Sub-Shot-Noise Correlation of Total Photon Number Using Macroscopic Twin Pulses of Light

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We have measured whole-pulse photon statistics of macroscopic twin pulses of light generated by coherently seeding a two-mode optical parametric amplifier equally in each mode. We are able to produce 300 ps, near-transform-limited twin pulses ($\sim 10^6$ photons) with a difference photon number having a variance measured to be 73% below the shot-noise level. We have measured probability distributions of the photoelectron difference number, which are the only photoelectron distributions in the macroscopic regime which cannot be explained using standard semiclassical detection theory.

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When light is detected by photoelectric means there is always noise associated with the random nature of the light field and the generation of electrons in the detector. The shot-noise level (SNL) is defined to be the lower limit to the photocurrent noise for coherent states of the field. These states are examples of states which have positive-definite Glauber-Sudarshan P distributions [1]. Only recently have light fields been produced and detected which are not describable with a positive-definite Glauber-Sudarshan P distribution [2–4]. Possible manifestations of this include photoelectron distributions with sub-SNL variances. Examples are field-quadrature-squeezed beams [5], strongly sub-Poisson beams from semiconductor lasers [6] and from optical parametric generators with measurement feedback [7], and twin beams of light from optical parametric amplification [8,9]. These experiments verified that the photocurrent produced by detecting a light beam (or the difference current from detecting two light beams and subtracting) can possess sub-SNL variances at certain frequencies, as observed by analyzing the current with a radio-frequency (rf) spectrum analyzer. This means the detector current noise spectral density is below the SNL; the SNL was thought previously to be an intrinsic minimum associated with the photoelectron generation process. Measurements of the distributions of the total photon number in macroscopic light pulses yielding sub-SNL correlations have not been previously carried out.

This paper describes measurements of sub-SNL correlations between the total number of photons contained in two 300 ps pulses having macroscopic amounts of energy ($\sim 10^6$ photons), produced by amplifying two coherent seed pulses of equal amplitude injected into an optical parametric amplifier (OPA). We electronically integrate the difference current of a pair of high-efficiency photodiodes, each exposed to one of the amplified pulses. This amounts to counting the photoelectrons (n_1, n_2) in each pulse, with a resolution (electronic noise) equal to about 580 photoelectrons in our case, and subtracting the results to give $N = n_1 - n_2$. By repeating the measurement many times we obtain the probability distribution $P(N)$ for the difference number, and find that its variance has a value of about one-fourth of the SNL when the amplification factor is 10. The experiment thus demonstrates sub-SNL photon-number correlations between "twin" pulses of light in the macroscopic regime.

The merits of this "whole-pulse" measurement scheme relative to previous measurements of the temporal modulation of photon number are the following. First, it becomes possible to measure the probability density of the photoelectron number, or photoelectron difference number. Second, there is a conceptual simplicity in determining the value of the expected shot-noise level. Third, from an experimental veiwpoint, this scheme allows measurement of low-repetition-rate pulses having durations shorter than the detector response time. Finally, with a repetitively pulsed source it becomes possible to perform the measurements synchronously with the pulses. This is essential if one wants to use the light to transmit information by amplitude or phase modulation of individual pulses. In contrast, previous studies using spectrum analysis monitored the intensity noise at frequencies other than the pulse repetition rate.

The experimental setup is diagramed in Fig. 1. A Nd-doped yttrium aluminum garnet (Nd:YAG) laser produces linearly polarized pulses at 1.064 μm at a repetition rate of 100 Hz. This fundamental field at 1.064 μm is frequency doubled by a $KTiOPO_4$ (KTP) nonlinear optical crystal which produces 532 nm light nearly collinear

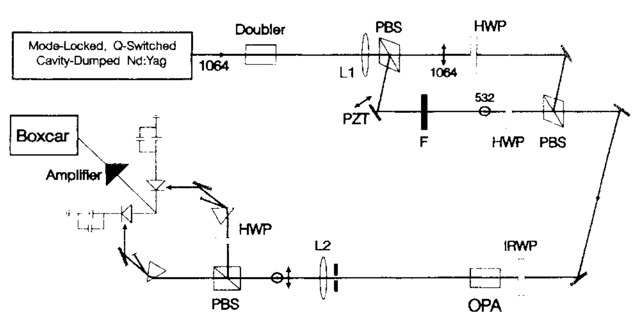

FIG. 1. The experimental setup for whole-pulse detection of sub-SNL intensity correlations.

