Appl. Phys. B 66, 755–758 (1998)

Applied Physics B
Lasers
and Optics

Generation of two-mode quadrature-phase squeezing and intensity-difference squeezing from a cw-NOPO

K.C. Peng, Q. Pan, H. Wang, Y. Zhang, H. Su, C.D. Xie

Institute of Opto-Electronics, Shanxi University, Taiyuan, Shanxi, 030006, P.R. China
(E-mail: kcpeng@deer.szu.edu.cn)

Received: 17 January 1998

Abstract. The configuration of a semimonolithic continuous wave nondegenerate optical parametric oscillator (cw-NOPO) consisting of an α-cut KTP crystal pumped by an intracavity frequency-doubled and frequency-stabilized Nd:YAP laser is reported. Both two-mode quadrature-phase squeezing of 3.7 dB and intensity-difference squeezing of 7 dB have been generated from the cw-NOPO operating respectively below and above the oscillation threshold through the frequency down-conversion process.

PACS: 42.65.Ky; 42.50.Dv

Continous nondegenerate optical parametric oscillators (cw-NOPOs) are one of the most efficient devices for the generation of a nonclassical state of light. Two-mode quadrature squeezed states have been generated from triply resonant NOPOs operating below pump threshold with frequency-degenerate but orthogonally polarized signal and idler fields [1, 2]. Twin beams with intensity quantum correlation have also been produced from NOPOs above threshold in the frequency- and polarization-nondegenerate configuration [3, 4]. The nonclassical light generated from OPOs has been successfuly applied to the quantum nondemolition detection (QND), sub-shot-noise optical measurments and nonclassical excitation for atoms [5–7]. Due to their intrinsic narrow linewidth and wide tunability cw-NOPOs turn out to be very promising sources for high-resolution spectroscopy and atomic trapping.

The potassium titanyl phosphate (KTP) cut in type-II phase matching is a favorite crystal for high-efficiency frequency conversion because of its large nonlinear coefficient together with wide phase matching temperature range, large nonlinear acceptance angle, and extremely low absorption loss between 0.5 μm and 1.4 μm. Usually Nd:YAG lasers were used as the pump sources. However it is impossible to realize frequency doubling and degenerate- or near-degenerate frequency down conversion in KTP crystal through type-II 90° noncritical phase-matching processes with 1.064 μm or 0.53 μm wavelengths of YAG. The beam walk-off within the crystal and polarization mixing effects resulting from the possible type-II critical tuning scheme inevitably confine the performance of KTP inside a high-finesse resonator. Although a pair of properly oriented KTP crystals has been successfully utilized in NOPOs to eliminate beam walk-off, the intracavity losses are increased, which is very unfavorable for nonclassical-state light generation [2]. Following the report about type-II 90° noncritical phase matching in an α-cut KTP crystal at 1.08 μm from Garmash et al. [8], J.Kimble's group accomplished experiments for frequency doubling from 1.08 to 0.54 μm [9] as well as frequency down conversion from 0.54 to 1.08 μm in a ring NOPO operating below threshold to realize the EPR paradox for continuous variables [1] and QND measurement [5].

In this paper, we report experimental results of nonclassical light generation from a semimonolithic cw-NOPO consisting of an α-cut KTP crystal and a concave mirror pumped by an intracavity frequency-doubled ring Nd:YAP laser. A two-mode quadrature-phase squeezed vacuum-state of light is obtained from the subthreshold cw-NOPO operated in a frequency-degenerate but polarization-nondegenerate mode. Twin beams having highly correlated intensity fluctuations in the orthogonally polarized signal and idler modes are produced in the cw-NOPO operated above the oscillation threshold. The quantum noise in the difference of intensities between the twin beams is reduced below the standard quantum limit (SQL). A quadrature-phase squeezing of 3.7 dB and an intensity-difference squeezing of 7 dB are observed. The system can stably operate to generate squeezed light for over half an hour.

