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Experimental investigation of intensity difference squeezing using Nd:YAP laser as pump source*

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Abstract. A strong quantum correlation between twin-beams at 1.08 μm wavelength was observed. The intensity difference noise of twin-beams, which is generated by a semimonolithic OPO cavity pumped by a frequency-doubled and stabilized Nd:YAP laser, is about 80% (7 dB) below the short noise limit at the measurement frequency of 1.5 MHz. The threshold of the optical parametric oscillator is about 20 mW. The parametric dependence of the quantum correlation is experimentally investigated. The experimental results agree with the theory well.

1. Introduction

The generation of twin-beams and their quantum correlation have been extensively studied because they have potential applications in high-sensitivity optical measurements [1, 2]. Idler and signal photons, which are generated simultaneously in the paramatric downconversion process, are known to have a strong quantum correlation and the noise of their intensity difference is expected to be below the short noise level (SNL) at the frequencies within the cavity bandwidth. 'Twin-beams' were first investigated theoretically by Reyaud *et al* [3]. A 30% quantum noise reduction was obtained by using an optical parametric oscillator (OPO) cavity pumped by a single-mode Ar-ion laser at 0.528 μm in 1987 [4]. This result was improved with a larger transmission of the output mirror of the OPO (6.3% instead of 0.8%) and a better pump source (intracavity frequency-doubled Nd:YAG laser instead of the Ar-ion laser). A quantum noise reduction of 86% was observed at the pump threshold of 390 mW [5].

Recently we obtained a twin-beam quantum noise reduction of 50% using an OPO pumped by an intracavity frequency-doubled and stabilized Nd:YAG laser. The infrared transmission coefficient of the OPO output mirror was 3%. However, it is impossible to attain type II 90° non-critical phase matching in a KTP crystal with the 0.53 μm light produced by a Nd:YAG laser. The walk-off effect and polarization mixing effects affect the improvement of the conversion efficiency. To solve this problem, a pair of properly oriented KTP crystals was inserted inside the OPO cavity [6, 7], but this increased the intracavity loss and degraded the quantum correlation. Thus, we designed the frequency-doubled and stablilized Nd:YAP laser [8], which produces light at 0.54 μm that can realize type II 90° non-critical phase matching in an α-cut KTP crystal [9, 10].

The intracavity losses are reduced and the efficiency of downconversion is improved by using an OPO cavity which consists of a semimonolithic KTP crystal and an output mirror. When the transmissions of the output mirror are 1.5%, 3% and 5%, the thresholds of OPO are 20, 50 and 80 mW respectively. When the pump powers are 30, 60 and 90 mW, the output powers of the subharmonic fields are 6, 10 and 20 mW and the corresponding quantum noise squeezing of the intensity difference between the twin-beams are 50%, 68% and 80% respectively. Taking the quantum efficiency of the detection system into account the actual quantum noise reductions of the outputs are 56%, 78% and 90% respectively. By increasing the pump power, the quantum noise does not change at the same output coupling efficiency. This shows that the noise reduction of the twin-beam intensity difference is insensitive to pump power, but varies with the output coupling efficiency.

2. Theoretical model

The measured intensity difference spectrum of a twin-beam which is generated by non-degenerate parametric downconversion is expressed by [4, 11].

$$S(\Omega) = S_{SNL}\left(1 - \frac{\eta\xi}{1 + \Omega^2\tau_c^2}\right) \qquad (1)$$

where Ω is the noise frequency, S_{SNL} is the shot noise limit, τ_c is the cavity storage time, η is the quantum efficiency

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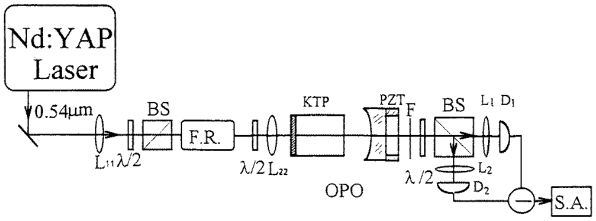

Figure 1. Experiment set-up. L$_{11}$, L$_{22}$, mode-matching lenses; BS, beam splitter; FR, Farady rotator; $\lambda/2$, half-wave plate; F, filter; KTP, semimonolithic KTP crystal; L$_1$, L$_2$, focusing lenses; D$_1$, D$_2$, detectors; SA, spectrum analyser.

of the detection system, $\xi = T/(T+\delta)$ is the OPO output coupling efficiency, T is the transmission coefficient of the cavity output coupling mirror and δ is extra-cavity loss.

