Observation of Quantum Noise Reduction on Twin Laser Beams

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We have used a two-mode optical parametric oscillator operating above threshold to generate high-intensity twin beams which exhibit quantum correlations. The noise power measured on the intensity difference between two such beams is reduced by 30% below the shot-noise limit. Noise reduction is observed over a broad range of frequencies.

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Sensitivity in optical measurements has long been considered to be ultimately limited by the shot-noise limit (SNL) obtained for ideal laser light. Recent experiments[1-5] have proved that it is possible to reduce the fluctuations of one quadrature component of an electromagnetic field below the vacuum fluctuation level, allowing one to beat the shot-noise limit, for example, in interferrometric measurements.[6,7]

It can also be useful to generate light beams having an intensity noise below the SNL.[8-15] A possible way to approach such states is the generation of twin laser beams, i.e., two beams of intensities I_1 and I_2 having the same intensity fluctuations. One can then use one of the beams in a servo loop to stabilize the other one below the SNL.[8,12] Unfortunately, the usual beam splitters (semireflecting plate, polarizing beam splitter, . . .) randomly distribute photons in their two output ports and therefore cannot overcome the SNL.[16] In contrast, parametric downconversion is known to produce highly correlated "twin photons" at the signal and idler frequencies.[17-20] If the parametric medium is inserted in an optical cavity resonant for both signal and idler frequencies, oscillation on a single pair of modes takes place. We have theoretically shown[21-23] that such a two-mode optical parametric oscillator (OPO) operating above threshold produces two intense "twin beams," having intensities correlated to better than SNL. Actually, this intensity correlation corresponds to a squeezing of the amplitude difference between the twin fields.[21,23]

This quantum correlation property can be simply understood in terms of photons.[22] Twin photons are produced simultaneously by the parametric process and then stored in the cavity during a time of the order of the cavity storage time τ_c. Therefore, counting of photons outside the OPO during a time much longer than τ_c will give equal numbers of signal and idler photons. In the frequency domain, the noise on the intensity difference $I = I_1 - I_2$ between the two beams is expected to be below the SNL for noise frequencies lower than τ_c^{-1}. A simple model leads to the following expression for the noise power spectrum $S_I(\Omega)$ at frequency Ω:

$$S_I(\Omega) = S_{\mathrm{SNL}}[1 - \epsilon/(1 + \Omega^2 \tau_c^2)], \tag{1}$$

where S_{SNL} is the shot-noise level for a beam of intensity $I_1 + I_2$; ϵ is the probability for an emitted photon to be detected, taking into account the various optical losses and the photodiode quantum efficiencies. The lowest residual noise is reached at zero frequency and is proportional to the loss per photon $(1-\epsilon)$. Let us emphasize that this result is valid above oscillation threshold, independent of the output intensities.

In this Letter, we report the first experimental observation of such an effect. We have produced high-intensity correlated beams, for which the noise on the intensity difference lies well below the SNL in an extended frequency range. Figure 1 shows our experimental arrangement. The OPO is pumped by a single-mode Ar^+-ion laser at 528 nm, stabilized on an external Fabry-Perot cavity (residual frequency jitter of 100 kHz). A Faraday rotator (FR) and an acousto-optic

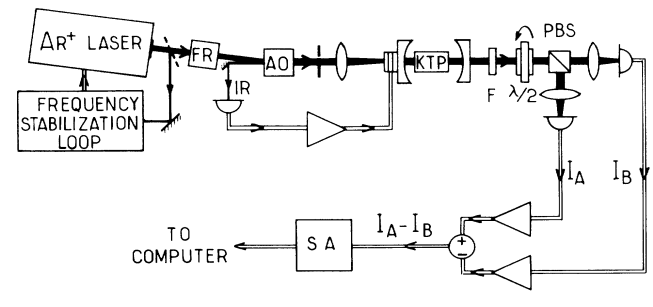

FIG. 1. Experimental setup, FR, Faraday rotator; AO, acousto-optic modulator; F, green filter; $\lambda/2$, half-wave plate; PBS, polarizing beamsplitter; SA, spectrum analyzer.