1 Experimental principle

The nonclassical lights are generated through the nondegenerate parametric frequency down-conversion process in OPO containing $\chi^{(2)}$-nonlinear medium. In Fig. 1 a_0, a_1, and a_2 stand for the pump field, output signal, and idler modes respectively. The coupled-mode of a_1 and a_2 is defined as [10]

$$d = (a_1 + a_2)/\sqrt{2}\,, \quad d^+ = (a_1^+ + a_2^+)/\sqrt{2}$$

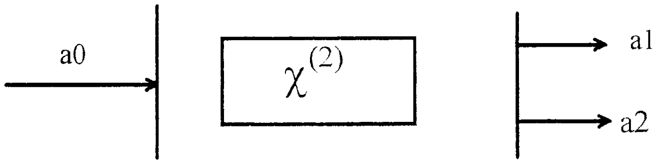

Fig. 1. Experimental principle

and the quadrature components of coupled-mode are

$$D_+ = \sqrt{2}(a_1 + a_2 + a_1^+ + a_2^+)/2\,,$$
$$D_- = \sqrt{2}\mathrm{i}(a_1 + a_2 - a_1^+ - a_2^+)/2\,.$$

The product of quantum fluctuations of the two components is limited by the uncertainty principle, that is [10]

$$\langle(\triangle D_+^2)\rangle\langle(\triangle D_-^2)\rangle \geq \frac{1}{16}\,.$$

If the variance of one of the quadrature components is less than the SQL of $\frac{1}{4}$, the coupled mode is in a two-mode quadrature squeezed state of electromagnetic field. For the NOPO operating below the oscillation threshold, it is a two-mode quadrature squeezed vacuum state, the noise of which is lower than the vacuum noise level.

When the NOPO is operating above the oscillation threshold the intensities of signal and idler modes (I_{a1} and I_{a2}) are quantum correlated, so that the fluctuation of the intensity difference between I_{a1} and I_{a2} is less than that of the corresponding shot-noise-limit (SNL), i.e. the standard quantum limit. According to [3] the SQL is the fluctuation of the "mixed" field of the signal and idler modes:

$$\langle\triangle^2 I_{\mathrm{SQL}}\rangle = \langle\triangle^2 (I_{a1} + I_{a2})\rangle\,.$$

In the case of

$$\langle\triangle^2 (I_{a1} - I_{a2})\rangle < \langle\triangle^2 I_{\mathrm{SQL}}\rangle$$

the fluctuations of the intensity difference between the signal and idler modes are squeezed [3, 10]. The two signal and idler beams are known as twin beams because they are always "born" together.

2 Configurations of Nd:YAP laser and NOPO

A home-made intracavity frequency-doubled and stabilized CW ring Nd:YAP laser was used as the pump source in the experiment [11]. The six-mirror ring cavity, with a total length of 130 cm, is built on an Invar structure. The YAP rod (3 × 77 mm) provides maximum gain at 1.08 μm transition in *c* polarization. In our laser one of the four plane cavity mirrors is a thin film polarizer with reflectivity $R \approx 99.5\%$ for *s* polarization and $R = 8\%$ for *p* polarization. The YAP rod must be orientated carefully to make the *c* axis parallel with the *s* polarization of the cavity mirror. The α-cut KTP nonlinear crystal was placed between two concave cavity mirrors, with curvature radius of 102 mm and reflectivity 99.8% at 1.08 μm, which form a near confocal configuration. The temperature of KTP was actively controlled at the phase-matching temperature (63.5 °C ± 0.01). For the output power of 800 mW at 0.54 μm the intensity fluctuations are less than ±2.5% and the frequency stability is better than ±1 MHz with the frequency-locking system on.

