Pulsed Twin Beams of Light

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Pulsed twin beams of light have been generated using an optical-parametric amplifier that is pumped by the second harmonic of a mode-locked and Q-switched Nd:YAlG laser. The intensity noise levels on the direct-detected signal and idler beams are found to be correlated by more than 15 dB, and the subtracted noise falls below the quantum limit by more than 6 dB (75%). To our knowledge, this is the first observation of *pulsed* twin beams of light, and yields the highest quantum-noise reduction observed in any experiment to date. Our measurements are in excellent agreement with the quantum theory of a nondegenerate optical-parametric amplifier.

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Quantum-noise reduction has been the subject of extensive research over the last decade. Although most of the experimental effort has centered around the generation and applications of quadrature-squeezed light,[1-3] amplitude-squeezed light[4,5] and intensity-correlated twin beams[6,7] have also been produced. For quadrature-squeezed light, the noise in one quadrature of the electromagnetic field, as measured with a homodyne detector, is less than the coherent-state noise level. In this case, $\langle\Delta\hat{a}_\phi^2\rangle=\langle\hat{a}_\phi^2\rangle-\langle\hat{a}_\phi\rangle^2<\frac{1}{4}$, where $\hat{a}_\phi=\hat{a}_1\cos\phi-\hat{a}_2\times\sin\phi$ is the quadrature combination measured with a homodyne local oscillator of phase ϕ, and $\hat{a}=\hat{a}_1+i\hat{a}_2$ is the annihilation operator, $\hat{a}_1$ and $\hat{a}_2$ being the two quadratures. For amplitude-squeezed light, on the other hand, the photon-number noise is less than that of coherent-state light; i.e., $\langle\Delta\hat{n}^2\rangle=\langle\hat{n}^2\rangle-\langle\hat{n}\rangle^2<\langle\hat{n}\rangle$, where $\hat{n}\equiv\hat{a}^\dagger\hat{a}$ is the photon-number operator. In this case, noise can be measured using direct detection, a technically simpler scheme than homodyne detection. Twin beams are two separate beams of light that bear almost identical intensity (photon-number) fluctuations. Therefore, the photocurrents upon individual direct detection are correlated to a high degree, and can be subtracted from each other to yield quantum-noise reduction; i.e., $\langle\Delta(\hat{n}_1-\hat{n}_2)^2\rangle<\langle\hat{n}_1\rangle+\langle\hat{n}_2\rangle$, where $\hat{n}_1$ and $\hat{n}_2$ are the photon-number operators of the two beams. The intensity noise on the individual beams, however, may or may not be at the quantum limit (coherent-state noise level) where $\langle\Delta\hat{n}^2\rangle=\langle\hat{n}\rangle$. For example, it is possible to have $\langle\Delta\hat{n}_1^2\rangle>\langle\hat{n}_1\rangle$ and $\langle\Delta\hat{n}_2^2\rangle>\langle\hat{n}_2\rangle$, while still achieving quantum-noise reduction on the difference photocurrent.

Almost all of the experiments aimed at quantum-noise reduction employ optical nonlinearities wherein the interaction strength increases with pump intensity. Since the currently available cw lasers are short of delivering power levels sufficient for large noise reduction, experimenters have employed optical cavities in order to enhance the nonlinear interaction. However, this method not only increases the complexity of the system, but also limits the bandwidth of noise reduction to that of the cavity. Another approach to increasing the nonlinear interaction is to use pulsed pump lasers that provide high peak powers. Quadrature-squeezed light has been generated in two experiments taking such an approach, one with a mode-locked[2] and the other with a Q-switched laser.[3] The quantum-noise reduction levels measured in these experiments still fall short of those with cavities. The highest level, prior to our experiment, was obtained by Debuisschert *et al.* in a cw-twin-beam experiment using an optical cavity.[8]

In this Letter, we report an experiment in which *pulsed* twin beams of light are generated using a traveling-wave optical-parametric amplifier (OPA) that is pumped by a frequency-doubled mode-locked and Q-switched laser. The intensity (photon-number) noise levels on the signal and idler beams at the output of the OPA are measured using direct detection. The fluctuations on the signal and idler photocurrents are found to be correlated by more than 15 dB, and the subtracted noise falls below the quantum limit by more than 6 dB (75%). To our knowledge, this is the highest quantum-noise reduction ever observed in any experiment to date.

