Experimental continuous-variable entanglement from a phase-difference-locked optical parametric oscillator

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We observed continuous-variable entanglement between the bright beams emitted above threshold by an ultrastable optical parametric oscillator (OPO), classically phase locked at a frequency difference of 161.827 324 0(5) MHz. The amplitude-difference squeezing is −3 dB and the phase-sum one is −1.35 dB. Besides proving entanglement in a phase-locked OPO, such outstanding frequency-difference stability paves the way for transferring entanglement between different optical frequencies and densely implementing continuous-variable quantum information in the frequency domain.

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The nondegenerate optical parametric oscillator (OPO) is a natural source of continuous-variable- (CV-) entangled electromagnetic fields [1]. Below threshold, it is a phase-sensitive amplifier whose quantum evolution can be described by a unitary two-mode squeeze operator [2], which, in the ideal case yields, for example, a common eigenstate of the amplitude-difference and phase-sum field quadratures. Since the amplitude and phase of a quantized field correspond exactly to the position and momentum of a mechanical quantum oscillator, this two-mode squeezed state is identical to that of the Einstein-Podolsky-Rosen (EPR) paradox [3], which has been implemented experimentally with finite squeezing [4] and used in CV quantum information (CVQI) [5,6]. Above threshold, the OPO is a true oscillator rather than an amplifier and its dynamics become richer: as is well known, the phase difference of the two OPO signal beams undergoes, above threshold, an undamped diffusion process, driven by vacuum fluctuations and analogous to that of the phase of a laser beam, resulting in the Schawlow-Townes linewidth [7]. There is, therefore, excess quantum noise on the phase difference of the OPO signal beams, compared to that of two independent ideal laser beams of the same power. This is a consequence of the number-phase Heisenberg uncertainty for the photon-number-correlated OPO beams. We made the first experimental measurement of this excess quantum noise, which can also be understood as a macroscopic Hong-Ou-Mandel interference experiment [8]. It is, however, possible to suppress the Schawlow-Townes phase-difference drift by locking the phase difference of the signal beams of the OPO, thereby profoundly altering its natural dynamics and quantum properties. Indeed, perfect locking of the phase difference implies phase-difference squeezing, which means that the expected photon-number correlations in such a two-photon emitter are lost. This is clearly a different physical system from the standard OPO. Recently, CV entanglement was observed above threshold in standard OPO’s [9,10] with unbridled Schawlow-Townes phase-difference drift. An elegant self-phase-locked type-II OPO, using polarization coupling from an intracavity wave plate, was demonstrated [11], and theoretical studies predicted quantum properties very different from those of a regular OPO, as well as potential for entanglement generation for small values of the polarization coupling parameter [12]. Experimental studies produced a record amount of CV entanglement below threshold [13] but none above [14].

In this Rapid Communication, we report the observation of CV entanglement above threshold in a different type of phase-difference-locked OPO, in which the polarization coupling is derived from a classical beat note signal and applied electro-optically to the OPO nonlinear crystal. No theoretical model has yet been developed for this OPO. Unlike the aforementioned self-phase-locked OPO, the frequency difference of our OPO beams is not restricted to zero and can have any value within the phase-matching and electronics bandwidths. This is essential to enable entanglement and teleportation between different optical frequencies, e.g., an atomic resonance and the low-loss window of an optical fiber. Phase locking also suppresses uncontrolled phase and frequency drifts, which are detrimental to joint measurements of the quantum channel with external fields in teleportation. Finally, it opens the way to the fascinating regime of phase- and frequency-stable CVQI, combining the techniques of quantum optics with those of ultrastable frequency standards. One example is quantum heterodyne multiplexing, where multiple entangled mode pairs, with different frequency differences but the same frequency sum (as could be produced by a type-I OPO [15]) can all be heterodyne detected [16,17] simultaneously using a single local oscillator, if their respective phase differences are locked [18]. Another example is the use of mode-locked optical oscillators and their frequency-comb spectrum as candidates for large-scale multipartite CV entanglement [19,20]. This experimental realization of CV entanglement of phase-locked bright cw beams used an ultrastable, doubly resonant, type-II near-concentric OPO based on an X-cut sodium-doped potassium titanyl phosphate (Na:KTP) nonlinear crystal, temperature stabilized at a few tenths of millidegrees, in which pump photons at 532 nm were down-converted into cross-polarized pairs at 1064 nm. This interaction was noncritically and collinearly phase matched. The same OPO was used in our previous demonstration of

