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Experimental demonstration of frequency-degenerate bright EPR beams with a self-phase-locked optical parametric oscillator

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We report the first experimental observation of bright EPR beams produced by a type-II optical parametric oscillator operating above threshold at frequency degeneracy. The degenerate operation is obtained by introducing a birefringent plate inside the cavity resulting in phase locking. After filtering the pump noise, which plays a critical role, continuous-variable EPR correlations between the orthogonally polarized signal and idler beams are demonstrated.

Beyond a fundamental significance, entanglement has proven to be a necessary resource for quantum information protocols [1]. In parallel to the photon-counting regime, an active direction focuses on continuous variables of light [2]. In this context, different techniques have been used to generate entangled beams. The more efficient ones rely on parametric interaction in an optical cavity. Type-I parametric amplifiers enable to generate squeezed states and mixing two of them on a beam-splitter result in entangled beams [3, 4, 5]. Another way is to use type-II amplifiers, which directly provide orthogonally-polarized entangled beams [6, 7, 8, 9]. These devices are now widely used for generating deterministic entanglement and entanglement of formation as high as 1.1 ebits has been obtained [9].

Such non-linear systems can also be used above threshold. Although strong quantum intensity correlations have been repeatedly obtained with type-II optical parametric oscillators (OPO) [10, 11, 12], phase anticorrelations are difficult to demonstrate experimentally. Above threshold, an OPO behaves as an active oscillator, which chooses its working point providing the lowest oscillation threshold. In particular, the signal and idler beams are only accidentally at the same frequency. As a result, homodyne detection cannot be implemented. Only very recently, different groups working with type-II OPO managed to produce and characterize bright entangled beams [13, 14, 15, 16]. In these recent experiments, the beams were not at the same frequency but complicated techniques of noise measurement have been successfully used. We present here what is the first experimental generation of bright frequency-degenerate EPR beams with an OPO, characterized by homodyne detection.

The main device of the experimental setup is a type-II self-phase-locked OPO, namely an OPO with an additional linear coupling between the signal and idler fields. This device, initially proposed by Mason and Wong [17] and later described by Fabre et al. [18], has been extensively studied theoretically in [19] and its quantum properties have been detailed in [20]. The frequency-degenerate operation is enabled by a classical, all-optical coupling between the signal (A_1) and the idler (A_2), induced by a birefringent plate inside the OPO cavity, which forces the phase-locked operation of the system within a finite range of parameter space. For very small angles of the plate, it has been shown theoretically [20] that such a configuration preserves the strong entanglement between the signal and idler modes predicted in an OPO above threshold: they exhibit quantum correlations and anti-correlations on orthogonal quadratures. Frequency degenerate operation has been demonstrated in this system and enabled us the use of homodyne detection. However, phase anticorrelations were above the shot noise limit and prevented us from demonstrating entanglement in this regime [12]. The main reason has been identified as the pump excess noise. Its reduction and the subsequent demonstration of entanglement and even of EPR correlations is reported here.

The experimental setup is sketched in Fig. 1. The laser source is a continuous-wave Nd:YAG laser (Innolight-*Diabolo*) internally frequency doubled. The output at 532 nm pumps a triply-resonant OPO, based on a type-II 10 mm-long KTP crystal. The OPO is locked on the pump resonance by the Pound-Drever-Hall technique (PDH). In order to reduce the effect of the laser classical noise, the pump is filtered by a 760 mm-long triangular cavity. This filtering cavity is made of two flat mirrors with a reflectivity 97% and a third mirror, with a radius of curvature of 750 mm and a HR coating at 532 nm; the corresponding linewidth is 3.5 MHz. The cavity is locked on the maximum of transmission by PDH. In order to achieve better mechanical stability and reduce losses, a semi-monolithic configuration has been used for the OPO: the input cavity mirror is directly coated on the crystal face. The input coupler is HR at 1064 nm and has a reflectivity of 95.5% for the pump. The output mirror, HR at 532 nm, has a reflectivity at 1064 nm of 95%, and a radius of curvature of 38 mm. The crystal temperature is actively controlled, with residual oscillation of the order of the mK. A birefringent plate, $\lambda/4$ for the infrared and approximately λ for the pump, is inserted inside the cavity. It can be finely rotated relative to the axis of the non-linear crystal by steps of 0.01° thanks to a mount controlled by a piezo-electric actuator (New Focus Model 8401 and picomotor): for the results presented here, it is rotated by a very small angle ($\leq$0.02°). The measured OPO thresh-