The experimental setup is sketched in Fig. 1. The second harmonic of a mode-locked and Q-switched Nd-doped yttrium-aluminum-garnet (Nd:YAlG) laser (Quantronix, Model No. 416) is used to pump an OPA at 532 nm. A portion of the fundamental laser beam at 1064 nm is separated by a beam splitter (BS) and used as a signal input to the OPA. The mode-locked Nd:YAlG laser is Q switched at a repetition rate of 1 kHz. The resulting Q-switched envelopes of the pump and signal pulses are 150 and 270 ns in duration, respectively. The mode-locked pulses underneath these Q-switch pulse envelopes are estimated to be 140 and 200 ps long for the pump and signal beams, respectively. The traveling-wave OPA consists of a type-II phase-matched $KTiOPO_4$ (KTP) crystal. Both the pump and signal beams are polarized along the e axis of the crystal. The idler beam generated in the amplification process is polarized orthogonal to the signal beam as a result of type-II phase matching. After the pump beam is dispersed away at the output of the OPA with the use of a prism, the output signal and idler beams are separated using a beam-splitting polarizer (BSP) and detected with

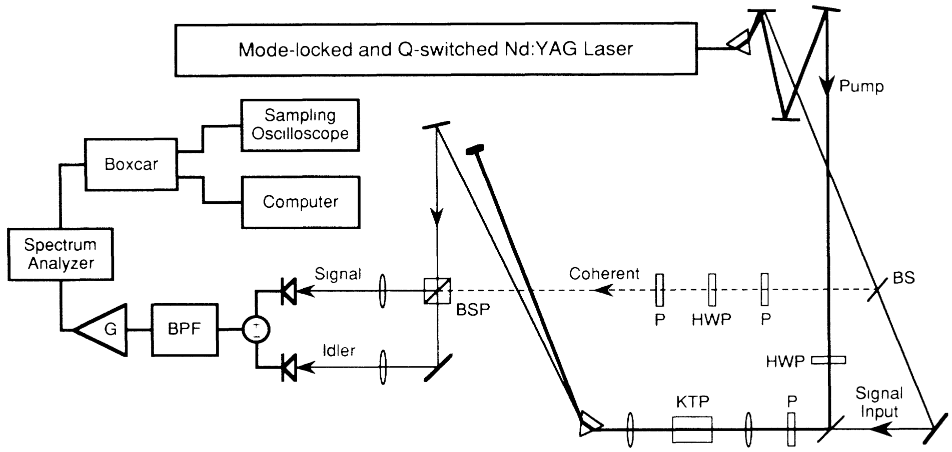

FIG. 1. Schematic of the experimental setup. The second harmonic of the Nd:YAlG laser is used to pump the OPA (KTP crystal) at 532 nm. The fundamental beam from the laser is used as a signal input to the OPA. The output signal and idler beams are separated and detected with InGaAs *p-i-n* photodiodes. The dashed line shows the coherent-state beam used for calibrating the quantum limit.

InGaAs *p-i-n* photodiodes. The path lengths of the various beams from the Nd:YAlG laser to the OPA and then to the photodetectors are made equal within a few millimeters. Calibration of the quantum limit is achieved by illuminating the two detectors with coherent beams from the Nd:YAlG laser having peak powers that are the same as those of the signal and idler beams at the detectors.

In order to measure the intensity noise levels, the photocurrents from the two detectors are subtracted from each other, and the difference is fed to a bandpass filter having a 12-MHz bandwidth around 25 MHz.[9] Filtering is necessary to insure that the strong Fourier components of the signal and idler pulses do not saturate the detectors and/or the subsequent electronics. The noise process at the output of the bandpass filter is analyzed with a pulse-noise measurement scheme[10] employing a radio-frequency spectrum analyzer, a boxcar averager, a sampling oscilloscope, and a computer with analog-to-digital conversion capabilities. Low-noise wideband amplifiers bring the average noise power more than 10 dB above the spectrum-analyzer noise floor. For the measurements described in this Letter, the analyzer is set at a frequency of 28 MHz with a resolution bandwidth of 3 MHz. The large resolution bandwidth allows the output of the analyzer to follow the *Q*-switch noise-pulse envelopes without integrating them. The peak of the noise power pulse is sampled with the boxcar using a gate width of 20 ns. The samples, in turn, are fed to the computer that calculates the average over 16000 pulses. To measure the noise power level at all points along the *Q*-switch pulse, the gate is scanned across the pulse profile at a rate of 20 ns/s while an exponential moving average of the samples is computed with the boxcar and recorded by the oscilloscope.

