a spectrum analyzer, and the measured results are depicted in Fig. 4. They exhibit a fine balance between the amplitude quadrature difference and phase quadrature sum quantum correlations, just as that of phase-sensitive OPA.[13]

The observed maximum quantum correlations for the amplitude quadrature difference and phase quadrature sum are 3.30 dB and 3.35 dB, respectively, at analysis frequency of 1.37 MHz. In Fig. 4, electronic dark noise of around 10.2 dB below quantum noise limit (QNL) has been subtracted. Using the experimental values of $\langle\Delta^2(\hat{X}_1-\hat{X}_2)\rangle = 0.468$ and $\langle\Delta^2(\hat{Y}_1+\hat{Y}_2)\rangle = 0.462$, the Duan *et al.*[16] criteria are clearly violated: $\langle\Delta^2(\hat{X}_1-\hat{X}_2)\rangle+\langle\Delta^2(\hat{Y}_1+\hat{Y}_2)\rangle=0.93<2$, which indicates the two-color down-converted fields from the phase-insensitive OPA are indeed quantum entangled.

In summary, we have experimentally demonstrated the generation of bright two-color CV entangled beams by utilizing an OPA with only signal field injected. The demonstrated scheme does not require a precise phase control between the injected field and the pump field and enables robust generation of two-color CV entangled states. The compact and stable configuration will find potential applications in the realization of practical quantum repeater and future quantum network.

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