with the fundamental beam with a near-transform-limited pulse duration of approximately 300 ps and energy of approximately 200 μJ. After passing through a 40-cm focal-length lens (L1), the two frequencies are separated and recombined with two calcite polarizing beam splitters (PBS) in order to correct the beam overlap error due to Poynting vector walkoff in KTP. Also, by moving a mirror between the beam splitters with a piezoelectric translator (PZT), we control the phase shift of one field with respect to the other. Half-wave plates (HWP) are placed in each beam to provide variable attenuation for each field. A filter (F) is used to block the infrared in the 532 nm beam. After carefully aligning the two beams, the recombined light is passed through a harmonic wave plate (IRWP) which provides $\lambda/2$ retardation for the 1.064 μm infrared (IR) light while retarding the green 532 nm (pump) light by λ. This allows us to rotate the IR polarization vector to 45° relative to the pump polarization. At the position at which the pump comes to a focus, a traveling-wave optical parametric amplifier consisting of a 7-mm-long KTP crystal is placed and adjusted to yield efficient parametric amplification of the IR. Since the parametric interaction is type-II phase matched, the IR field is decomposed into equal-amplitude signal and idler fields, with polarizations parallel and orthogonal to that of the pump, respectively. It is very important in our experiment to seed the two polarizations equally in order to ensure balanced detection. After the OPA, a 2-mm-diam iris is placed just before a 30-cm collimating lens (L2) to block any spontaneous down-conversion that is not collinear with the IR seed. For the seed intensity used, the light transmitted by the iris is strongly dominated by the near-transform-limited, amplified seed, which can be described approximately as a single temporal mode. This is in contrast to spontaneous down-conversion which is typically generated in thousands of modes [10].

The gain G of an OPA with equal seed pulses will be defined as the ratio of the average number of output signal (idler) photons to input signal (idler) photons. As a function of the relative phase of the pump and seed fields, we observe amplification or deamplification of the seeds. The gain is measured by blocking and unblocking the pump and measuring the average signal (idler) energy with a photodiode.

The amplified signal and idler pulses are directed into a balanced detector [11]: A polarizer separates the two orthogonally polarized signal and idler pulses each of which is then passed through Brewster dispersing prisms and filters to eliminate the strong green pump. Two 19-mm focal-length lenses focus the signal and idler pulses onto 500-μm-diam, reverse-biased InGaAs p-i-n photodiodes (Epitax Etx500t) with response times of <2 ns and quantum efficiencies of (85–90)% as specified by the manufacturer. By biasing the two diodes with opposite polarity and summing their outputs on a strip line, one obtains the subtracted current. The current is detected with a low-noise, charge-sensitive preamplifier (Amptek A-225) which we accurately calibrate. The impulse-response function of this amplifier is a voltage pulse of a few μs duration, with a peak voltage proportional to the number of input electrons. This peak voltage is sampled by a calibrated boxcar integrator with a 20-ns window, digitized, and recorded by a microcomputer. The overall calibration is known to an accuracy of 5%. The recorded data are proportional to the difference number of photoelectrons which carries information about the difference number of signal and idler photons. The overall electronic detection noise is 580 electrons rms. The excess classical noise common to both the signal and the idler, due to 5% laser energy fluctuations, is efficiently rejected by the balanced detector to better than 1 part in 1000. At the signal levels that we work at (low relative to previous studies) the detection system is highly linear.