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macroscopic Hong-Ou-Mandel interference [8]. The experimental setup is sketched in Fig. 1. The OPO pump and LO beams, at 532 and 1064 nm, respectively, were provided by a neodymium-doped yttrium aluminum garnet (Nd:YAG) laser with an external resonant frequency doubler (“Diabolo,” Innolight). Both beams were spatially and temporally filtered by “mode-cleaner” cavities, of respective half widths at half maximum (HWHMs) 160 and 170 kHz. The twin OPO beams at 1064 nm exited through mirror $M_\theta$, with typical operating powers from 1 to 10 mW (controlled by the pump power above its 65 mW threshold), and were separated by a polarizing beam splitter (PBS). The reflected OPO-depleted pump beam was used as error signal of the OPO cavity lock loop (CLL). A weak leak at 1064 nm through $M_\theta$ was picked off by a dichroic mirror and the resulting beat note of the twin beams was phase locked to a stable synthesized radio frequency at $2\Omega/(2\pi)=161.827324$ MHz, by applying a correction voltage along the $Z$ axis of the Na:KTP crystal. With only the temperature lock and CLL, the frequency-difference error was $\pm 150$ kHz [21], due to large doping inhomogeneities in the crystal coupled to residual vibrations of the optical table. The phase-difference lock loop (PDLL) reduced this error by more than five orders of magnitude to less than 1 Hz (Fig. 2), while keeping the frequency difference continuously tunable over tens of megahertz. The individual OPO frequencies had a residual jitter of 10 kHz, measured by beating the OPO against the kilohertz-linewidth local oscillator (LO) laser. Note that the PDLL was purely classical, since its error signal was obtained from a balanced heterodyne measurement through a very-low-transmission mirror, both properties which independently cause the OPO quantum phase-difference noise to be replaced by vacuum fluctuations [8]. Hence, the PDLL phase-difference noise reduction could, in principle, degrade neither the conjugate amplitude-difference squeezing nor the entanglement. In order to observe the latter, i.e., the EPR correlation between the twin beams, we set up two standard balanced homodyne detection (BHD) systems, with low- and high-pass outputs. An acousto-optic modulator (AOM) was utilized to simultaneously upshift and downshift the frequencies of the LO, yielding two beams at frequencies $\omega \pm \Omega$, where $\omega$ is the fundamental laser frequency and $\Omega/(2\pi)=80.913\,662$ MHz is the driver frequency of the AOM. The 1064 nm mode cleaner was built with a free spectral range of $\Omega/(3\pi)$ so as to allow simultaneous resonance of both frequency-shifted LO beams. The two cross-polarized outputs of this mode cleaner were suitable LO beams for the two BHD systems since the frequency difference of the twin beams was phase locked to $2\Omega$ by means of the PDLL. The two synthesizers working at $\Omega$ and $2\Omega$ were also electronically phase locked together, which suppressed any effect on the experiment of residual synthesizer frequency drifts. The optical part of the experiment was stabilized by six servo loops that controlled the OPO and mode-cleaner optical cavities (CLL), the OPO temperature ($T$), its phase difference (PDLL), and one of the LO phases, i.e., OPO quadratures (QLL), the other one being scanned for the purpose of data acquisition but lockable as well.

Figure 3 shows a typical intensity-difference squeezing spectrum of the OPO, measured by blocking the local oscillator beams, sending each OPO beam into a single photodiode, and electronically subtracting the photocurrents. The shot noise trace was obtained by rotating the OPO polarizations by $45^\circ$ before the PBS. Technical noise from the pump

FIG. 1. (Color) Experimental setup (see text). OPO mirror $M_\theta$ has transmittivities $T(532\text{ nm})$ = 0.98 and $T(1064\text{ nm})$ = $5 \times 10^{-5}$; $M_z$ has $T(532\text{ nm})$ = $5 \times 10^{-5}$. $T(1064\text{ nm})$ = $1.8 \times 10^{-2}$. AOM: acousto-optic modulator. CLL: cavity-lock loop. DM: dichroic mirror. EOM: electro-optic modulator. FR: Faraday rotator. HWP: half-wave plate. MC: mode cleaner. P(D)LL: phase-(difference-)lock loop. PZT: piezoelectric transducer. QLL: quadrature-lock loop. The 12 MHz EOM is integrated in the laser.