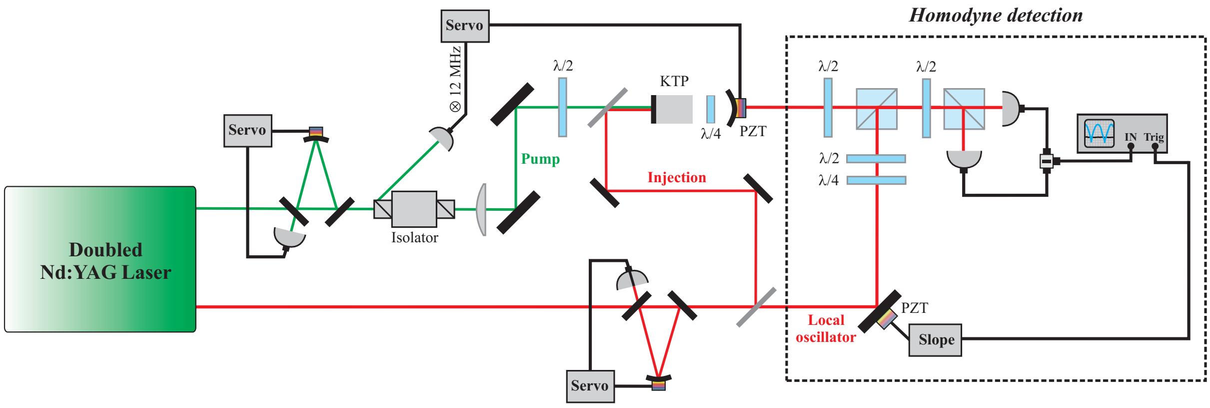

FIG. 1: The 532 nm output of a cw frequency-doubled Nd:YAG laser is filtered and used as the pump of a type-II OPO. The OPO operates above threshold at frequency degeneracy thanks to a quarter-wave plate inserted inside the cavity. The generated two-mode state is characterized by homodyne detection.

old is 20 mW, with a cavity bandwidth for the infrared around 50 MHz. To reach the degenerate operation, adjustment of both the crystal temperature and frequency of the pump is required. A small fraction of the laser output at 1064 nm can be injected into the OPO and exploited for finding the triple resonance. This beam is blocked while performing the quadrature measurements on the OPO output.

To characterize its noise properties, the OPO output is sent to a homodyne detection. A half-wave plate followed by a polarizing beam splitter enables to choose the modes to be detected: the signal A_1, the idler A_2, or the $\pm45°$ rotated modes $A_\pm$. The local oscillator (LO) is provided by the coherent laser output at 1064 nm, filtered by a high finesse ($\sim$ 2500) triangular cavity, locked on resonance by tilt-locking. The homodyne detection is based on two balanced InGaAs photodiodes (Epitaxx ETX300 without cap, quantum efficiency: 95%). The visibility reaches ≈ 0.98. A quarter-wave plate on the LO path allows correcting the polarizing beam-splitters imperfections, while the LO phase can be scanned thanks to a mirror mounted on a piezoelectric actuator. The homodyne photocurrent is sent to a spectrum analyzer (Agilent E4411B). The quadratures of the modes $A_\pm$ and $A_{1,2}$ are measured for different values of the noise analysis frequency, within the OPO bandwidth. All measurements have been performed for a pump power approximately equal to 1.1 times the oscillation threshold.

Let us recall that entanglement between the orthogonally-polarized modes A_1 and A_2 can be characterized in terms of the properties of the $\pm45°$ rotated modes defined by [21]:

$$A_+ = \frac{A_1 + A_2}{\sqrt{2}} \quad \text{and} \quad A_- = \frac{A_1 - A_2}{\sqrt{2}}. \qquad (1)$$