In our experiment the SNL is that noise which would be obtained by detecting two coherent state fields and subtracting the photoelectron numbers [1]. This noise is given by $\bar{n}_S+\bar{n}_I$, where $\bar{n}_S$ and $\bar{n}_I$ are the average number of photoelectrons emitted per pulse by the signal and idler detectors, respectively. To determine this, we block the idler detector and measure $\bar{n}_S$. Since $\bar{n}_S=\bar{n}_I$, due to balancing, the SNL is given by $\Delta N^2_{\mathrm{SNL}}=2\bar{n}_S$. This method, which determines the calculated SNL, relies on our calibration of the detection system. The SNL is verified by sending pulses of light from the laser, with average energy equal to twice that of the amplified signal, into the balanced detector and determining the variance of the resulting difference number. This method, which determines the measured SNL, consistently gives results in agreement with the calculated result to within 8%. The measured SNL is found to be a linear function of $2\bar{n}_S$ and has a slope of one as expected for shot-noise-limited detection.

As a result of our being able to measure the difference N in the number of signal and idler photoelectrons on each pulse, we are able to determine the probability $P(N)\delta N$ for N to fall within a bin of width δN. We measure 20000 realizations of N and construct a normalized histogram that displays $P(N)\delta N$ vs N, with a chosen bin width $\delta N=324$ photoelectrons. Figure 2 shows two such histograms, where in each case the average photoelectron number from each detector was adjusted to be $(1.1\pm0.2)\times10^6$. Figure 2(a) is the near-shot-noise distribution for laser pulses incident on the balanced detector (with the green pump blocked). When the pump is unblocked and adjusted for a gain of 10, and the seed levels are adjusted to produce amplified signal and idler beams that generate the same average photoelectron numbers as in Fig. 2(a), the resulting histogram is shown in Fig. 2(b). This distribution is clearly narrower than that in Fig. 2(a), illustrating the sub-SNL correlation between signal and idler photon numbers. The calculated variance shows a 69% reduction in the noise below the SNL.

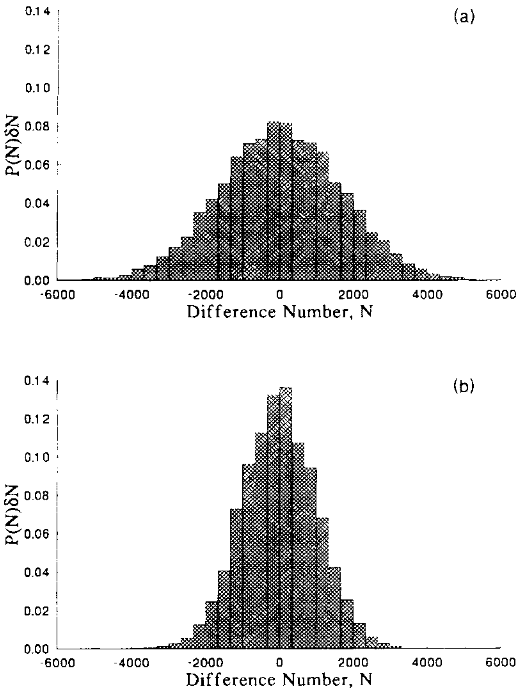

FIG. 2. Probability distributions for detecting difference photoelectron number N within a bin of width $\delta N = 324$ photoelectrons. The distributions are not corrected for electronic noise (580 electrons rms). (a) Shot-noise distribution for a classical (laser) input with $(1.1 \pm 0.2) \times 10^6$ average photoelectrons per detector. The standard deviation is 1645 photoelectrons. (b) Sub-SNL noise distribution for twin pulses with the same average numbers of photoelectrons as in (a). The standard deviation is 1012 photoelectrons. When corrected for electronic noise, the variance of the distribution in (a) is 8% above the calculated SNL, while that in (b) is 69% below the calculated SNL.

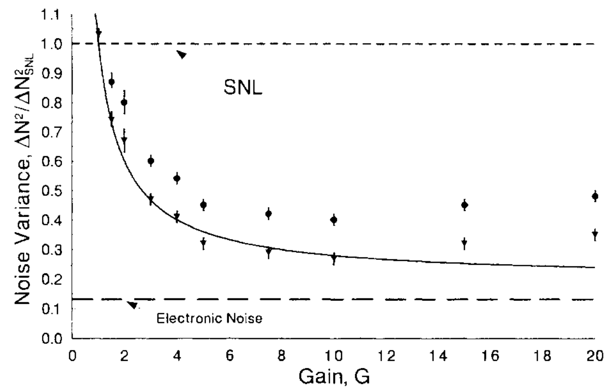

FIG. 3. Normalized noise variance as a function of OPA gain G, for 10000 laser shots. The circles are measured values of the variance without correction for the electronic noise. The triangles are noise measurements corrected for the electronic noise. The error bars represent maximum and minimum values of five repeated measurements of 2000 shots each. The solid line is the theoretical prediction of Eq. (4) plotted for an overall detection efficiency of $\eta = 0.8$.

