Observation of High-Intensity Sub-Poissonian Light Using an Optical Parametric Oscillator

J. Mertz, A. Heidmann, C. Fabre, E. Giacobino, and S. Reynaud

Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure, Université Pierre et Marie Curie, 75252 Paris CEDEX 05, France

(Received 23 February 1990)

We report the observation of high-intensity sub-Poissonian light using the correlated "twin" beams generated by an optical parametric oscillator. The intensity fluctuations in one of these beams are reduced by a feedforward correction mechanism that monitors the intensity of the second beam. The observed reduction in noise power is up to 24% below the shot-noise limit.

PACS numbers: 42.50.Dv, 42.65.Ky

Recently, the possibility of generating squeezed states by acting on the quantum fluctuations of the electromagnetic field has prompted much investigation.[1] These nonclassical states of light are characterized by a reduction in the fluctuations of some component of the field below the vacuum fluctuation level, making them potentially useful for improving the signal-to-noise ratio in experiments limited by the shot noise of standard laser light. Amplitude squeezed light, in particular, is defined by a reduction in the fluctuations of the amplitude component of the field. In the small-fluctuation limit it exhibits sub-Poissonian photon statistics, which is of interest for experiments involving direct intensity measurements.

Two techniques have been used so far in the generation of amplitude squeezed light. The first, a direct-conversion technique, relies on an inherently "quiet" source,[2-5] such as a constant-current-driven laser diode, where a maximum photon noise reduction of 26% was reported.[4] The second technique relies on external control of the amplitude fluctuations, using, for example, feedback correction. Large degrees of amplitude squeezing have been observed using "closed" configurations[6,7] where all the light is lost on detection to provide a feedback signal. The squeezed light in these systems is unavailable since it is restricted to internal paths of the loop, and several "open" configurations have been proposed for its extraction.[8-11] One such configuration makes use of the in-loop generation of two quantum-correlated light beams, one beam providing a feedback signal to stabilize the other beam below the shot-noise level. Recently, a quantum noise reduction of 22% has been observed in low-intensity incoherent light using feedback from spontaneous parametric down conversion.[12]

A particularly effective generator of quantum-correlated light beams is an optical parametric oscillator (OPO),[13] comprising a nonlinear crystal in an optical cavity. Such a device is based on the parametric down conversion of pump photons into pairs of signal photons, resulting in "twin" output beams whose photon numbers are nearly equal when counted over times longer than the cavity storage time.[14] In practice, the amount of correlation between the two output beams is limited only by spurious optical losses undermining the pairwise detection of the beam photons, and quantum noise reductions as large as 69% have been attained in the intensity difference between the beams.[15] The additional feature that the output beams are laserlike and of high intensity makes them particularly convenient for the generation of sub-Poissonian light using configurations where the control signal from one beam is either fed back to the pump or fed forward directly to the second beam. In this Letter, we report the first experimental observation of high-intensity sub-Poissonian light using an OPO in a feedforward configuration.

The experimental layout is shown in Fig. 1 and is similar to the one described in Ref. 15. An optical parametric oscillator is pumped above threshold by the 528-nm line of a single-mode cw argon-ion laser, isolated from OPO back reflections by an acousto-optic modulator (AO). The OPO cavity mirrors, 35 mm apart with the radii of curvature 20 mm, are transmitting in the visible and present a low finesse for the pump light. The nonlinear medium is a 7-mm-long potassium-titanyl phos-

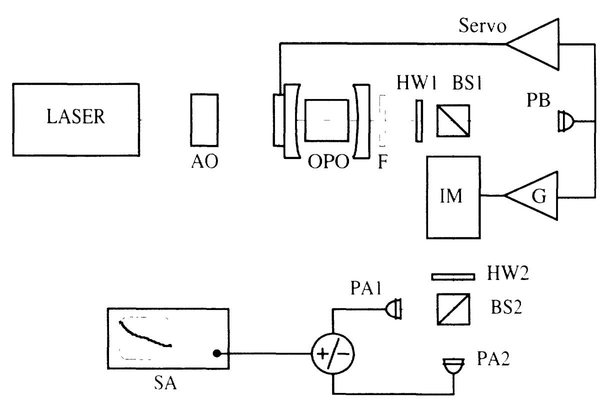

FIG. 1. Experimental setup. AO: acousto-optic modulator; F: dichroic filter; HW1,HW2: half-wave plates; BS1,BS2: polarizing beam splitters; IM: intensity modulator; PA1, PA2,PB: photodetectors; SA: spectrum analyzer.