Considering the noise spectrum of the sum or difference of signal and idler fluctuations is strictly equivalent to considering the noise spectrum of the rotated modes. For entangled modes A_1 and A_2, the noise fluctuations of the modes $A_\pm$ are squeezed below the standard quantum limit (normalized to 1 in the following), respectively on the phase quadrature (Y_+) and the orthogonal quadrature (X_-). For an OPO above threshold, and a self-phase locked OPO in the limit of very small linear coupling, the noise variances can be written as

$$G_X = 1 - \frac{T}{T+\mu}\frac{1}{1+\Omega^2} \qquad (2)$$

$$G_Y = 1 - \frac{T}{T+\mu}\frac{1-2(V_0-1)(\sigma-1)}{\Omega^2+\sigma^2} \qquad (3)$$

with $G_X = \langle\Delta X_-\rangle^2$ and $G_Y = \langle\Delta Y_+\rangle^2$. σ corresponds to the pumping parameter defined as the input pump amplitude normalized to the threshold. T stands for the transmission of the output coupler, and μ for the extra-losses in the cavity. V_0 is the phase noise of the pump normalized to the standard quantum limit. In the ideal case, the signal and idler beams generated by the OPO above threshold exhibit perfect intensity correlations and phase anticorrelations, or, in other words, a perfect noise suppression on the phase quadrature of the fields sum Y_+ and simultaneously on the orthogonal quadrature of the fields difference X_-. However, in the experiments, the presence of classical phase noise on the pump beam can seriously affect the phase anticorrelations as stated by eq. 2. Let us underline that this limitation is not present below threshold where the pump noise does not affect the output noise suppression.

Different criteria have been developed to prove entanglement [22]. The inseparability criterion developed by Mancini [23] or the one by Duan *et al.* [24] and Simon [25] are sufficient conditions for A_1 and A_2 to be inseparable. They can be written respectively, in their simpler experimentally testable form as:

$$G_X.G_Y < 1 \quad \text{and} \quad \frac{G_X+G_Y}{2} < 1. \qquad (4)$$

The last quantity will be called separability in the following. The third criterion is the EPR criterion, which

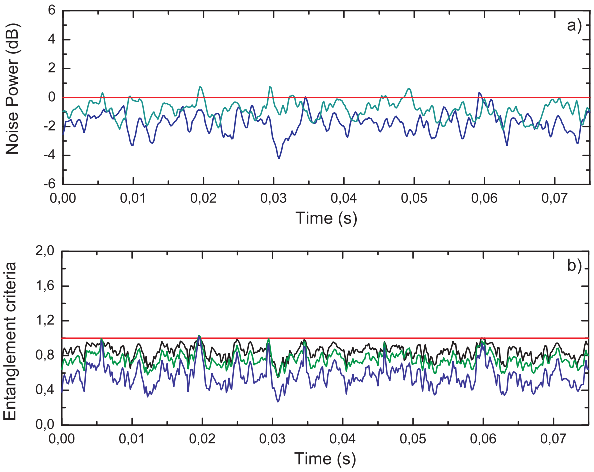

FIG. 2: (a) Normalized noise variances at 20 MHz of the $\pm 45°$ modes and (b) entanglement criteria : Duan (green), Mancini (violet) and EPR (black). The resolution bandwidth is set to 100 kHz and the video bandwidth to 300 Hz.

characterizes a higher degree of quantum correlations and is related to the situation described in 1935 by Einstein, Podolsky and Rosen [26]. This criterion states that the beams are EPR-entangled if, by performing a measurement on one of them, it is possible to retrieve the values of two non-commuting observables on the other beam within the quantum noise. The signal and idler beams exhibit EPR correlations if they verify [27]:

$$V\left(X_1|X_2\right)V\left(Y_1|Y_2\right) < 1. \quad (5)$$

The quantity $V(A|B)$ corresponds to the conditional variance on the observable A obtained from a measurement of B. In terms of the quantities G_X and G_Y, the criterion reads as:

$$\left(2G_Y - \frac{G_Y^2}{\langle\Delta Y\rangle^2}\right)\left(2G_X - \frac{G_X^2}{\langle\Delta X\rangle^2}\right) < 1 \quad (6)$$

with $\langle\Delta Y\rangle^2$ and $\langle\Delta X\rangle^2$ the amplitude and phase variances for the signal or the idler.

