Generation and application of twin beams from an optical parametric oscillator including an α-cut KTP crystal

Jiangrui Gao, Fuyun Cui, Chenyang Xue, Changde Xie, and Peng Kunchi

Institute of Opto-Electronics, Shanxi University, Taiyuan 030006 Shanxi, China

Received January 20, 1998

Measurement slight amounts of absorption of light with accuracy beyond the standard quantum limit has been experimentally demonstrated. The quantum-correlated twin beams used in the measurement were generated from a nondegenerate optical parametric oscillator including an α-cut $KTiOPO_4$ crystal pumped by an intracavity frequency-doubled Nd:YAG laser. The noise in the intensity difference between the twin beams was reduced by 88% below the standard quantum limit (SQL). The signal-to-noise ratio was improved by 7 dB with respect to the SQL of the total light employed in the experiment and by 4 dB with respect to that of the signal light.

OCIS codes: 330.1880, 190.4410, 190.4970, 270.6570.

In recent years, optical parametric oscillators (OPO's) have become important devices to produce nonclassic light with observed fluctuations below the standard quantum limit (SQL).[1] Quadrature phase squeezing of the electromagnetic field was obtained by Wu *et al.*[2] in 1986 with a degenerate OPO operating below the oscillation threshold. Twin beams with highly correlated intensity fluctuations were generated from the nondegenerate OPO's above threshold.[3,4] The quantum noise of the intensity difference between the twin beams was reduced significantly below the SQL. In 1995 the Wigner function of a continuous-wave, strongly squeezed vacuum state was reconstructed in a subthreshold monolithic lithium niobate OPO.[5] Squeezing with an adjustable direction of the noise ellipse from the pump beam reflected by a triply resonant OPO was observed in 1997.[6]

Squeezed light from OPO's has been used to improve the precision of optical measurements with sensitivities beyond the SQL. The quadrature-squeezed vacuum states of light were employed in 1987 to demonstrate sub-shot-noise measurements in weak absorption[7] and interferometry.[8] The intense twin beams have also been used to improve the sensitivity of signal recovery,[9] slight absorption measurement[10] and two-photon absorption spectroscopy.[11] In the research reported in Refs. 9–11 the improvement in the signal-to-noise ratio with respect to the SQL's of the total light used in each of the respective experiments was 2.2, 2.5, and 1.9 dB.

Here we report new experimental results of the generation and application of twin beams to measure slight amounts of absorption. Using an α-cut $KTiOPO_4$ (KTP) crystal in an OPO, we reduced the noise power of the intensity difference between the twin beams by 9.2 dB below the SQL and demonstrated the sub-shot-noise measurement. The signal-to-noise ratio was improved by ~7 dB relative to the SQL of the intensity amounts and by 4 dB relative to that of the signal light.

For frequency doubling and frequency downconversion with a degenerate frequency it is impossible to attain type II 90° noncritical phase matching in a KTP crystal with the light produced by a YAG laser.[12] Usually the KTP crystals are cut according to the requirements for angular phase matching (~22.3° relative to the x axis of the crystal).[3,4] In this case the walk-off effect among the pump, signal, and idler beams inevitably affects the conversion efficiency. However, for frequency-nondegenerate downconversion α-cut (that is, $\theta = 90°$, $\varphi = 0°$) KTP can perform 90° noncritical phase matching with a pump wavelength of 0.53 μm. Frequency conversion from 0.53 to 1.090 and 1.039 μm was accomplished by Yang *et al.*[13] in a singly resonant OPO including an α-cut KTP. The 90° noncritical phase matching permitted collinear transmission of the three modes in an OPO, so the nonlinear conversion efficiency could be significantly improved.

The experimental setup for twin-beam generation and sub-shot-noise measurement is shown schematically in Fig. 1. The pump source is an intracavity frequency-doubled and frequency-stabilized Nd:YAG laser.[14] The triply resonant OPO consists of two concave mirrors with 20-mm radii of curvature. The transmissions for the input coupler are 14% at 532 nm and high reflectivity at the infrared wave lengths of the signal and the idler modes (1090 and 1039 nm, respectively). The transmissions for the output coupler