Figure 3 shows the normalized noise variance as a function of measured gain. For each gain, the seed level was adjusted to produce amplified signal and idler pulses of the same average photoelectron numbers $(1.1 \pm 0.2) \times 10^6$. The raw variances are shown as circles, while the variances corrected by subtracting the electronic noise in quadrature are shown as triangles. The error bars are determined by the maximum and minimum of five repetitions of the measurement. For relatively low gains, the noise decreases with increasing gain, as one would expect, reaching a minimum value that is 73% below the SNL. For increasingly high gains, the noise begins to increase. This increase may be a result of spontaneous down-conversion at nondegenerate frequencies passing through the iris and onto the detectors. For reasons not completely understood, the spontaneous signal and idler, although detectable, cannot be subtracted well by the detector. Another possible cause of the noise increase might be related to beam distortion at high gains [12].

The strong correlation between signal and idler beams was predicted by Mollow and Glauber, using a two-mode model of the OPA [13]. The solutions of their Heisenberg-picture equations of motion for the slowly varying annihilation operators of the signal and idler modes, at the amplifier output, can be written in the form

$$\hat{a}_S = \mu \hat{a}_S(0) + \nu \hat{a}_I^\dagger(0), \qquad \hat{a}_I = \mu \hat{a}_I(0) + \nu \hat{a}_S^\dagger(0), \tag{1}$$

where $\hat{a}_S(0)$ and $\hat{a}_I(0)$ are the signal and idler operators at the input. Recent theories show that the parameters μ and ν can be expressed for a traveling-wave OPA, in the case of perfect phase matching, as [14]

$$\mu = \cosh(\gamma z), \qquad \nu = i e^{i\theta_P} \sinh(\gamma z), \tag{2}$$

where γ is a positive gain coefficient, z is the medium length, and θ_P is the phase of the pump field. As pointed out by Mollow and Glauber, the difference photon number $\hat{a}_S^\dagger \hat{a}_S - \hat{a}_I^\dagger \hat{a}_I$ is a constant of the motion, and "since the magnitudes of both $\hat{a}_S^\dagger \hat{a}_S$ and $\hat{a}_I^\dagger \hat{a}_I$ increase exponentially,. . . the relative magnitude of the difference between them becomes exceedingly small" [12]. To analyze our experiment the overall detection efficiency η, which degrades the correlation somewhat, can be accounted for by the standard method of mixing in vacuum field operators [11], $\hat{a}_{v1}, \hat{a}_{v2}$, to form the following operators at each detector:

$$\hat{a}_1 = \hat{a}_S \sqrt{\eta} + i \hat{a}_{v1} \sqrt{1-\eta}, \quad \hat{a}_2 = \hat{a}_I \sqrt{\eta} + i \hat{a}_{v2} \sqrt{1-\eta}. \tag{3}$$

The difference of the photoelectron numbers at the detectors is represented by the operator $\hat{N} = \hat{a}_1^\dagger \hat{a}_1 - \hat{a}_2^\dagger \hat{a}_2$.

If the signal and idler inputs are coherent states with equal amplitudes $\alpha_S(0)=\alpha_I(0)=|\alpha|\exp(i\phi)$, then the variance of $\hat{N}$, normalized to the SNL ($\Delta N^2_{\rm SNL}=\langle\hat{a}_1^\dagger\hat{a}_1\rangle+\langle\hat{a}_2^\dagger\hat{a}_2\rangle$), is found to be

$$\Delta N^2/\Delta N^2_{\rm SNL}=1-\eta+\eta/G\,, \tag{4}$$

where we have neglected the small spontaneous down-conversion intensities, and the gain, $G=\langle\hat{a}_S^\dagger\hat{a}_S\rangle/\langle\hat{a}_S^\dagger(0)\times\hat{a}_S(0)\rangle$, is given by