modulator (AO) are used to isolate the laser optically from the strong back-reflected light coming from the OPO. The pump light is then focused in the parametric medium, which is a 7-mm-long, type-II phase-matched KTP ($KTiOPO_4$) crystal, inserted in an optical cavity of length 17 mm. The input mirror, with a 2-cm radius of curvature, is highly reflecting for the infrared signal and idler beams and transmitting for the pump beam. The output mirror is flat and transmits 0.8% of the infrared light and a large part of the green light. Consequently, the cavity finesse is high for the signal and idler fields and low for the pump field. The four OPO oscillation conditions (energy conservation, phase-matching condition, and cavity resonance conditions for both signal and idler) are only fulfilled for a discrete series of cavity length values. In practice, oscillation occurs only in very small length intervals (a few nanometers) around these values. This is the cause of the well-known high sensitivity of the OPO to vibrations.[24] Thus, the OPO length has to be actively stabilized by electronic feedback so that it delivers a nearly constant output intensity. For this purpose the OPO output is monitored on the weak counterpropagating infrared beam (ir) which is transmitted back through the input mirror and not deflected by the acousto-optic modulator. Above threshold (80 mW of green light), the OPO emits two cross-polarized twin beams (with intensities of a few milliwatts for 200 mW of green light). The emission wavelengths, $\lambda_1=1.048$ μm and $\lambda_2=1.067$ μm, are determined by the collinear phase-matching conditions. The remaining transmitted pump beam is stopped by a filter. The twin beams are separated by a polarizing beam splitter (PBS) and then focused on two InGaAs photodiodes which have quantum efficiencies of 90%.[25] All surfaces encountered by the two infrared beams are antireflection coated. The two photocurrents are amplified, and then subtracted with a 180° power combiner. The noise on the resulting difference is monitored by a spectrum analyzer connected to a computer for data analysis.

The characteristics of the detection channels have been carefully checked: the imperfections of the polarizing beam splitter are less than 1%; the amplifier voltage gains are matched within 1%. The overall common mode rejection between the two channels has been measured by our modulating the pump beam at a frequency 10 MHz and measuring the corresponding coherent peak reduction on the spectrum analyzer. The result of this measurement is 25 dB.

A key point for the reliability of such an experiment is the calibration of the shot-noise level. As a first test, we have used a rotating half-wave plate inserted in front of the polarizing beam splitter (labeled $\lambda/2$ in Fig. 1). The two fields E_1 and E_2 emitted by the OPO undergo a polarization rotation of 2θ in the half-wave plate, where θ is the angle between the axes of the plate and of the polarizer. The two fields E_A and E_B, respectively transmitted and reflected by the polarizing beam splitter, are

$$E_A=(\cos 2\theta)E_1-(\sin 2\theta)E_2, \tag{2a}$$

$$E_B=(\sin 2\theta)E_1+(\cos 2\theta)E_2. \tag{2b}$$

When $\theta=0°$ (modulo 45°), the half-wave plate plays no role and the measured signal is the difference between the twin beam intensities. When $\theta=22.5°$ (modulo 45°), the system of half-wave plate and polarizing beam splitter acts like a usual 50% beam splitter. Since in our experimental conditions the beat frequency between the twin fields is about 5 THz, the crossed terms between the two modes do not appear in the observed frequency range. Consequently the measured signal gives the shot-noise level for a beam of intensity I_1+I_2. One can show from Eqs. (2) that the noise power spectrum $S_\theta(\Omega)$ for the signal I_A-I_B varies sinusoidally as a function of the angle θ:

$$S_\theta(\Omega)=S_I(\Omega)\cos^2 4\theta+S_{\rm SNL}\sin^2 4\theta. \tag{3}$$

Figure 2 shows the variation of $S_\theta(\Omega)$ recorded at a fixed frequency $\Omega/2\pi=8$ MHz. One observes a strong modulation of the noise level with the expected periodicity of 45°: The noise level at 0° is about 30% lower than that at 22.5°.