Figure 2 shows pulses of intensity noise at 28 MHz as measured, curve *a*, on the signal beam, and, curve *c*, on the signal and idler beams with the photocurrents subtracted. Noise pulse *b* is obtained when the detectors are illuminated with coherent light from the Nd:YAlG laser having the same peak powers as the signal and idler beams. Thus, noise pulse *b* defines the coherent-state noise level (quantum limit) for the optical powers incident on the two detectors. The vertical scale is with respect to the stationary background (thermal pulse amplifier) noise level. Clearly, the subtracted noise pulse falls below the quantum limit by 5.0 dB, corresponding to 6.4 ± 0.5 dB of quantum-noise reduction when the background noise is subtracted. The noise levels of the individual signal and idler beams, as measured by blocking the other beam, exceed their coherent-state limits by about 11 dB. And yet, the correlation is so strong that the subtracted noise falls below the quantum limit by more than 6 dB. The signal and idler beams in our experiment are not in coherent states, in contrast to the ex-

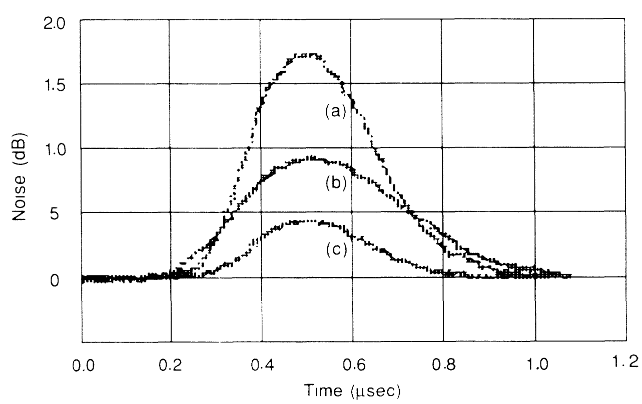

FIG. 2. Pulses of shot noise measured at 28 MHz: curve *a*, the signal; curve *b*, the coherent state; curve *c*, the signal-idler difference. The vertical scale is relative to the background noise level. The spectrum-analyzer resolution bandwidth is 3 MHz and the boxcar gate width is 20 ns.

periment reported by Heidmann *et al.*[6] employing a cw optical-parametric oscillator.

Although the measurements in our experiment are made at a radio frequency of 28 MHz, a simple degenerate theory can be used to describe the results. This is possible because of the large bandwidth of the parametric interaction process. In our experiment, residual phase mismatch limits the interaction bandwidth to about 100 GHz. Under the undepleted-pump approximation, a lossless traveling-wave OPA can be described by[11]

$$\hat{b}_S = \mu \hat{a}_S + \nu \hat{a}_I^\dagger , \tag{1}$$

$$\hat{b}_I = \mu \hat{a}_I + \nu \hat{a}_S^\dagger , \tag{2}$$

where $\hat{a}_S$ and $\hat{a}_I$ are the input and $\hat{b}_S$ and $\hat{b}_I$ are the output annihilation operators for the signal and idler modes, respectively, and $|\mu|^2 - |\nu|^2 = 1$. Since the photocurrents are proportional to $\hat{I}_S \equiv \hat{b}_S^\dagger \hat{b}_S$ and $\hat{I}_I \equiv \hat{b}_I^\dagger \hat{b}_I$ when the output modes are detected separately by ideal detectors, the difference photocurrent can be described by the operator $\hat{I} \equiv \hat{I}_S - \hat{I}_I = \hat{b}_S^\dagger \hat{b}_S - \hat{b}_I^\dagger \hat{b}_I$. Using Eqs. (1) and (2), it is easily shown that $\hat{I} = \hat{a}_S^\dagger \hat{a}_S - \hat{a}_I^\dagger \hat{a}_I$, which contains only the input modes. Therefore, the statistics of the difference photocurrent $\hat{I}$ depend only on the states of the input modes. If the input signal mode is in a coherent state $|\alpha_S\rangle_S$ and the input idler mode is in the vacuum state $|0\rangle_I$ (as is the case in our experiment), the difference photocurrent noise power is proportional to $\langle \Delta \hat{I}^2 \rangle = |\alpha_S|^2$, while

$$\langle \hat{I}_S \rangle = |\mu|^2 |\alpha_S|^2 + |\nu|^2 \simeq |\mu|^2 |\alpha_S|^2$$

and

$$\langle \hat{I}_I \rangle = |\nu|^2 |\alpha_S|^2 + |\nu|^2 \simeq |\nu|^2 |\alpha_S|^2 ,$$

for $|\alpha_S|^2 \gg |\nu|^2$. Coherent-state modes leading to mean photocurrents $\langle \hat{I}_S \rangle$ and $\langle \hat{I}_I \rangle$, on the other hand, would have

$$\langle \Delta \hat{I}_C^2 \rangle = \langle \Delta \hat{I}_{S,C}^2 \rangle + \langle \Delta \hat{I}_{I,C}^2 \rangle = (|\mu|^2 + |\nu|^2) |\alpha_S|^2 .$$