3. Experimental details

The experimental set-up is shown in figure 1. The OPO operates above threshold. The pump laser is a frequency-doubled and stabilized Nd:YAP laser, its frequency is stabilized on an external Fabry-Pérot cavity. The long-term frequency stability is about 2 MHz. The total output is 800 mW with 4% intensity stability.

A half-wave plate and a polarizing beam splitter are used to adjust the power in front of the OPO. A Faraday rotator (FR) and a polarizing beam splitter form an optical isolator. L$_{11}$ and L$_{22}$ are mode-matching lenses of 400 and 150 mm focal length respectively. In order to reduce the transmission losses and the reflection disturbance, all surfaces encountered by the green beam are antireflection coated.

The OPO cavity consists of a 10 mm long α-cut semimonolithic KTP crystal and a concave mirror of 20 mm curvature. The front face of the KTP crystal is coated for use as the input coupler with a transmission of 15% at 0.54 μm and high reflectivity at 1.08 μm. The output coupler is highly reflective for 0.54 μm wavelengths and with a certain transmission for 1.08 μm. The length of the OPO cavity is 19 mm. When the output transmissions are 1.5%, 3% and 5%, the measured cavity finesses for 1.08 μm are 170, 140 and 110 respectively. The total extra losses (surface scattering, crystal absorption and residual reflection, etc) are estimated to be 1%, 0.7% and 0.3% and output coupling efficiencies are 0.6, 0.81 and 0.94. The finesses for 0.54 μm are 43, 44 and 47 respectively.

The b-axis of the crystal KTP is parallel to the horizontal (less than 0.5°), so that the output light is polarized in horizontal and vertical directions. In our experiment, we ensure the pump mode is e$_2$ by rotating the half-wave plate, i.e. the pump polarization is parallel to the b-axis of the crystal. The KTP crystal is cut according to the need for frequency doubling at 1.08 μm with type II 90° non-critical phase matching, so that the downconverted twin infrared beams are cross polarized with near degeneracy at 1.08 μm.

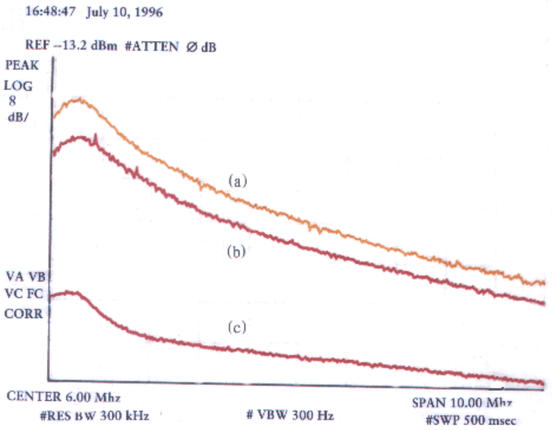

Figure 2. Experiment results. Curve (a) is the associated shot noise power spectrum, (b) is the beam intensity difference noise power spectrum and (c) the electrical noise level.

The characteristics of the detection system have been carefully checked. The imperfection of the polarizing beam splitter used in our experiment was less than 1%.

The length of the OPO can be tuned by a PZT attached to the output coupler. The temperature of the crystal is actively controlled at the phase-matching temperature. A twin-beam is produced when the OPO is operating above the threshold. Compared with previously used Nd:YAG systems, our Nd:YAP system has a much lower pump threshold for parametric downconversion. The thresholds for output transmissions of 1.5%, 3% and 5% are only 20, 50 and 80 mW. When the pump powers are 30, 60 and 90 mW, the output powers of subharmonic fields are 6, 16 and 20 mW.

Slight leaks of pump light from the OPO are blocked by a filter. The outgoing downconverted beams are separated by a polarizing beam splitter and monitored by photodiodes D1 and D2 (ETX500T). The outputs of the photodiodes are amplified and subtracted; the noise of the intensity difference is recorded by a spectrum analyser. To ensure balance of the detection system, the photodiodes were carefully chosen and electronic compensation is included. The total quantum efficiency of the detection system is 88%.