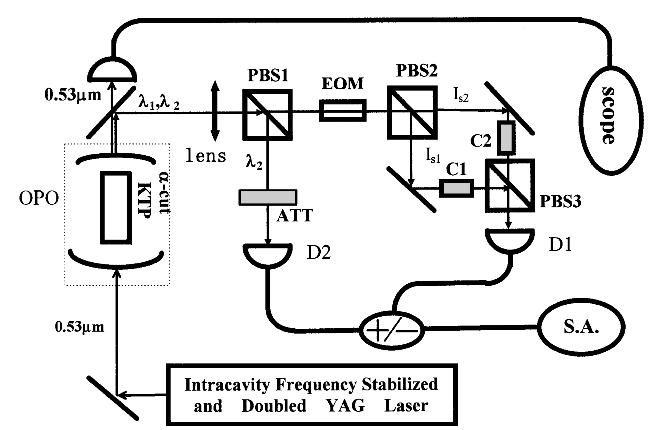

Fig. 1. Schematic of the experiment for twin-beam generation and weak absorption measurement.

0146-9592/98/110870-03$15.00/0

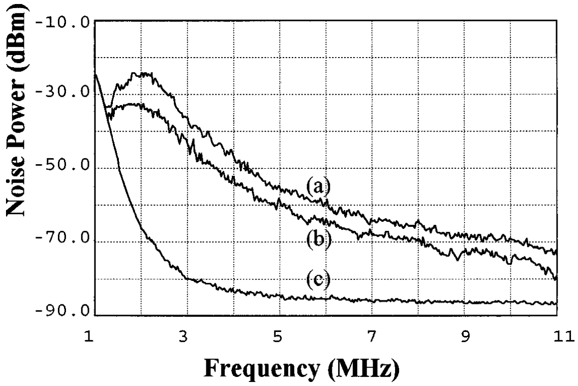

Fig. 2. Noise power spectrum of the intensity difference between the twin beams. Resolution bandwidth, 30 kHz; video bandwidth, 3 kHz. (a) Shot-noise limit of the total intensity of the twin beams, (b) noise power spectrum of the intensity difference between the twin beams, (c) electronic noise power.

are 7.2% at the range from 1000 to 1100 nm and highly reflective at 532 nm. An α-cut KTP crystal 10 mm long is placed in the center of the OPO with a cavity length of 3.8 mm. The waists of the beams in the cavity are $\sim$50 μm for infrared light and $\sim$35 μm for green light. The total intracavity extra loss for the subharmonic waves is $\sim$0.4%. The crystal is actively controlled around the phase-matching temperature, which is close to room temperature. The oscillation threshold of OPO is less than 100 mW in the case of exact triple resonance, which can be achieved by adjustment of the temperature of the crystal in the phase-matching range. The cavity length of the OPO is modulated at 20 kHz by a piezoelectric transducer attached to an input coupler, and a lock-in technique is applied to the infrared intensity to generate the error signal used in the electronic loop. PBS1–PBS3 are polarizing beam splitters. The signal and the idler beams from the OPO are separated by PBS1; then the idler beam ($\lambda_2 = 1039$ nm) is detected by InGaAs photodiode D_2 (Epitaxx Model EXT300). The amplitude of the signal beam ($\lambda_1 = 1090$ nm) is modulated near 2 MHz in an electro-optical modulator (EOM). The modulated signal is separated by PBS2 into two equal parts, I_{s1} and I_{s2}; then they are recombined by PBS3 and detected by photodiode D1. In this system if $I_{s1} = I_{s2}$ the modulated signals will be canceled after recombining at PBS3 because of the opposite orientation of the modulation peaks in I_{s1} and I_{s2}. An intensity attenuator (ATT) is inserted before D2 to balance the dc photocurrents in the signal and the idler channels. The outputs of D1 and D2 are amplified and subtracted at the 180° power combiner ($-$). The noise of the differential photocurrent is recorded by a spectrum analyzer (S.A.).

We measured the noise power spectrum of the intensity difference between the twin beams by placing D1 and D2 directly behind the two output ports of PBS1. Figure 2 shows the measured noise power spectra in which curves (a)–(c), respectively, show the SQL that is obtained and aligned according to the method described in Ref. 3, the noise power spectrum of the intensity difference between the twin beams, and the electronic noise floor. The total power of the twin beams is 12 mW at the pump power of 160 mW. The maximum noise reduction near 2 MHz is $\sim$88% ($\sim$9.2 dB) below the SQL. If the efficiency of the detection system ($\sim$92%) is taken into account, the exact noise reduction at the output of OPO should be 94%.