The semimonolithic NOPO consists of a 10-mm-long α-cut KTP crystal ($\theta = 90°$, $\varphi = 0°$), the front face of which is coated for use as input coupler with a transmission of 12% at 0.54 μm and high reflectivity at 1.08 μm, and a concave mirror of 50 mm curvature as the output coupler with a transmission of 5% at 1.08 μm and high reflectivity at 0.54 μm. The length of NOPO cavity is 49 mm. The measured finesse of NOPO is 80 for 1.08 μm. A PZT is stuck on the output coupler to tune the length of cavity.

3 Experiment of quadrature-phase squeezing

For obtaining the quadrature-phase squeezing of coupled mode, the NOPO must be operated in a frequency-degenerate mode. Above the oscillation threshold the multiplicity of modes and the mode-hopping lead to an inherent instability of the NOPO. Our observation for the quadrature-phase squeezing concentrates on the below-threshold region. The harmonic conversion in KTP is a type-II process so that the polarizations of the subharmonic modes are orthogonal. The generation of squeezing requires the simultaneous resonance of pump field, signal, and idler modes. For the alignment of NOPO below threshold a weak infrared emission from the Nd:YAP laser at 1.08 μm is injected into the NOPO (not indicated in Fig. 1). When the length of cavity is scanned by PZT1 mounted on the output coupler (M), the transmission peaks of the three longitudinal modes can be observed on an oscilloscope. By tuning the temperature of crystal the double resonance of orthogonally polarized signal and idler modes can be achieved. Then by inserting an optical wedge (W) in the cavity to compensate the dispersion between pump and subharmonic fields, and slowly tuning the temperature of crystal, the triple resonance is realized when the three peaks are brought to overlap. With the optical wedge, the measured finesse of the NOPO is 80 at 1.08 μm and the total extra intracavity losses are estimated to be 1.3%. After the triple resonance is completed the NOPO is locked on the frequency of pump field via a standard FM-sideband technique [12], and the injected auxiliary infrared beam is blocked to start the squeezing measurement.

The local beam (LO) at 1.08 μm from the pump laser passes through a mode-cleaning cavity (C) to increase the homodyne efficiency and reduce the excess amplitude noise of the LO at high frequencies. The two-mode vacuum squeezing of the output field from the NOPO is observed by combining signal and idler modes with the local oscillator polarized at 45° with respect to both modes. The phase of the local oscillator is scanned by a mirror in the path of LO, which is mounted on a piezoelectric ceramic (PZT2). The overall detection efficiency resulting from the combination of cavity escape efficiency, propagation efficiency, homodyne efficiency for the composite mode formed from signal and idler beams, and photodetector quantum efficiency, is 89%. The phase dependence of the rms noise voltage $V(\theta)$ from the balanced homodyne receivers as a function of local-oscillator phase (θ) at a fixed analysis frequency Ω(2 MHz) is shown in Fig. 3. The phase-independent trace (a) corresponds to the noise voltage (V_0) set by vacuum fluctuations and is ob-

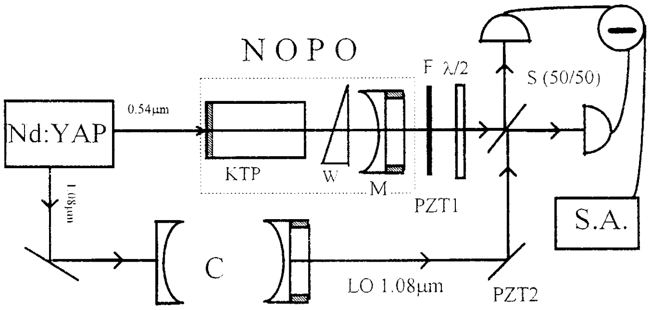

Fig. 2. Generation of quadurature-phase squeezing and detection

tained by blocking the signal input to the balanced detector. Trace (b) exhibits phase-sensitive deviations both below and above the vacuum level, with the dips below trace (a) representing a 57% (≈ 3.7 dB) reduction in noise power relative to the vacuum level. The phase-dependent trace (b) is obtained with the NOPO input present.