phate ($KTiOPO_4$) crystal, type-II phase matched so the down-converted twin infrared beams are cross polarized with nondegenerate wavelengths $\lambda_1 = 1.048$ μm and $\lambda_2 = 1.067$ μm. The output mirror is 1.6% transmitting in the infrared and the total losses (including input mirror transmission and crystal absorption) are of the order of 0.5%, resulting in an infrared emission threshold at about 200-mW incident pump power.

A dichroic filter (F), placed at the output of the cavity, blocks the transmitted pump light while letting pass the two emitted infrared beams which are then separated by a polarizing beam splitter (BS1) into detection arms *A* and *B*. The detectors (PA1, PA2, and PB) are all reverse-biased Epitax 300 *p-i-n* photodiodes with quantum efficiencies measured near 0.9. The intensities of the infrared beams are sensitive to cavity detuning and are actively stabilized to 6 mW for an incident pump intensity of 420 mW, using the dc output (dc-30 kHz) from detector *B* to servocontrol the OPO cavity length.

The feedforward correction loop consists of a variable gain amplifier (G) driven by the ac signal (1-20 MHz) from detector *B*, and applied to an intensity modulator (IM) inserted in arm *A*. This modulator (an electro-optic modulator followed by a polarizer) acts as an analog shutter with a transmission proportional to the applied voltage from G. Total optical losses through path *A*, including losses due to the modulator transmission bias, are about 20%.

To calibrate the noise in beam *A* to its shot-noise reference level, a double-balanced detector is used in arm *A* made of a 50% beam-splitting mechanism (half-wave plate HW2 and polarizing beam splitter BS2) and two photodetectors (PA1 and PA2). The ac signals (1-20 MHz) from each photodetector can be either added or subtracted using an amplifier which is commuted between a summing or differencing configuration, and the resultant signal is observed on a spectrum analyzer (SA). The total noise in beam *A* and its associated shot-noise level are measured almost simultaneously by switching from one configuration to another.

The performance of the double-balanced detector *A* was carefully ascertained. The gain balance between the two configurations was checked by adding and subtracting two noises from independent electronic sources and observing the same result to within 1%. The total electrical and optical common mode rejection, measured by modulating the beam-*A* intensity and observing the reduction in the modulation peak when passing from the sum to the difference mode, was found to be -30 dB for a modulation frequency of 5 MHz, and no greater than -25 dB in the 1-20-MHz range. Linearity in the detection channel was also verified for optical powers up to 6 mW by inserting a variable attenuator in front of the double-balanced detector and plotting the shot-noise power as a function of the mean intensity in beam *A*.

Figure 2 shows various noise spectra of beam *A*, taken while stabilized on the same infrared resonance peak.

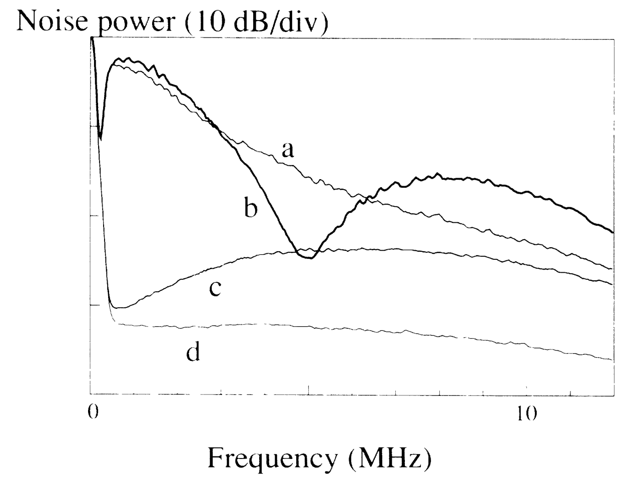

FIG. 2. Experimental noise spectra of beam *A* (curve *a*) without feedforward correction, (curve *b*) with feedforward correction, (curve *c*) associated shot-noise level, and (curve *d*) electronic noise.

