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Experimental investigation of amplitude and phase quantum correlations in a type II OPO above threshold: from the non-degenerate to the degenerate operation

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We describe a very stable type II optical parametric oscillator operated above threshold which provides 9.7 ± 0.5 dB (89%) of quantum noise reduction on the intensity difference of the signal and idler modes. We also report the first experimental study by homodyne detection of the generated bright two-mode state in the case of frequency degenerate operation obtained by introducing a birefringent plate inside the optical cavity.

Type II optical parametric oscillators are well-known to generate above threshold highly quantum correlated bright twin beams. Intensity correlations were experimentally observed several years ago and applied to measurements of weak physical effects [1, 2, 3]. Phase anticorrelations are also theoretically predicted [4]: a type II OPO above threshold could be thus, in principle, a very efficient source of bright EPR beams, which can be used in continuous variable quantum information protocols such as cryptography, teleportation, secret sharing or optical-atomic interfacing [5]. However, the non frequency-degenerate operation makes difficult the study of the phase properties by usual homodyne detection techniques [6]. Frequency degeneracy occurs only accidentally since it corresponds to a single point in the experimental parameter space. Actually, up to now, no direct evidence of anti-correlations has been observed. The generation of EPR beams with type II OPO has been thus restricted to the below threshold regime where it behaves as a passive amplifier [7, 8, 9], unlike above threshold where it is an active oscillator choosing its working point.

In 1998, while working on optical frequency divider, E.J. Mason and N.C. Wong proposed an elegant way to achieve frequency degenerate operation above threshold [10, 11]: a birefringent plate inside the optical cavity and making an angle with the axis of the non-linear crystal induces a linear coupling between the signal and idler and results in a locking phenomenon, which is well-known for coupled mechanical or electrical oscillators [12]. In this original device called "self-phase-locked" OPO, we have shown theoretically that quantum correlations are preserved for small angles of the plate and that the system produces non separable states in a wide range of parameters [13]. We describe here an improvement of the intensity correlations in a "standard" OPO and then report the first experimental demonstration of homodyne detection operated on the bright two-mode state. Our results are finally interpreted as polarization squeezing.

The experimental setup is shown in Fig. 1. A continuous-wave frequency-doubled Nd:YAG laser ("Diabolo", Innolight GmbH) pumps a triply resonant OPO above threshold, made of a semi-monolithic linear cavity: in order to improve the mechanical stability and reduce the reflections losses, the input flat mirror is directly coated on one face of the 10mm-long KTP crystal. The intensity reflection coefficients for the input coupler are 95% for the pump at 532 nm and almost 100% for the signal and idler beams at 1064 nm. The output mirror, with a radius of curvature of 38 mm, is highly reflective for the pump and its transmission coefficient T can be chosen to be 5 or 10%. With $T = 5\%$, at exact triple resonance, the oscillation threshold is less than 15 mW. The OPO length is actively locked on the pump resonance by the Pound-Drever-Hall technique: a remaining 12 MHz mod-

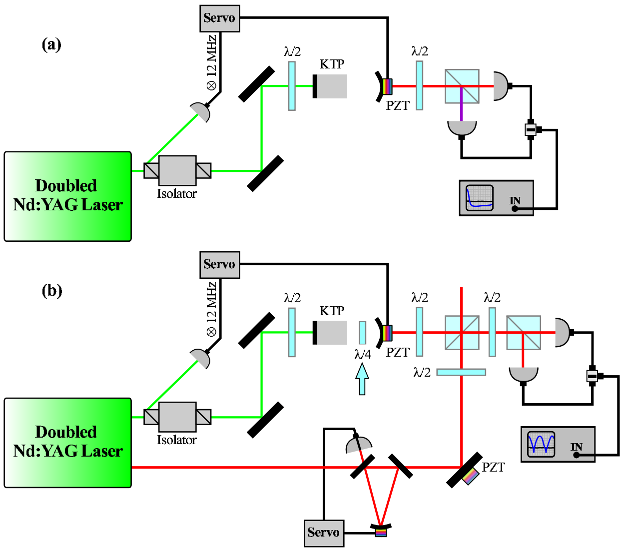

FIG. 1: A doubled Nd:YAG laser pumps above threshold a type II OPO (a) without or (b) with a $\lambda/4$ plate inside the cavity. In (a), intensity correlations are directly measured by a balanced detection scheme. In (b), the frequency-degenerate operation opens the possibility to implement an homodyne detection. The infrared output of the laser is used as local oscillator after filtering.