4 Experiment of intensity-difference squeezing

To produce twin beams characterized by the intensity-difference squeezing, the cw-NOPO is operated above the oscillation threshold. Compared to quadrature-phase squeezing of two-mode, the quantum-correlated twin beams are relatively easier to obtain. For twin-beam generation the exact frequency-degeneracy of signal and idler modes is not needed, so the optical wedge (W) is not inserted in the cavity. The finesse of NOPO is 110 for 1.08 μm wavelength and the oscillation threshold is 50 mW. An output power of 16 mW of the subharmoic modes is detected at 100 mW pump power. For the detection of intensity-difference squeezing, a polarized beamsplitter is used instead of the above-mentioned 50% beamsplitter (S) and the local beam is blocked (Fig. 2). The noise power spectrum of the intensity difference between twin beams is shown in Fig. 4. The analyzed frequency range is from 1 to 6 MHz. Trace (a) is the shot-noise-limit measured by rotating the polarization of the output signal and idler beams to 45° relative to the polarization direction of the polarized beamsplitter [3]. Trace (b) is the noise spectrum of the intensity difference between twin beams and (c) is the electronic noise floor. The maximum quantum noise reduction is 80% (7 dB) around 2.5 MHz. If one takes into account the efficiency of the detection system, the actual squeezing for the output twin beams from the OPO is 90%.

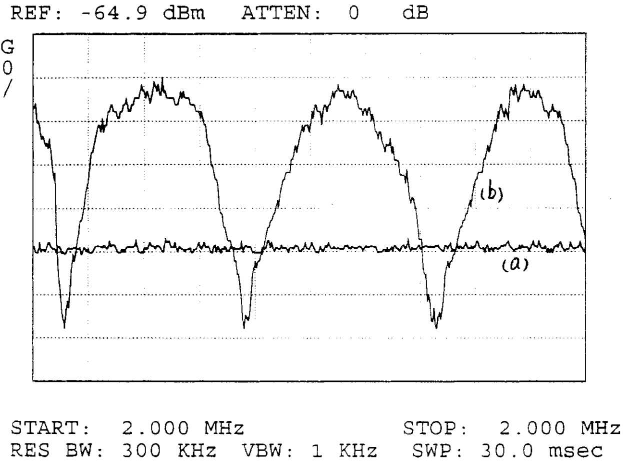

Fig. 3. Dependence of noise voltage on local-oscillator phase

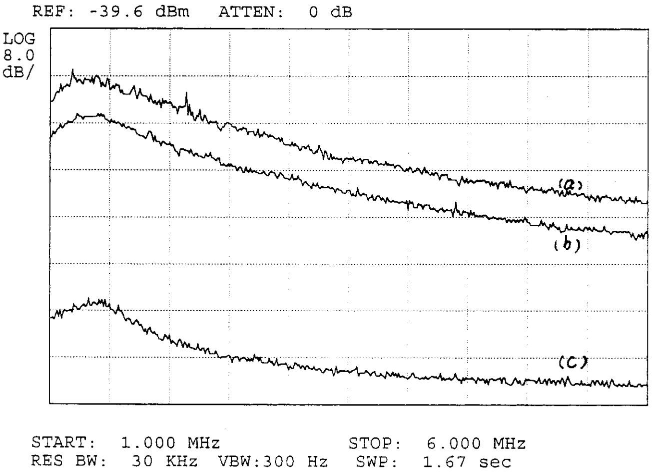

Fig. 4. Experimental result of intensity difference squeezing. (Time of the entire sweep 1.67 s, analysis bandwidth 30 kHz, video bandwidth 300 Hz). Trace (a) is the shot-noise-limit, (b) is the noise spectrum of the twin-beam intensity difference, and (c) is the electronic noise floor