Curve *a* is the total noise power in beam *A*, taken in summation mode (PA1+PA2), with no optoelectronic noise correction (feedforward gain G equal to 0). Curve *c* is the associated shot-noise level, taken in the differencing mode (PA1 $-$PA2). It is clear from these spectra that the infrared beams generated by the OPO have a large amount of excess noise, due to the fact that the OPO is stabilized off resonance and close to oscillation threshold.[13] The excess noise at 5 MHz is typically 5 to 10 dB above the shot-noise level, depending on OPO cavity alignment and detuning. Curve *b* of Fig. 2 is the noise power in beam *A* when the optoelectronic feedforward correction is turned on. The observed noise reduction is sensitive to both the gain and phase lag of the feedforward correction signal. The latter is fixed by filters in the feedforward electronics that prevent low-frequency saturation, allowing the gain to be properly matched in a frequency range centered here about 5 MHz.

To evaluate the quantum noise reduction, we divide the noise power spectrum (Fig. 2, curve *b*) by the shot-noise spectrum (Fig. 2, curve *c*), having corrected both for electronic noise (Fig. 2, curve *d*). The resulting normalized noise power spectrum $S_{ff}(\Omega)$ is shown in Fig. 3, curve *a*. $S_{ff}(\Omega)$ drops below 1 over a 700-kHz frequency range around 5 MHz. The reduction in noise power is up to 24%(± 2%) below the shot-noise level.

These experimental results can be compared with a simple theoretical model, using a semiclassical input-output formalism.[16] Writing the semiclassical field-amplitude fluctuations of the two infrared beams at the OPO output as $\delta\alpha_A$ and $\delta\alpha_B$, the significant effect of the feedforward loop is to correct the fluctuations $\delta\alpha_A$ of beam *A* by a term proportional to the fluctuations $\delta\alpha_B$ of beam *B*. Neglecting losses in arm *A*, the field-amplitude

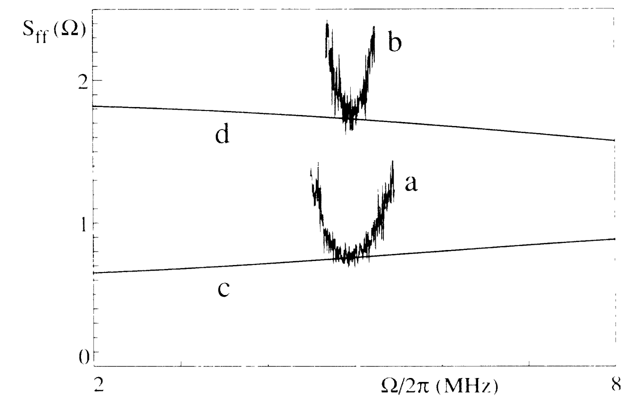

FIG. 3. Experimental noise spectra of beam A, normalized to the shot-noise level, (curve a) when the two beams at the OPO output are quantum correlated and (curve b) decorrelated by the beam mixer HW1+BS1. The largest noise power reduction is 24% below the shot-noise level (curve a). Theoretical curves (c and d) represent the minimum obtainable noise powers for these cases when the gain is optimized at every frequency.

