Preparation and measurement of tunable high-power sub-Poissonian light using twin beams

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Widely frequency tunable bright sub-Poissonian field preparation has been experimentally achieved with quantum-correlated twin beams in the continuously variable regime. The noise of the sub-Poissonian field is reduced to more than 2 dB below the shot-noise level throughout the entire wavelength-tunable range of 7.4 nm. A maximum noise reduction of 45% (2.6 dB) is observed. The statistical distribution of a sub-Poissonian field is also obtained. © 2006 Optical Society of America

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In the past 20 years there has been much interest in the generation and application of various nonclassical light sources, such as squeezed-state entanglement, quantum-correlated twin beams, and sub-Poissonian light; for which improved signal-to-noise ratios and measurement precision beyond the quantum-noise limit are anticipated. In particular, sub-Poissonian light is an important light source in studies of quantum information and optical communication.[1–8] Sub-Poissonian light is also the light with the largest communication capacity in known light fields.[9]

There are three techniques for generation of sub-Poissonian light: direct conversion, a feedback technique, and a feed-forward technique.[1–6] In 1990 Mertz *et al.* obtained sub-Poissonian light by using the feed-forward technique and a nondegenerate optical parametric oscillator (NOPO) pumped by the 528 nm line of an argon-ion laser; the observed noise reduction was as much as 24% below the shot-noise limit (SNL).[6] Subsequently, Kim and Kumar analyzed theoretically the generation of tunable sub-Poissonian light with an intensity feed-forward scheme for application in precision absorption spectroscopy.[7] Next, they and others experimentally obtained sub-Poissonian pulses of light by traveling-wave optical parametric deamplification.[8] At present, optical parametric oscillation (OPO) is one of the most efficient methods of obtaining nonclassical light. During the past 20 years, some of the best experimental results have been achieved by optical parametric methods.

Zhang *et al.* presented statistics on twin beams emerging from a nondegenerate OPO.[10] They recorded the twin beams' photocurrent difference fluctuation and demonstrated sub-Poissonian distributions of the twin beams' intensity difference. Laurat *et al.* reported their experimental demonstration of the conditional preparation of a continuously variable nonclassical state of light from twin beams by a data-acquisition system[11]; this is a kind of postselected sub-Poissonian light.

In this Letter we report the achievement of a frequency-tunable high-intensity sub-Poissonian state with feed-forward and quantum-correlated twin beams. A maximum noise reduction of 2.6 dB (45%) below the SNL was measured, and a wavelength-tunable range of 7.4 nm was demonstrated. Sub-Poissonian distribution with twin beams was also demonstrated by direct measurement of the sub-Poissonian state.

Generation of quantum-correlated twin beams is a prerequisite to our scheme. It is well known that a NOPO running above threshold is one of the best choices for intensity-correlated twin beams.[12,13] Several groups of scientists have demonstrated experimentally quantum correlation of the intensity of twin beams.[14–17] The intensity feed-forward scheme is shown schematically in Fig. 1. Beams A and B from the NOPO are quantum-correlated twin beams (signal and idler). Beam B is detected directly to correct beam A. After optimum correction, intensity noise $S_A{}^{\mathrm{opt}}(\Omega)$ of beam A at analysis frequency Ω becomes[6,18]

$$S_A{}^{\mathrm{opt}}(\Omega) = 2S_{A-B}(\Omega)\left[1 - \frac{S_{A-B}(\Omega)}{2S(\Omega)}\right], \qquad (1)$$

where $S(\Omega)$ is the intensity noise spectrum of a single beam (beam A or beam B) and $S_{A-B}(\Omega)$ is the noise spectrum of the intensity difference between the twin beams, which characterizes the quantum correlation between the twin beams. Both $S(\Omega)$ and $S_{A-B}(\Omega)$ are normalized to their respective SNLs. The intensity noise of a single beam is decided mainly by the OPO's

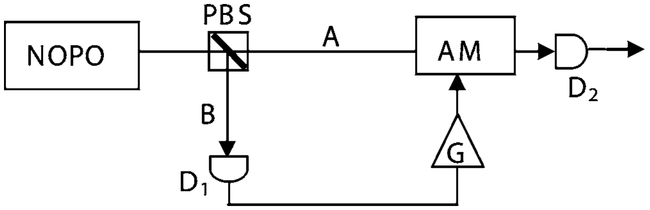

Fig. 1. Schematic of the feed-forward scheme. The quantum-correlated signal and idler beams from the NOPO are separated into beams A and B. Beam B is directly detected by detector D$_1$ to correct beam A by modulation. PBS, polarization beam splitter; G, amplifier; AM, amplitude modulator; NOPO, nondegenerate optical parametric oscillator.