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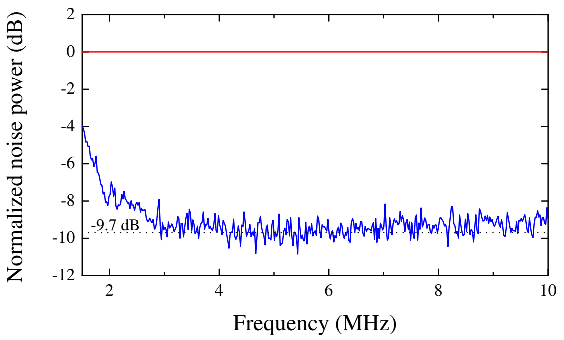

FIG. 2: Normalized noise power of the intensity difference of the signal and idler as a function of the frequency, after correction of the electronic noise. A reduction of 9.7 ± 0.5 dB is reached around 5 MHz.

ulation present in the pump laser is detected by reflection and the error signal is sent to a home-made proportional-integral controller. In order to stabilize the OPO output infrared intensity, the temperature of the crystal is servo-locked at the requested temperature within a mK. In spite of the triple resonance which generally makes OPOs much more sensitive to disturbances, these controls enable a long-term stability: the OPO operates stably during more than one hour without mode-hopping. Depending on the presence of the plate, the output state is characterized by different techniques.

Without the plate, intensity correlations are directly measured by a balanced detection scheme (Fig. 1(a)). The signal and idler orthogonally polarized beams, with different frequencies, are separated on a polarizing beam splitter and detected on a pair of high quantum efficiency InGaAs photodiodes (Epitaxx ETX300). A half-wave plate is inserted before the polarizing beam splitter. When the polarization of the twin beams is turned by 45° with respect to its axes, it behaves as a 50-50 usual beam splitter, which allows to measure the shot noise level. With a transmission $T = 10\%$ for the output mirror, we obtained a noise reduction of 9.7 ± 0.5 dB (89%) around 5 MHz (Fig. 2). To the best of our knowledge, this noise reduction is the strongest reported to date in the experimental quantum optics field.

Intensity correlations can be measured even with non-frequency degenerate beams but the measurement of phase anti-correlations is much easier with degenerate beams and the use of a local oscillator. To achieve the frequency-degenerate operation, a birefringent plate is introduced inside the OPO cavity [10, 11]. This plate is chosen to be exactly $\lambda/4$ at 1064 nm and almost λ at 532 nm pump wavelength. For a well-defined range of parameters – reached by the adjustment of both the crystal temperature and the frequency of the pump laser – a frequency locking phenomenon occurs and can be maintained during more than hour. Degenerate operation is confirmed by interference of the generated beams with a local oscillator or, more directly, by the fact that the generated mode has now a fixed polarization. At the minimum threshold point, the generated state is linearly polarized at +45°. An ellipticity around 2% has been measured.

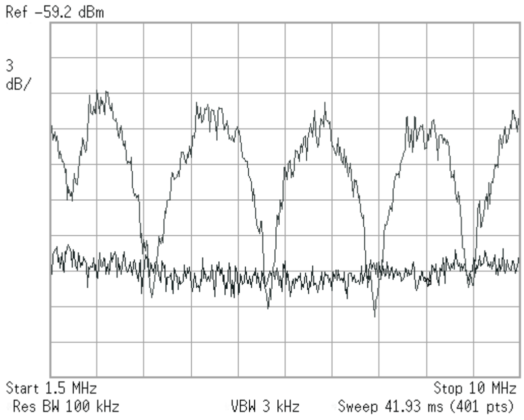

FIG. 3: Noise power of the mode A_- while scanning simultaneously the phase of the local oscillator and the noise frequency between 1.5 and 10 MHz. The lower trace gives the shot noise level.