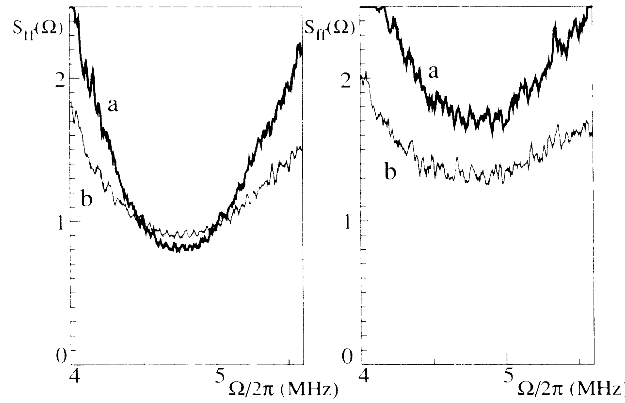

FIG. 4. Effect of a 50% attenuator inserted in beam A after the intensity modulator, (left) when the two beams at the OPO output are quantum correlated and (right) decorrelated. Curves a are the noise spectra of beam A without attenuation, while curves b are the noise spectra with attenuation. As expected, the attenuated noise tends toward the shot-noise level in proportion to the amount of attenuation.

fluctuations $\delta\alpha_{ff}$ after correction become

$$\delta\alpha_{ff} = \delta\alpha_A - g\delta\alpha_B \,, \tag{1}$$

where g is a parameter related to the gain of the feedforward loop. The intensity noise spectrum $S_{ff}(\Omega)$, normalized to its shot-noise reference, is given directly by the variance of the field fluctuations $\delta\alpha_{ff}(\Omega)$ at frequency Ω:[17]

$$S_{ff}(\Omega) = \langle |\delta\alpha_{ff}(\Omega)|^2 \rangle \tag{2a}$$

$$= (1-g)^2 S_I(\Omega) + 2g S_{A\text{-}B}(\Omega) \,, \tag{2b}$$

where $S_I(\Omega)$ is the intensity noise spectrum of a single beam at the OPO output (assumed to be the same for A and B), and $S_{A\text{-}B}(\Omega)$ is the noise spectrum of the intensity difference between the output fields, characterizing the quantum correlation between the twin beams. S_I and $S_{A\text{-}B}$ are normalized to their associated shot-noise levels. For an optimum gain,

$$g_{\rm opt} = 1 - \frac{S_{A\text{-}B}(\Omega_0)}{S_I(\Omega_0)} \,, \tag{3}$$

the intensity noise $S_{ff}(\Omega_0)$ at frequency Ω_0 reaches its minimum value,

$$S_{ff}(\Omega_0) = 2S_{A\text{-}B}(\Omega_0) \left[1 - \frac{S_{A\text{-}B}(\Omega_0)}{2S_I(\Omega_0)} \right] . \tag{4}$$

$S_{A\text{-}B}$ is less than 1 when beams A and B are correlated at the quantum level, and was measured to be around 0.35 at 5 MHz.[15] Neglecting losses, S_I is identified with the noise spectrum of beam A with no optoelectronic correction, and is everywhere greater than 1 for this experiment. The theoretical optimum intensity noise $S_{ff}(\Omega_0)$ is traced in Fig. 3, curve c, as a function of frequency Ω_0, where factors such as intensity modulator loss, nonideal detection efficiency, beam imbalance at the OPO output, and electrical noise are taken into account.[18] The experimental result (curve a), shown superposed, effectively attains this optimum.

It is interesting at this point to consider a separate case where beams A and B are not correlated ($S_{A\text{-}B} = 1$). As shown in Fig. 3, curve d, the optimum feedforward gain for this case, while still correcting for much of the excess noise in beam A, does not reduce the noise even to the shot-noise level. This situation is readily attainable experimentally by inserting a half-wave plate (HW1 in Fig. 1) at the output of the OPO to rotate the polarization of each twin beam by 45°. Instead of separating the two cross-polarized infrared beams, the beam splitter BS1 then randomly distributes them into arms A and B.[15] The resulting experimental noise reduction, with the feedforward gain optimized for a minimum noise around 5 MHz, is shown in Fig. 3, curve b. As in the case of correlated beams, the experimental results are in good agreement with theory.