5 Conclusion

Both quadrature-phase squeezing of 3.7 dB and intensity-difference squeezing of 7 dB have been generated with a cw-NOPO. For quadrature-phase squeezing the application of an optical wedge instead of the dispersion gas [13] can avoid the influence of intracavity gas flow, and therefore the stability of our semimonolithic NOPO is quite good. With the entire system locked in, a stable cw nonclassical light can be generated in an uninterrupted fashion for over half an hour. These two kinds of nonclassical light have already been employed in a variety of sub-shot-noise optical measurements [5, 6, 9]. Higher conversion efficiency, lower pump power, relatively simple configuration, and better stability are the advantages of our system. If single-mode frequency-stabilized LD-pumped Nd:YAP lasers are available, the cw-NOPO with an α-cut KTP crystal at type-II noncritical phase-matching would be a practical nonclassical light source for highly sensitive spectroscopy and optical measurements with the sensitivity beyond the standard quantum limit.

Acknowledgements. This work was supported in part by the National Natural Science Foundation of China (No. 69438010) and Shanxi Provincial Science Foundation.

References

1. Z.Y. Ou, S.F. Fereira, H.J. Kimble, Kunchi Peng: Phys. Rev. Lett. **68**(25), 3663 (1992)
2. Peng Kunchi, Huang Maoquan, Liu Jing et al.: Acta Phys. Sinica **42**(7), 1079 (1993), in Chinese

3. A. Heidmann, R.J. Horowicz, S. Reynaud, E. Giacobino, C. Fabre, G. Camy: Phys. Rev. Lett. **59**, 2555 (1987); C. Nabors, R. Shelby: Phys. Rev. Lett. A **42**, 556 (1990); J. Mertz, T. Debuisschert, A. Heidmann, C. Fabre, E. Giacobino: Opt. Lett. **16**, 1234 (1991)
4. Qing Pan, Yun Zhang, Tiancai Zhang, Changde Xie, Kunchi Peng: J. Phys. D **30**, 1588 (1997)
5. S.F. Fereira, Z.Y. Ou, H.J. Kimble: Phys. Rev. Lett. **72**(2), 214 (1994); Min Xiao, Lingan Wu, H.J. Kimble: Phys. Rev. Lett. **59**, 278 (1987); P. Grangier, R. Slusher, B. Yurke, A. Laporta: Phys. Rev. Lett. **59**, 2153 (1987); E. Polzik, J. Carri, H. Kimble: Phys. Rev. Lett. **68**, 3020 (1992)
6. Wang Hai, Xie Changde, Pan Qing, Xue Chenyang, Zhang Yun, Peng Kunchi: Proceedings of the Third International Conference on Quantum Communication & Measurement, Hakone, Japan (1996); P.H. Souto, Ribeiro, C. Schwob, A. Maitre, C. Fabre: Opt. Lett. **22**, 1893 (1997)
7. N.Ph. Georgiades, E.S. Poizik, K. Edamatsu, H. Kimble: Phys. Rev. Lett. **75**, 3426 (1995)
8. V.M. Garmash, G.A. Ermakov, N.I. Parlova, A.V. Tarasor: Sov. Tech. Phys. Lett. **12**, 505 (1986)
9. Z.Y. Ou, S.F. Pereira, E.S. Polzik, H.J. Kimble: Opt. Lett. **17**, 640 (1992)
10. K.J. McNeil, C.W. Gardiner: J. Phys. A **28**(3), 1560 (1998); Tiancai, Zhang, Chande Xie, Kunchi Peng: Sci. China (Ser. A) **37**(2), 227 (1994)
11. Pan Qing, Zhang Jun, Zhang Tiancai, Li Ruining, Peng Kunchi: Chin. J. Laser **23**, 6 (1996), in Chinese
12. R.W.P. Drever, J.L. Hall, F.V. Kowalski, J. Hough,G.M. Ford, A.J. Munley, M. Ward: Appl. Phys. B **31**, 97 (1983)
13. S.F. Pereira, Peng Kunchi, H.J. Kimble: *Coherence and Quantum Optics* VI (Plenum, New York 1990) p. 889