The theoretical quantum properties of the device have been studied by L. Longchambon *et al.* [13]: for a small angle of the plate, with respect to the transmission of the output mirror, quantum correlations and anti-correlations are preserved. Instead of measuring correlations and anti-correlations, it is equivalent to measure the noise spectrum of the ±45° polarized modes, A_+ and A_-. These orthogonally polarized modes have squeezed fluctuations: for instance the squeezing of A_+ is given by the phase anticorrelations. It should be stressed that this characterization method is strictly equivalent to correlation measurements: the inseparability criterion [14] is defined as the half sum of these two noise reductions. Let us underline, due to the defined phase relation, A_+ is a bright mode, which corresponds to the mean field, and A_- has a zero mean value.

The homodyne detection scheme is depicted on Fig. 1(b). The coherent 1064 nm output is used as a local oscillator after filtering by a triangular 45cm-long cavity with a finesse of 3000. This cavity is locked on the maximum of transmission by the tilt-locking technique [15] and 80% of transmission is obtained. The fringe visibility reaches 0.97. The shot noise level is obtained by blocking the output of the OPO. For the zero mean value mode, A_-, this procedure directly gives the shot noise level. For the bright mode, the incoming power is taken equal to the power of the local oscillator: the shot noise level is thus 3 dB higher than the measured noise.

Figure 3 gives the noise power of the mode A_- while scanning the local oscillator phase, for a transmission $T = 5\%$ and a plate angle of 0.1°. The noise frequency is also scanned in order to give both the noise reduction and its frequency dependance. As expected, more than 3 dB of squeezing is obtained around a few MHz. One

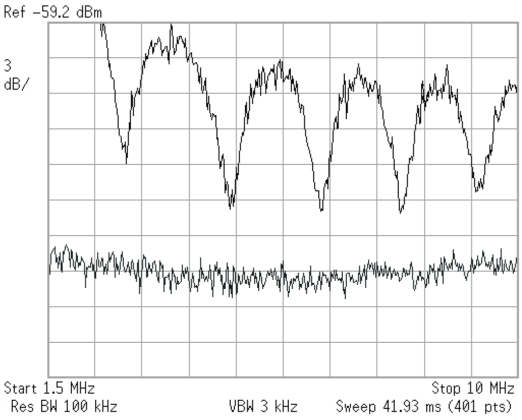

FIG. 4: Noise power of the mode A_+ while scanning the phase of the local oscillator, for a noise frequency between 1.5 and 10 MHz. The shot noise level is given by the lower trace plus 3 dB.

can also make a measurement as a function of the local oscillator phase for a given noise frequency: in this case we have measured at 3.5 MHz a value of squeezing of 4.5 dB. This strong reduction on the mode A_- confirms the quantum correlations of the signal and idler modes.

Figure 4 shows the noise power of the mode A_+ in the same condition. A similar amount of noise reduction is expected. However, a slight excess noise of 3 dB is measured for the minimal noise quadrature: the anticorrelations are thus degraded, probably by external noise sources.

Thus, despite this slight excess noise which prevents from reaching EPR correlations, the generated state is squeezed on the polarization orthogonal to the mean field: A_+ is the main mode and A_- the squeezed vacuum one. This condition is required to obtain a so-called "polarization squeezed" state [16, 17, 18]. 4.5 dB of polarization squeezing has been thus generated by our original self-phase-locked OPO. This is the first experimental demonstration of polarization squeezing with an OPO above threshold. Such states have recently raised great interest, in particular because of the possibility to map quantum polarization state of light onto an atomic ensemble [19].

In conclusion, we have built a compact and very stable type II triply resonant OPO and explored this device above threshold, in different regimes. Thanks to a great stability, the strongest quantum noise reduction to date has been obtained. By adding a plate inside the optical cavity, the frequency degenerate operation then has been reached and has permitted the experimental demonstration of homodyne detection operated above threshold. This result opens a very promising way to the direct generation of intense entangled beams and offers a new and simple method to achieve strong polarization squeezing.

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