For a last verification of the accuracy of the experiment an attenuator was inserted in beam A immediately before the double-balanced detector. A specific signature of sub-Poissonian light is that the noise power normalized to its shot-noise level is increased with attenuation, whereas for classical light it is decreased or left unchanged. The normalized noise spectra of beam A are shown in Fig. 4, when the beams at the OPO output are quantum correlated ($S_{A\text{-}B} < 1$, left figure) or decorrelated ($S_{A\text{-}B} = 1$, right figure) for the cases without attenuation (curves a) or with a 50% attenuator (curves b). It is verified that the noise tends toward 1 in proportion to the amount of attenuation, and that quantum noise reduction is degraded by a factor of 2 (left figure). Note that the accuracy of the shot-noise calibration can be determined from these four spectra using linear extrapolation. One finds an uncertainty in the shot-noise level less than 1%.

In conclusion, a quantum noise reduction of 24% in the intensity noise of an intense light beam was observed. The generation of this amplitude squeezed light was obtained by optoelectronic feedforward correction, using the quantum correlation properties of twin beams generated by an optical parametric oscillator. Such a technique seems attractive for potential applications, particularly with the advent of monolithic OPO technology.[19] Moreover, larger noise reductions can be expected with improved OPO characteristics,[13] such as smaller cavity losses (or larger transmission of the output mirror) and higher pump power.

This work was partially supported by Direction des Recherches Etudes et Techniques Contract No. 87/091. We acknowledge the helpful assistance of T. Debuisschert and L. Hilico. Laboratoire de Spectroscopie Hertzienne de l'Ecole Normale Supérieure is a Laboratoire Associé au CNRS à l'Ecole Normale Supérieure et à l'Université Pierre et Marie Curie.

[1]See papers contained in J. Opt. Soc. Am. B **4**, 10 (1987); J. Mod. Opt. **36**, 6/7 (1987).

[2]M. C. Teich and B. E. A. Saleh, J. Opt. Soc. Am. B **2**, 275 (1985).

[3]P. R. Tapster, J. G. Rarity, and J. S. Satchell, Europhys. Lett. **4**, 293 (1987).

[4]S. Machida, Y. Yamamoto, and Y. Itaya, Phys. Rev. Lett. **58**, 1000 (1987); S. Machida and Y. Yamamoto, Opt. Lett. **14**, 1045 (1989).

[5]W. H. Richardson and R. M. Shelby, Phys. Rev. Lett. **64**, 400 (1990).

[6]J. G. Walker and E. Jakeman, Proc. Soc. Photo-Opt. Instrum. Eng. **492**, 274 (1985).

[7]S. Machida and Y. Yamamoto, Opt. Commun. **57**, 290 (1986).

[8]Y. Yamamoto, N. Imoto, and S. Machida, Phys. Rev. A **33**, 3243 (1986).

[9]F. Capasso and M. C. Teich, Phys. Rev. Lett. **57**, 1417 (1986).

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

[11]G. Björk and Y. Yamamoto, Phys. Rev. A **37**, 125 (1988).

[12]P. R. Tapster, J. G. Rarity, and G. S. Satchell, Phys. Rev. A **37**, 2963 (1988).

[13]C. Fabre, E. Giacobino, A. Heidmann, and S. Reynaud, J. Phys. (Paris) **50**, 1209 (1989).

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

[15]A. Heidmann, R. J. Horowicz, S. Reynaud, E. Giacobino, and C. Fabre, Phys. Rev. Lett. **59**, 2555 (1987); T. Debuisschert, S. Reynaud, A. Heidmann, E. Giacobino, and C. Fabre, Quantum Opt. **1**, 3 (1989).

[16]S. Reynaud, C. Fabre, and E. Giacobino, J. Opt. Soc. Am. B **4**, 1520 (1987).

[17]S. Reynaud and A. Heidmann, Opt. Commun. **71**, 209 (1989).

[18]J. Mertz, C. Fabre, A. Heidmann, and S. Reynaud (to be published).

[19]C. D. Nabors and R. M. Shelby, Stanford University report, 1990 (to be published).