For the weak absorption measurement two identical absorption cells with solvents C1 and C2 were placed in I_{s1} and I_{s2}. The two arms were carefully balanced to cancel the modulated signal. After adjusting the attenuator to obtain equal dc photocurrents from D1 and D2, we dropped a few of absorption media into one of the cells such that the balance was destroyed and the modulated signal emerged from the noise background. In Fig. 3 curve (a) is the result measured with coherent light, the intensity of which is exactly equal to that of the twin beams used in the measurement. Curve (b) is obtained with the twin beams of quantum correlation. It is obvious that because of the reduction of noise in curve (b) the signal-to-noise ratio is improved approximately 7 dB. Compared with that in Fig. 2, the intensity noise in Fig. 3 is reduced by 2.2 dB because the insertion losses of the modulator and absorption cells reduce the quantum correlation between the twin beams.

Strictly speaking, when we refer to a sub-shot-noise measurement the SQL of the noise should be that of the signal beam rather than that of the twin beams. For a good experimental system the losses of the signal and the idler beams should be made as nearly equal as possible; therefore the intensities of these beams can be considered identical. In this case the SQL of the signal beam should be 3 dB less than that of the twin beams ($\Delta N = \overline{N}$; the noise of the photon number is equal to the average photon numbers). Curve (a) of Fig. 4 shows the SQL for the signal beam, which is measured with half the amount of coherent light used in Fig. 3 ($\sim$6 mW). An improvement of the signal-to-noise ratio of $\sim$4-dB is achieved by use of the twin beams [curve (b)], in accordance with the above discussion. Curves (c) in Figs. 3 and 4 are the

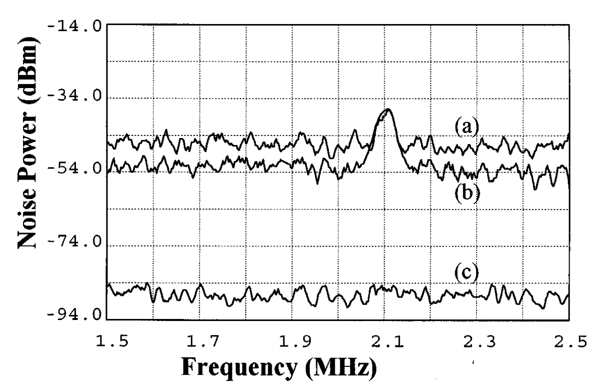

Fig. 3. Measurement of sub-shot-noise weak absorption. Resolution bandwidth, 3 kHz; video bandwidth, 3 kHz. (a) Shot-noise limit of the total intensity of the twin beams, (b) noise power spectrum of the intensity difference between the twin beams with the absorption information, (c) electronic noise power.

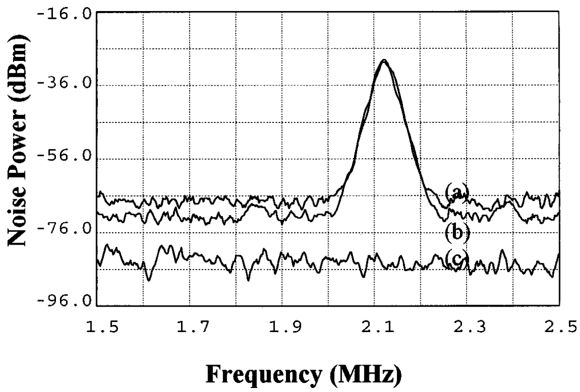

Fig. 4. Measurement of sub-shot-noise weak absorption. Resolution bandwidth, 3 kHz; video bandwidth, 3 kHz. (a) Shot-noise limit of the total intensity of the signal beam, (b) noise power spectrum of the intensity difference between the twin beams with the absorption information, (c) electronic noise power.

electronic noise floors. In the rigorous meaning, only when the quantum noise of the intensity difference between the twin beams is 3 dB less than the SQL can the sub-shot-noise measurement be made.

It should be mentioned that the minimum detectable absorption is limited by the modulation ratio.[15] For the electro-optical modulator used in our experiment the modulation ratio is only 49 dB; otherwise the extra noise would be too high and therefore the minimum detectable absorption would be rather poor ($\sim 3.5 \times 10^{-3}$), much less even than that of shot-noise-limited detection ($\sim 10^{-7}$) found by Wong and Hall.[15] However, our experiment has demonstrated that the minimum detectable absorption can be reduced by a factor of $\sqrt{R}$ (R is the normalized noise power of the intensity difference between the twin beams; $R = 0.2$ for the noise power reduction of 7 dB) when the quantum-correlated twin beams are used instead of the coherent state light.[10] It is obvious that if a better modulator is employed, better absolute sensitivity of measurement can be achieved with our system.