As a second test, we have used a cw yttrium-aluminum-garnet (YAlG) laser to yield an independent characterization of the shot-noise level. We have checked that the YAlG laser was shot-noise limited at

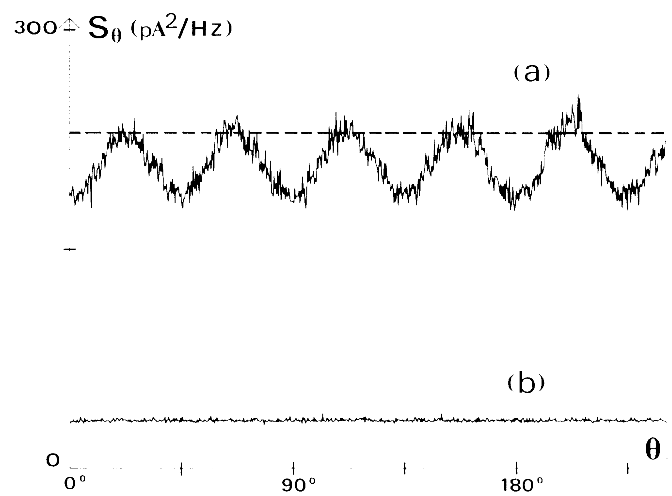

FIG. 2. Trace a, variation of the noise power $S_\theta(\Omega)$ as a function of θ for $\Omega/2\pi=8$ MHz (measured as noise spectrum of the photodiode currents). Trace b, input noise level equivalent to the whole electronic noise. The dashed line shows the shot-noise level measured on a YAlG laser having the same intensity. Traces a and b are recorded with a scan time of 50 s, without video filter.

frequencies higher than 2 MHz. We have then measured the noise levels of the OPO and YAlG with equal mean intensities. From this test, we can assert that the upper level of Fig. 2 ($\theta=22.5°$) coincides within 1% with the shot-noise level (dashed line in Fig. 2).

Figure 3 gives the noise reduction factor $R(\Omega)$ which is the ratio of the "squeezed" noise spectrum, recorded at $\theta=0°$, to the shot-noise spectrum, recorded at $\theta=22.5°$. (Both spectra have been correlated from electronics noise.) The curve is clearly below 1 over a broad frequency range. A maximum noise reduction of 30% ± 5% is observed at a frequency of 8 MHz. The noise reduction is better than 15% from 3 to 13 MHz.

In the low-frequency domain, the noise increases because the large extra noise on each beam is not completely rejected in the difference process. Moreover, the mean intensities are not exactly equal, which we attribute to a slight difference in the losses for the two infrared beams. This is a cause for additional fluctuations to be coupled back into the measured signal.

At high frequencies, $R(\Omega)$ is seen to go to 1: The noise of I_1-I_2 rises back to the shot noise for frequencies higher than the cavity bandwidth. This is in agreement with the Lorentzian shape predicted by Eq. (1). A quantitative comparison of our results with theory requires a more realistic model which is under development. However, the reliability of its predictions is presently limited by the experimental uncertainties on the various loss parameters.

In conclusion, we have observed a strong correlation between high-intensity twin beams. The noise on the intensity difference lies well below the shot-noise limit over an extended frequency range. Such a quantum correlation can be used in numerous applications, e.g., production of amplitude-squeezed beams by electronic feedback,[8,12] optical communications,[26–28] and high-sensitivity absorption measurements by the monitoring of the absorption signal on the intensity difference I_1-I_2.