$$G=|\mu|^2+|\nu|^2+|2\mu\nu|\sin(2\phi+\theta_P)\,. \tag{5}$$

The maximum gain, $G_{\max}=\exp(2\gamma z)$, is obtained for a relative phase $2\phi+\theta_P=\pi/2$, and the maximum deamplification, $G_{\min}=\exp(-2\gamma z)$, is obtained at a phase of $2\phi+\theta_P=-\pi/2$. For $G>1$ the noise is below the SNL, while for $G<1$ the noise becomes greater than the SNL. Equation (4) is plotted as a solid curve in Fig. 3, assuming an overall detection efficiency of $\eta=0.8$. This value for η is a reasonable estimate, given detector quantum efficiency and optical losses. Furthermore, the actual gain is less than that given in Eq. (5), due to imperfect mode matching; we use the measured value for G in Fig. 3.

In conclusion, we have observed sub-SNL intensity correlations between macroscopic ($\sim 10^6$ photons) twin pulses of light generated by an OPA using a whole-pulse detection method which gives direct information about the photoelectron difference number, and thereby the photon difference number. We have measured probability distributions of the photoelectron difference number, which are the only photoelectron distributions in the macroscopic regime, to date, which cannot be explained using standard semiclassical detection theory as defined in [15]. In fact, the only other measured sub-SNL photoelectron distribution that is incompatible with semiclassical detection theory is for the correlations in spontaneous down-conversion at the microscopic level (0 or 1 photon) [16]. In contrast, other studies of light with sub-SNL correlations measured the photoelectron variance or photoelectron current spectral power density. Photoelectron distributions having sub-SNL variance were observed previously in a diode laser system with closed-loop feedback [17]. However, such results can be described using semiclassical theory including feedback, and as such can be described using a positive-definite Glauber-Sudarshan P distribution [15]. The nonexistence of this distribution is normally associated with the breakdown of the semiclassical detection theory. The new ability to generate and detect near-transform-limited pulses of light which exhibit sub-SNL correlations may enable one to study interesting quantum-mechanical properties such as phase-number uncertainty relations [18] and phase correlations [19].

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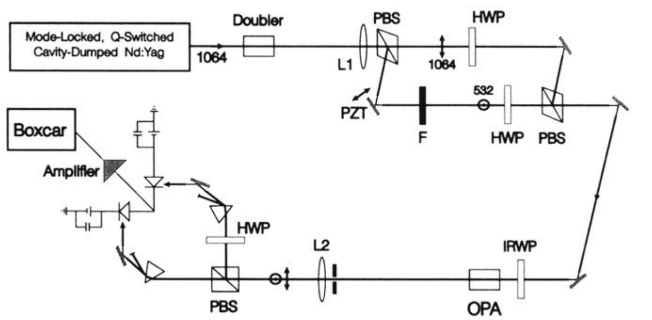
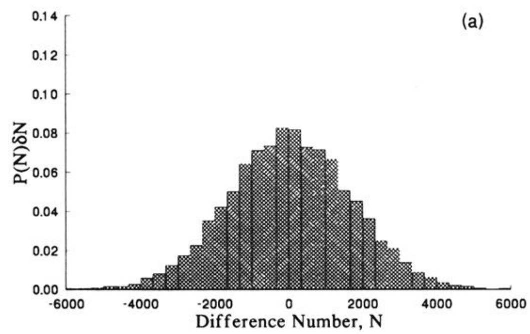
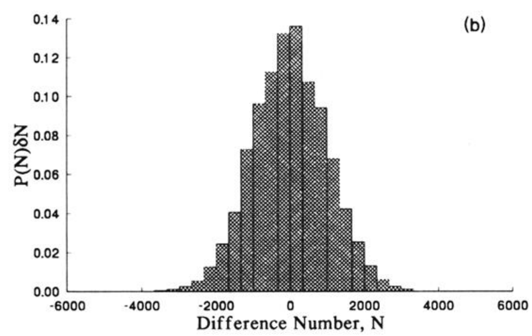


FIG. 1. The experimental setup for whole-pulse detection of sub-SNL intensity correlations.





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