FIG. 2. (Color online) Ultranarrow beat note of the phase-locked OPO. Resolution and video bandwidths are RBW=VBW = 1 Hz. Consecutive points are separated by 0.5 Hz. 100 averages.
laser below 1.5 MHz prevented us from reaching squeezing levels stronger than $S_\gamma=-3$ dB with respect to the shot noise limit at 1.7 MHz. This amplitude noise can be reduced further by adopting a mode cleaner of HWHM closer to the laser linewidth, i.e., a few kilohertz. Figure 4 shows the quadrature-sum noise of the twin beams versus one of the LO optical phases, the other LO phase being locked at $\pi/2$, i.e., to the phase quadrature. We verified on the dc interference fringe that the ac signal is squeezed only when the scanned quadrature is also the phase one, i.e., the phase shift is $\pi/2$. The raw phase-sum squeezing is $-0.9$ dB over, one must take into account the fact that the bright OPO quantum efficiencies of the photodetectors $\eta_1, \eta_2$, and the LO power $6.5$ mW per beam. We denote the ratio of the semiclassical amplitude and $\eta = \eta_1 = \eta_2 = 1$ yields $-1.35$ dB. The theoretical value for the squeezing amount can be derived from [1] in the ideal case and from a semiclassical analysis [22] including losses, and gives $-2.6$ dB at 1.7 MHz, given our cavity parameters. The cause of the 1 dB discrepancy may be uncorrected rf noise from the PDLL. This is thus a proof-of-principle demonstration. In order to improve it, one needs to better suppress the pump laser noise with a narrower mode cleaner and further optimize the PDLL filter, as the PDLL and CLL are coupled [23]. This will allow one to work at lower signal frequency, well within the squeezing bandwidth.

The reader will also have noticed that the fringe contrast $C_2 < C_1$, which substantially degrades the squeezing. This is due to an optical aberration in one of the OPO beams, stemming from the OPO crystal’s natural anisotropy: one of the two OPO beam sections is elliptical whereas the other is circular. We observed that the ellipse’s eccentricity increased with the length of the OPO’s near-concentric cavity. We believe this is caused by walkoff in the wings of the focused beam in the Na:KTP crystal. Even though the propagation direction in the crystal is the principal axis $X$ and should therefore give no walkoff, the beam is focused and its plane-wave angular spectrum does contain wave vectors at an angle with $X$. The $Z$ polarization experiences a strong birefringence in the extraordinary $XZ$ plane but not in the ordinary $XY$ plane. The $Y$ polarization, however, experiences only weak birefringence in the extraordinary $XY$ plane, since Na:KTP, like KTP, is close to uniaxial ($n_X = n_Y < n_Z$). Hence, only the $Z$ polarization acquires a significant mode mismatch with the TEM$_{00}$ LO mode. This could be corrected by inducing the same exact aberration on the LO mode, which is not trivial unless one uses the same OPO cavity to create the same eigenmode for the LO. To alleviate this problem, we defocused the beam inside the OPO cavity by reducing its
length. We then measured the Gaussian beam parameters by measuring the intensity profile with a scanning pinhole and found that the beam polarized along the Z axis (horizontal) of the crystal had a horizontal-to-vertical waist aspect ratio of 1.29(5) whereas the Y-polarized (vertical) beam had a waist aspect ratio of 0.98(5). This had, however, the adverse effect of increasing the cavity eigenmode waist and therefore the OPO threshold from 15 mW [21] to 65 mW, which led to higher output power in the same operating conditions (number of times above threshold of the pump power), i.e., a larger power ratio \( \rho \) as defined above and a consequent reduction of phase-sum squeezing. This issue can be alleviated by use of a stronger nonlinearity or of detectors that can withstand higher optical powers, both of which will yield a smaller \( \rho \).

The aforementioned squeezing levels (\( S_\perp = -3.0 \mbox{ dB} \), \( S_\parallel = -1.35 \mbox{ dB} \)) translate into \( \Delta (A_{1,0}-A_{2,0}) = 10^{5.2/20} = 0.71 < 1 \) and \( \Delta (A_{2,\pi 2}+A_{2,\pi 1}) = 10^{4.2/20} = 0.86 < 1 \), which proves squeezed-state entanglement [24]. Another quantitative measure of CV entanglement is the Duan-Simon criterion [25,26]

\[
\Delta \left( \frac{A_{1,0} - A_{2,0}}{\sqrt{2}} \right)^2 + \Delta \left( \frac{A_{1,\pi 2} + A_{2,\pi 1}}{\sqrt{2}} \right)^2 = 1.24 < 2. \quad (2)
\]

This is the strongest entanglement obtained to date to our knowledge for beams emitted by an OPO above threshold.

In conclusion, we have demonstrated that the bright CW beams emitted by an electronically phase-locked nondegenerate OPO above threshold can be entangled and that phase locking can, therefore, be used in a purely classical manner to yield the usual benefits of classical ultrastable operation for quantum information. There is no fundamental limitation to the frequency difference of the OPO beams and this result opens the way to quantum communication with intense ultrastable fields, as well as stable broadband two-mode and multimode [27] squeezing and entanglement for quantum communication and quantum heterodyne multiplexing.

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