Quantum-noise reduction R is defined as the ratio $R = \langle \Delta \hat{I}^2 \rangle / \langle \Delta \hat{I}_C^2 \rangle = 1/(2g-1)$, where $g \equiv \langle \hat{b}_S^\dagger \hat{b}_S \rangle / \langle \hat{a}_S^\dagger \hat{a}_S \rangle = |\mu|^2$ is the gain of the OPA.

The effects of subunity photodetector quantum efficiencies and linear losses in propagation from the OPA to the detectors can be included by coupling $\hat{b}_S$ and $\hat{b}_I$ to vacuum-state operators $\hat{v}_S$ and $\hat{v}_I$ through

$$\hat{c}_S = \sqrt{\eta} \hat{b}_S + \sqrt{1-\eta} \hat{v}_S , \tag{3}$$

$$\hat{c}_I = \sqrt{\eta} \hat{b}_I + \sqrt{1-\eta} \hat{v}_I , \tag{4}$$

where η is the total detection efficiency. The quantum-noise reduction becomes

$$R = 1 - \eta + \eta/(2g-1) , \tag{5}$$

where the gain $g = \langle \hat{c}_S^\dagger \hat{c}_S \rangle / \eta \langle \hat{a}_S^\dagger \hat{a}_S \rangle$. Since the signal and idler beams are not in coherent states, the individual signal and idler photocurrents carry more noise than

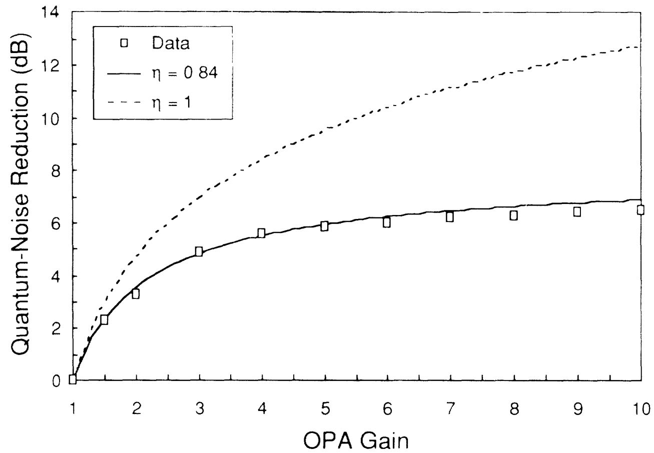

FIG. 3. Quantum-noise reduction R at the peak of the noise pulses as a function of the peak OPA gain g. The solid and dashed lines show theoretical values obtained from Eq. (5) for detection efficiencies of 0.84 and 1.0, respectively. The data points follow the $\eta = 0.84$ curve closely for OPA gains up to about 6, beyond which detector saturation effects tend to reduce the observed quantum-noise reduction.

coherent states of the same average photon number. The increase in signal and idler noise power levels are easily derived to be

$$\frac{\langle \Delta \hat{I}_S^2 \rangle}{\langle \Delta \hat{I}_{S,C}^2 \rangle} = \frac{\langle \Delta \hat{I}_I^2 \rangle}{\langle \Delta \hat{I}_{I,C}^2 \rangle} = 2\eta(g-1) + 1 , \tag{6}$$

from Eqs. (1)-(4).

In our experiment the total detection efficiency η is 0.84. When the data of Fig. 2 were taken the peak pump power density in the KTP crystal was approximately 0.6

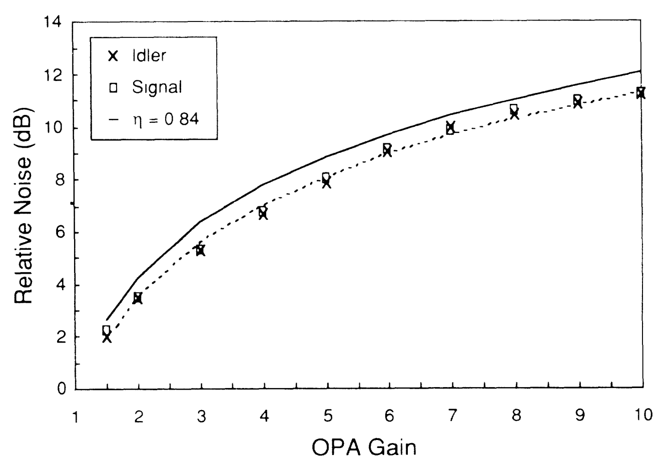

FIG. 4. Individual signal and idler noise powers at the peak of the noise pulses relative to their coherent-state limits as a function of the peak OPA gain g. The solid line shows theoretical values obtained from Eq. (6) for a detection efficiency of 0.84. The dashed line, which is obtained by subtracting 0.75 dB from Eq. (6) in order to account for attenuation at the resolution filter, is in agreement with the data.