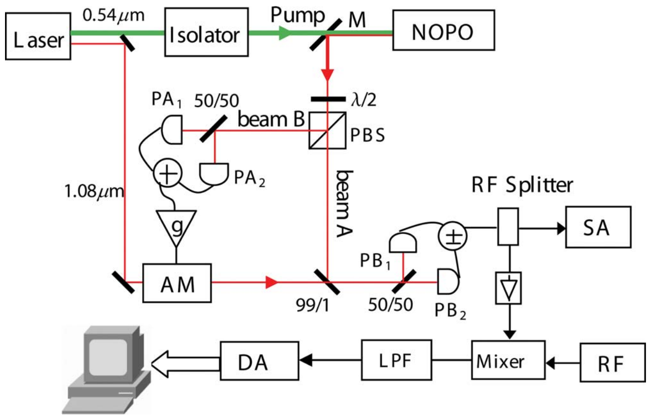

Fig. 2. (Color online) Experimental setup: PA_i, PB_i ($i=1,2$), photodetectors; AM, amplitude modulator; RF Splitter, radio-frequency power splitter; SA, spectrum analyzer; RF, high-frequency signal; LPF, low-pass filter; DA, data acquisition card; PBS, polarization beam splitter; M, mirror.

state of operation. While the OPO cavity operates close to oscillator threshold, each beam generated by the OPO in general has a large amount of excess noise.[6] Under the circumstances, the intensity noise spectrum of corrected beam A can be written approximately as

$$S_A{}^{\mathrm{opt}}(\Omega) = 2S_{A-B}(\Omega). \tag{2}$$

It is obvious that only when the intensity difference squeezing is more than 3 dB ($S_{A-B}<0.5$) can the noise power of the corrected signal beam be below the shot-noise level, that is, sub-Poissonian light.

A schematic of the experimental setup is shown in Fig. 2. A homemade intracavity frequency-doubled and frequency-stabilized cw ring neodymium:yttrium aluminum perovskite laser serves as the light source. The output second-harmonic wave at 540 nm is used to pump the semimonolithic NOPO.[19] The oscillation threshold is less than 120 mW, and an output power of 40 mW is obtained at a pump power of 170 mW.

The output infrared beams are reflected by dichroic mirror M and then separated by a polarizing beam splitter (PBS) into detection arms A and B. The detectors (PA_1, PA_2, PB_1, and PB_2) are Epitax 500 p-i-n photodiodes, with quantum efficiencies of ~ 0.94. The displacement operation is performed by use of an electro-optical modulator and a highly reflecting (99/1) mirror with the help of a local beam for reducing loss.

Experimental results are shown in Fig. 3. All the noise power spectra are normalized to their respective SNLs. Curve a is the noise power spectrum of beam A without feed-forward correction [$S(\Omega)$]; line b is the normalized SNL.[6] It is clear that the single beam has a large mount of excess noise. The excess noise is typically 6–10 dB above the SNL in the measurement 3–10 MHz. Curve d is the noise power spectrum of the intensity difference between the twin beams [$S_{A-B}(\Omega)$, the quantum correlation between beams A and B]. The curve exhibits a more than 5 dB intensity difference squeezing in the entire range, and the maximum value reaches 5.7 dB near 4.5 MHz. Curve c is the obtainable minimum noise power of the sub-Poissonian beam (corrected beam A) according to Eq. (1) with data curve a [$S(\Omega)$] and curve d [$S_{A-B}(\Omega)$]. Because there is much excess noise in each beam from the OPO, curve c is approximately 3 dB higher than curve d [Eq. (2)]. The filled circles in Fig. 3 are the directly measured noise power of prepared sub-Poissonian light at different analysis frequencies. It is clear that the maximum noise reduction is 2.6 dB (45%) below shot-noise level at 5.5 MHz frequency, and the experimental result accords well with the expected values of curve c.

We tuned the sub-Poissonian wavelength roughly by changing the KTP crystal temperature in the OPO.[19] A wavelength range from 1078.9 to 1083.8 nm is covered for a signal beam, and the noise of a sub-Poissonian field is reduced to more than 2 dB below the SNL throughout all the wavelength-tunable range, as shown in Fig. 4. If arm A is measured to control arm B, a range from 1076.4 to 1081.2 nm for the sub-Poissonian field will

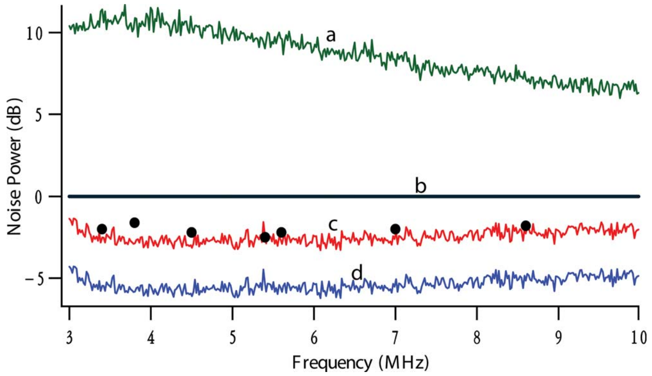

Fig. 3. (Color online) Noise spectra from 3 to 10 MHz. All noise power is normalized to the corresponding SNL. Curve a, noise without feed-forward correction; curve b, the SNL. Curve d, noise spectrum of the intensity difference between the signal and the idler fields. Curve c, obtainable noise of beam A [according to Eq. (1)] with data curve a and curve d. Filled circles, experimentally measured results.