By scanning the local oscillator phase, one obtains the whole quadrature noise properties of $A_\pm$. To evaluate the entanglement criteria, one can hold the local oscillator phase so that the measured quadrature would be the one with the minimum noise. Figure 2 (a) presents the minimum quadrature noises of the rotated modes, normalized to the shot noise, for an analyzing frequency of 20 MHz, where it has been measured that the pump excess noise can be neglected. Both quadrature are squeezed : the noise suppression is -0.8 ± 0.7 dB for A_+, and -1.7 ± 0.8 dB for A_-. The Duan and the Mancini criteria can be directly evaluated from these measurements (*cf.* Figure 2 (b) : one finds a separability of $0.7 \pm 0.1 < 1$, and $0.55 \pm 0.10 < 1$ for the Mancini criterion : the beams are indeed entangled. In order to check for the more restrictive EPR criterion, the fields A_1 and A_2 are also detected, as individual noises have to be taken into account to determine conditional variances. As theoretically predicted, the noise on these fields is phase-insensitive and they are found to be approximately shot noise limited. These results correspond to a value for the EPR criterion of $0.85 \pm 0.10 < 1$, thus proving the EPR type correlation between the signal and idler beams. A summary is given on Table 1.

For further applications, it would be interesting to violate the EPR criterion at lower frequencies. However, the residual phase noise on the pump beam limits the noise suppression as stated by eq. 2. To study this effect, we performed measurements at different frequencies. Figure 3 (a) presents the quadrature noise properties of the modes $A_\pm$, normalized to the shot noise as a function of the local oscillator phase, for a frequency of 3.5 MHz. For the mode difference A_-, the curve minima are below the standard quantum limit; by locking the LO phase on the squeezed quadrature, a noise reduction of -2.6 ± 0.3 dB is measured (see Fig. 3 (b). On the mode A_+, the quadrature noise shows a phase dependence similar to that observed on A_-, but it is always well above the reference level. Separability and EPR criterion are both above one. When increasing the frequency, the noise minimum reduces and falls below the standard quantum noise from 6 MHz. There, a squeezing of -0.5 ± 0.5 dB on A_+, and -2.7 ± 0.7 dB on A_- can be observed. These values correspond to an inseparability of $0.7 \pm 0.1 < 1$, thus proving entanglement between the signal and idler. The measured noise level is $+6.5 \pm 0.5$ dB both on A_1 and A_2, which leads to conditional variances in the EPR criterion both greater than 1: the pump excess noise is still too important at this frequency. As a matter of fact, we did not detect EPR-correlations below 20 MHz. Let us note that the observed correlation at 20 MHz is in qualitative agreement with the results reported in ref. [28] concerning the laser phase noise. Further experiments could reduce the low frequency limit for entanglement detection, by improving the pump technical noise suppression with a filtering cavity of higher finesse.

In conclusion, we have shown the ability of a compact device, a type-II self-phase-locked OPO, to directly generate bright EPR beams at the same frequency. The pump excess noise strongly affects the entanglement and the pump thus needs to be filtered. We have studied the effect of this noise and finally demonstrate EPR correla-

TABLE I: Inseparability and EPR criteria, and experimental values measured at 20 MHz.

Criterion	Expression	Measured
Mancini	$G_X.G_Y < 1$	0.55 ± 0.10
Duan	$(G_X + G_Y)/2 < 1$	0.7 ± 0.1
EPR (Reid)	$\left(2G_Y - \frac{G_Y^2}{\langle\Delta Y\rangle^2}\right)\left(2G_X - \frac{G_X^2}{\langle\Delta X\rangle^2}\right) < 1$	0.85 ± 0.10

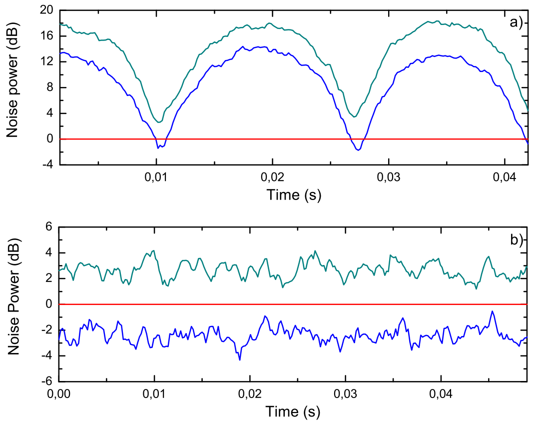

FIG. 3: Normalized noise variances at 3.5 MHz of the ±45° modes (a) while scanning the local oscillator phase and (b) while locking it on the squeezed quadratures. The resolution bandwidth is set to 100 kHz and the video bandwidth to 300 Hz.

tions in a frequency region where it can be reduced. This experiment explores a new regime about quantum properties of OPO above threshold and provides a useful tool for quantum communication protocols in the continuous variable regime.

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