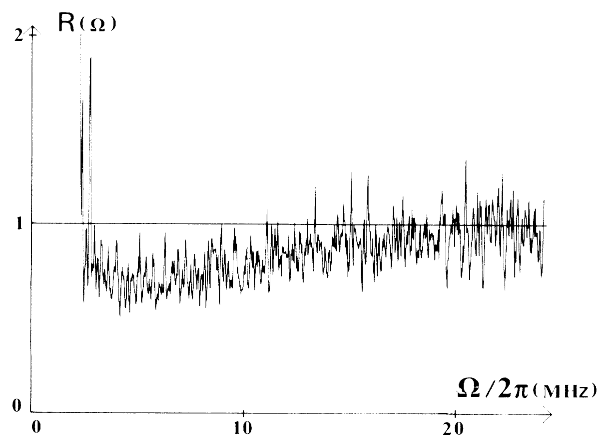

FIG. 3. Noise reduction factor $R(\Omega)$ as a function of the frequency Ω. It is obtained by the recording of three spectra—the squeezed noise ($\theta=0°$), the shot noise ($\theta=22.5°$), and the electronic noise (scan time 20 s, without video filter for each spectrum)—and then computing the ratio between the squeezed noise and the shot-noise spectra after correction from the electronic noise. Reduction below shot noise appears on an extended frequency range.

Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure and Laboratoire de Physique des Lasers are laboratoires associés au Centre National de la Recherche Scientifique.

[1]R. Slusher, L. Hollberg, B. Yurke, J. Mertz, and J. Valley, Phys. Rev. Lett. **55**, 2409 (1985).

[2]R. Shelby, M. Levenson, S. Perlmutter, R. De Voe, and D. Walls, Phys. Rev. Lett. **57**, 691 (1986).

[3]L. Wu, H. Kimble, J. Hall, and H. Wu, Phys. Rev. Lett. **57**, 2520 (1986).

[4]M. Maeda, P. Kumar, and J. Shapiro, Opt. Lett. **12**, 161 (1987).

[5]M. Raizen, L. Orozco, M. Xiao, T. Boyd, and H. Kimble, Phys. Rev. Lett. **59**, 198 (1987).

[6]M. Xiao, L. Wu, and H. Kimble, Phys. Rev. Lett. **59**, 278 (1987).

[7]P. Grangier, private communication.

[8]B. Saleh and M. Teich, Opt. Commun. **52**, 429 (1985).

[9]M. Kitagawa and Y. Yamamoto, Phys. Rev. A **34**, 3974 (1986).

[10]S. Machida, Y. Yamamoto, and Y. Itaya, Phys. Rev. Lett. **58**, 1000 (1987).

[11]P. Tapster, J. Rarity, and J. Satchell, Europhys. Lett. **4**, 293 (1987).

[12]H. Haus and Y. Yamamoto, Phys. Rev. A **34**, 270 (1986).

[13]H. Yuen, Phys. Rev. Lett. **56**, 2176 (1986).

[14]J. Rarity, P. Tapster, and E. Jakeman, Opt. Commun. **62**, 201 (1987).

[15]R. Shelby and M. Levenson, Phys. Rev. Lett. **57**, 2473 (1986), and **58**, 357 (1987).

[16]H. Yuen and V. Chan, Opt. Lett. **5**, 177 (1983).

[17]D. Burnham and D. Weinberg, Phys. Rev. Lett. **25**, 84 (1970).

[18]S. Friberg, C. Hong, and L. Mandel, Phys. Rev. Lett. **54**, 2011 (1985).

[19]B. Mollow, Phys. Rev. A **8**, 2684 (1973).

[20]C. Hong and L. Mandel, Phys. Rev. A **31**, 2409 (1985).

[21]S. Reynaud, C. Fabre, and E. Giacobino, J. Opt. Soc. Am. B **9** (to be published).

[22]S. Reynaud, Europhys. Lett. **4**, 427 (1987).

[23]E. Giacobino, C. Fabre, A. Heidmann, R. Horowicz, and S. Reynaud, in *Fundamentals of Quantum Optics II*, edited by F. Ehlotzky (Springer-Verlag, New York, 1987), p. 61.

[24]R. Smith, in *Laser Handbook I*, edited by T. Arecchi and E. Schultz-Dubois (North-Holland, Amsterdam, 1973), p. 837.

[25]The InGaAs photodiodes have been generously provided by M. De Cremoux from Thompson-C.S.F.

[26]C. Hong, S. Friberg, and L. Mandel, Appl. Opt. **24**, 3877 (1985).

[27]Y. Yamamoto and H. Haus, Rev. Mod. Phys. **58**, 1001 (1986).

[28]B. Saleh and M. Teich, Phys. Rev. Lett. **58**, 2656 (1987).