In conclusion, highly quantum-correlated twin beams characterized by an intensity difference noise reduction of as much as 9.2 dB have been generated from a triply resonant OPO including an α-cut KTP crystal pumped by a frequency-doubled Nd:YAG laser. The 90° noncritical phase matching eliminated the beam walk-off effect and ensured higher conversion efficiency at the relatively lower pump power. The frequency nondegeneracy between the signal and the idler beams does not influence the intensity quantum correlation if the response characteristics of the detectors are no longer different in frequency. In experiments using twin beams, sub-shot-noise measurement related to the SQL of a signal beam has been demonstrated for the first time to our knowledge. The improvement of signal-to-noise ratio was 4 dB beyond the SQL of the signal beam. Although the absolute sensitivity of the measurement is rather low in this experiment, we demonstrated that significant improvement of the signal-to-noise ratio beyond the SQL can be realized by use of correlated twin beams.

This research was partially supported by the National Natural Science Foundation of China (Approved No. 69438010, No. 69778015) and the Shanxi Provincial Science Foundation.

References

1. E. Giacobino and C. Fabre, eds., special issue on quantum noise reduction in optical systems: experiments, Appl. Phys. B **55,** 210–216, 250–265 (1992).
2. L.-A. Wu, H. J. Kimble, J. L. Hall, and H. Wu, Phys. Rev. Lett. **57,** 2520 (1986); L.-A. Wu, M. Xiao, and H. J. Kimble, J. Opt. Soc. Am. B **4,** 1465 (1987).
3. A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, C. Fabre, and G. Camy, Phys. Rev. Lett. **59,** 2555 (1987); J. Mertz, T. Debuisschert, A. Heidmarn, C. Fabre, and E. Giacobino, Opt. Lett. **16,** 1234 (1991).
4. H. Wang, C. D. Xie, J. R. Gao, and K. C. Peng, Acta Opt. Sin. **16,** 1144 (1996); Q. Pan, Y. Zhang, T. C. Zhang, C. D. Xie, and K. C. Peng, J. Phys. D **30,** 1588 (1997).
5. G. Breitenbach, T. Muller, S. F. Pereira, J.-Ph. Poizet, S. Schiller, and J. Mlynek, J. Opt. Soc. Am. B **11,** 2304 (1995).
6. K. Kasai, J. R. Gao, and C. Fabre, Europhys. Lett. **40,** 25 (1997).
7. M. Xiao, L.-A. Wu, and H. J. Kimble, Opt. Lett. **13,** 476 (1988).
8. M. Xiao, L.-A. Wu, and H. J. Kimble, Phys. Rev. Lett. **59,** 278 (1987); P. Grangier, R. E. Slusher, B. Yurke, and A. LaPorta, Phys. Rev. Lett. **59,** 2153 (1987).
9. C. D. Nabors and R. M. Shelby, Phys. Rev. A **42,** 556 (1990).
10. H. Wang, C. D. Xie, Q. Pan, C. Y. Xue, Y. Zhang, and K. C. Peng, in *Proceedings of the Third International Conference on Quantum Communication and Measurement* (Plenum, New York, 1997), p. 445.
11. C. Fabre, K. Kasi, J. R. Gao, C. Schwob, A. Maître, and P. H. Souto-Ribeiro, presented at the Fifth Conference, Balatanfuce, Hungary, May 1997; P. H. Souto Ribeiro, C. Schwob, A. Maître, and C. Fabre, Opt. Lett. **22,** 1893 (1997).
12. Z. Y. Ou, S. F. Pereira, H. J. Kimble, and K. C. Peng, Phys. Rev. Lett. **68,** 3663 (1992).
13. S. T. Yang, R. C. Eckardt, and R. L. Byer, Opt. Lett. **18,** 971 (1993).
14. J. R. Gao, H. Wang, C. D. Xie, and K. C. Peng, Appl. Opt. **34,** 1519 (1995).
15. N. C. Wong and J. L. Hall, J. Opt. Soc. Am. B **2,** 1527 (1985).