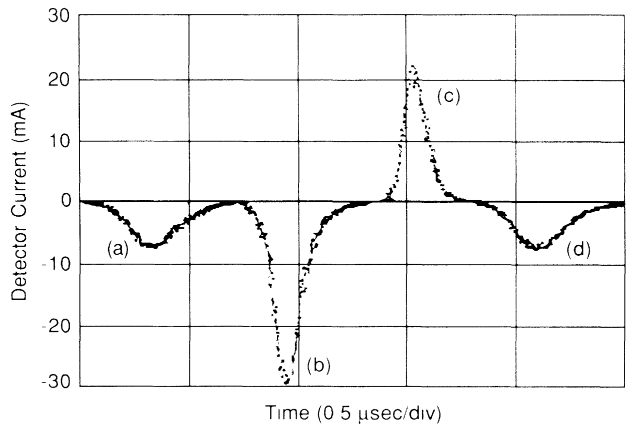

FIG. 5. Q-switch pulses for (a) signal input, (b) signal output, (c) idler output, and (d) signal-idler difference, when the peak OPA gain is 4. The input and difference pulses are 270 ns in duration, whereas the output idler pulse is 150 ns long, the same as the pump pulse.

GW/cm^2, yielding a peak OPA gain g of 9.8 in reasonable accordance with the theory.[12] For these values, Eq. (5) predicts a quantum-noise reduction of 6.9 dB, which is in good agreement with the measured value of 6.4 ± 0.5 dB. Figure 3 shows a plot of quantum-noise reduction measured at the peak of the noise pulses for various values of the peak OPA gain. Also included are the theoretical curves of Eq. (5) for detection efficiencies of $\eta = 1.0$ and 0.84. The experimental data points follow the $\eta = 0.84$ theoretical curve closely. In fact, η was used as an adjustable parameter to fit the data of Fig. 3 by Eq. (5). Independent measurements of propagation losses and detector quantum efficiencies confirmed the total efficiency value of 0.84. At gain values higher than 6, the individual signal and idler noise levels get large enough to start saturating the photodetectors, thereby reducing the photocurrent correlations. At present, detector saturation together with subunity detection efficiency is the key limitation in our experiment. Although we have measured peak OPA gains as high as 400 without damaging the KTP crystal, saturation effects become prohibitive at gains larger than 12, limiting the maximum observable quantum-noise reduction to 6.5 dB. In the future we hope to increase η to 0.9 with improved optical components and detectors, which would lead to a measured quantum-noise reduction of 8.3 dB at an OPA gain of 10. Furthermore, if detection limitations could be overcome ($\eta = 1$, and no detector saturation), an OPA gain of 400 would lead to a quantum-noise reduction of 29 dB according to Eq. (5).

Figure 4 shows a plot of the individual signal and idler noise powers measured relative to their coherent-state levels at the peak of the noise pulses for various values of the peak OPA gain. Also included is the theoretical curve of Eq. (6) with $\eta = 0.84$, the value used in Fig. 3. The measured data points are consistently lower than the theoretical curve by about 0.75 dB. This is because the 3-MHz resolution filter in the spectrum analyzer is not wide enough to pass the shorter-duration signal and idler noise pulses without integrating them.[13] In the time domain, this point is further verified as shown in Fig. 5 which depicts the classical response of the OPA. The Q-switch pulse shapes are shown for the signal input, signal output, idler output, and signal-idler difference. Since the pump pulse is shorter in duration than the input pulse, the output pulses are shorter, too. The difference pulse, in essence, is a replica of the input pulse, as expected.

In conclusion, we have demonstrated that large quantum-noise reductions can be obtained with pulsed twin beams of light generated by traveling-wave parametric amplification. Although the individual beams exhibit more intensity noise than a beam in a coherent state with the same average photon number, the intensity correlations make it possible for the difference photocurrent to fall below the quantum limit. The absence of interaction-enhancing cavities and the simplicity of direct detection make our approach to twin-beam generation particularly attractive for measurements beyond the quantum limit.

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