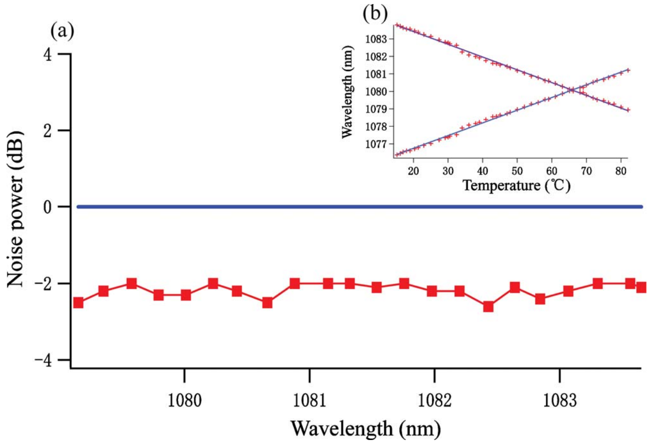

Fig. 4. (Color online) (a) Normalized sub-Poissonian light noise from 1079 to 1083.7 nm. (b) Wavelength of twin beams versus temperature of the crystal in the OPO.

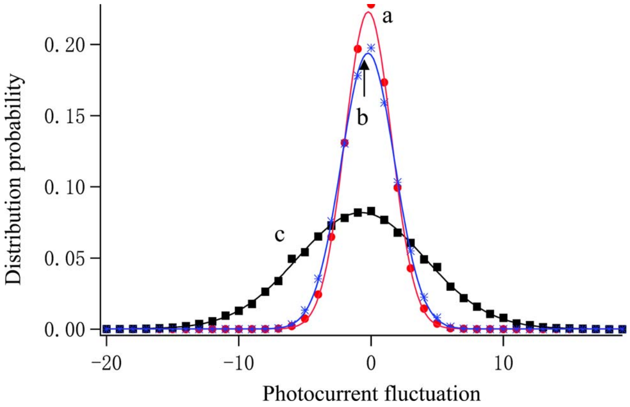

Fig. 5. (Color online) Intensity fluctuation distribution at 5.5 MHz. Curve *a*, prepared sub-Poissonian field; curve *b*, coherent light; curve *c*, single beam from the NOPO (beam A).

be demonstrated. One can also obtain continuous frequency tuning by tuning the laser frequency.[19]

Additionally, the distribution of sub-Poissonian light is acquired as shown in Fig. 5. In the experimental setup (Fig. 2), a part of the signal after rf splitting is mixed with a sinusoidal local oscillator at 5.5 MHz. After a 100 kHz low-pass filter, the signal is collected at a sampling rate of 500 kHz by a 12 bit acquisition card. The statistical distribution of the photocurrent fluctuation is shown in Fig. 5, with 200,000 points for each curve. The points in the figure are the experimental results, and the solid curves are Gaussian fits of the probability distribution. Curve a represents the probability distribution of the prepared sub-Poissonian field, curve b corresponds to a coherent state (the SNL), and curve c corresponds to single-beam field without correction. It is shown that the sub-Poissonian distribution of light fluctuation is narrower than a standard Gaussian distribution of the coherent state. The uncorrected single-beam fluctuation distribution is a super-Poissonian and is much broader than the standard Gaussian distribution. The photocurrent fluctuation of the sub-Poissonian field can also be compared with the standard Gaussian distribution. A noise reduction of 1.2 dB below the SNL is calculated from average half-widths (Fig. 5) and does not accord well with what we observed with the spectrum analyzer because of the narrow bandwidth of the prepared sub-Poissonian field and a nonideal low-pass filter. The calculated photocurrent fluctuation of a single beam is 9 dB above the SNL, which accords well with what we observed with the spectrum analyzer.

In conclusion, we have experimentally demonstrated the preparation of frequency-tunable sub-Poissonian light in a range of 7.4 nm and obtained the corresponding sub-Poissonian statistical distribution of the light. The maximum noise reduction of sub-Poissonian light was 2.6 dB below the SNL. The results are significant for the further development of continually variable quantum information.

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