A half-wave plate is insert in the twin-beam before the polarizing beam splitter. As shown by Heidmann *et al* [4], when the polarization of the two beams is rotated by an angle of 45°, the noise measured in the intensity difference is the shot noise limit, and when the two beams are rotated by an angle of 0°, the noise measured in the intensity difference is the intensity difference spectrum between the twin-beams.

4. Experimental results

Figure 2 shows the noise spectrum of a twin-beam generated by the OPO with 5% transmission of the output mirror. The frequency range is from 1 to 11 MHz. Curve (a) is the shot noise limit, curve (b) is the noise spectrum of the twin-beam intensity difference and

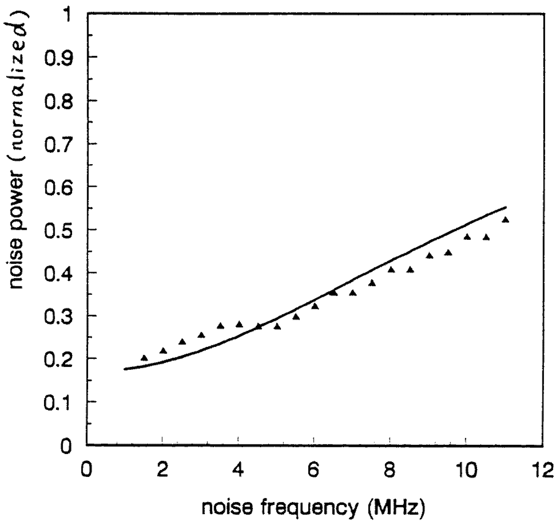

Figure 3. Comparison between experimental (symbols) and theoretical (full curve) results.

curve (c) is the electronic noise level. The maximum quantum noise reduction is 80% (7 dB) near 1.5 MHz which corresponds to 90% of actual squeezing.

Figure 3 shows the comparison between experimental and theoretical results; and full curve represents the theoretical results obtained from equation (1) with parameters $\xi = 0.94$ and $\eta = 0.88$. The triangles are the experimental results which fit the theoretical curve well.

When the transmissions of the output mirror are 1.5%, 3% and 5%, we observe quantum noise reductions of 50% (3 dB), 68% (5 dB) and 80% (7 dB) respectively. Figure 4 shows the relation between the quantum noise reduction and the pump power, where the full lines are the theoretical data and the symbols are the measured results which are slightly lower than those given by the theory. This is probably because the detection system efficiency η used in equation (1) is slightly higher than that in the actual system. The squeezing is not sensitive to pump power and increases with output coupling efficiency.

5. Conclusion

We observed a quantum noise reduction of up to 80% in the intensity difference between twin-beams generated by a non-degenerate type II 90° non-critical phase-matching optical parametric oscillator pumped by 0.54 μm green light operating above threshold. We verify that the quantum noise reduction is insensitive to the pump power but varies with the output coupling efficiency. The experimental results fit the theory quite well. Compared with an OPO pumped by a Nd:YAG laser, our system has several advantages: higher conversion efficiency, lower pump threshold, and relatively simple configuration. If the Nd:YAP crystal were pumped by laser diode (LD), an all-solid mini ‘squeezer’ may be designed. This non-classical ‘laserlike’ system with a certain intensity may be extensively used in many fields, such as high-sensitivity spectroscopy, the measurement of amplitude modulation and optical communications.

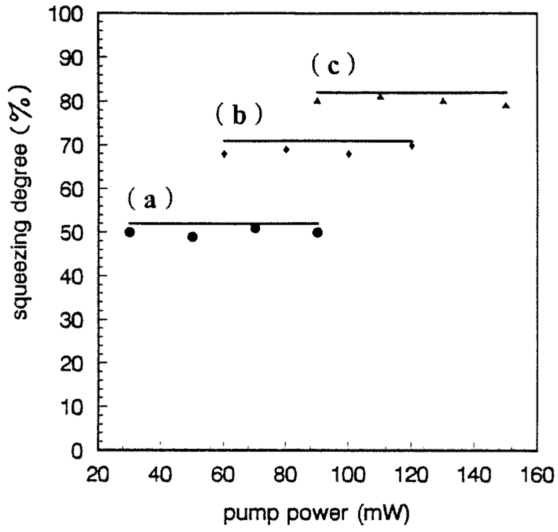

Figure 4. Squeezing degree versus pump power at 1.5 MHz. Full lines, theoretical values; symbols, experimental results. (a) ξ = 0.6, (b) ξ = 0.81, (c) ξ = 0.94.

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