Observation of Quantum Frequency Conversion

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Quantum frequency conversion, a process with which an input beam of light can be converted into an output beam of a different frequency while preserving the quantum state, is experimentally demonstrated for the first time. Nonclassical intensity correlation ($\simeq 3$ dB) between two beams at 1064 nm is used as the input quantum property. When the frequency of one of the beams is converted from 1064 to 532 nm, nonclassical intensity correlations ($\simeq 1.5$ dB) appear between the up-converted beam and the remaining beam. Our measurements are in excellent agreement with the quantum theory of frequency conversion. The development of tunable sources of novel quantum light states seems possible.

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Many novel quantum states of light, such as squeezed and twin-beam states, have recently been demonstrated [1]. The usefulness of such light states in interferometry [2] and precision measurement [3] has been verified. The progress of their application in spectroscopy [4], however, has been hampered by the lack of tunable sources of the novel quantum states. Present squeezed and twin-beam sources generate quantum-noise reduction around a fixed carrier frequency, whereas for spectroscopic applications, tunability of the carrier frequency is desirable [5]. Recently we proposed that quantum frequency conversion (QFC), a process in which an input beam of light is converted into an output beam of a different frequency while preserving the quantum state, could be used to obtain frequency tunable quantum states of light [6]. In this Letter we report on the first, to the best of our knowledge, observation of QFC.

An implementation of QFC requires that an input beam to a sum-frequency generator be completely upconverted [6]. One needs to generate a quantum state (e.g., a squeezed or a twin-beam state) at one frequency and then show that the properties of the same state appear at the up-converted frequency. We have chosen to use nonclassical intensity correlation of the twin beams as the input quantum property because large correlations can be easily obtained by pumping an optical parametric amplifier (OPA) with a mode-locked and Q-switched laser [7]. After one of the twin beams is up-converted, nonclassical intensity correlations appear between the up-converted beam and the remaining twin beam. In our experiment the 1064-nm output signal beam of the parametric amplifier, possessing $\simeq 3$ dB nonclassical intensity correlation with the 1064-nm output idler beam, is upconverted into a 532-nm beam. The 532-nm beam shows $\simeq 1.5$ dB nonclassical correlation with the 1064-nm idler beam, thus demonstrating the QFC process.

Assume that two light modes of angular frequencies ω_1 and ω_2 interact in a second-order nonlinear medium to generate a third mode at $\omega_3 = \omega_1 + \omega_2$. If the medium of length L is lossless and the amplitude of the pump mode at ω_2 is large, then [6]

$$\hat{b}_1 = \hat{a}_1 \cos\chi L - \hat{a}_3 \sin\chi L, \quad \hat{b}_3 = \hat{a}_1 \sin\chi L + \hat{a}_3 \cos\chi L\,, \qquad (1)$$

where $\hat{a}_i$ $(i=1,3)$ is the annihilation operator of the ith mode at the medium input and $\hat{b}_i$ is that at the output. χ is a coupling constant that is proportional to the amplitude of the pump mode. One can see that if the pump amplitude is adjusted such that $\chi = \pi/2L$, then complete conversion occurs from ω_1 to ω_3 (and vice versa) because

$$\hat{b}_1(\chi = \pi/2L) = -\hat{a}_3, \quad \hat{b}_3(\chi = \pi/2L) = \hat{a}_1\,. \qquad (2)$$

Using this result it was shown by Kumar [6] how one can obtain a tunable source of squeezed light. If the quantum state $|\Psi\rangle$ is such that $\hat{a}_3|\Psi\rangle = 0$, i.e., the input mode at ω_3 is in the vacuum state, then after complete conversion $\hat{b}_3|\Psi\rangle = 0$, implying that the output mode at ω_1 will be in the vacuum state. Moreover, if $\hat{a}_1$ is nonclassically correlated with another light mode (annihilation operator $\hat{d}$) that is not taking part in the frequency conversion process, then after complete conversion, nonclassical correlations will appear between $\hat{b}_3$ and $\hat{d}$. It is this transfer of quantum correlations from one frequency to the other that we demonstrate experimentally. In our experiment $\hat{a}_1$ and $\hat{d}$ are the quantum-correlated outputs of a polarization-nondegenerate OPA at 1064 nm. $\hat{b}_3$ is at 532 nm. If the pump beam frequency ω_2 is tunable, then a tunable beam of light possessing nonclassical correlations with mode $\hat{d}$ can be generated. Such beams can be employed in spectroscopy to obtain sub-shot-noise sensitivity [8].

A schematic of the experimental setup to demonstrate QFC is sketched in Fig. 1. A mode-locked, Q-switched, and frequency-doubled Nd-doped yttrium-aluminum-garnet (Nd:YAG) laser (Quantronix, model 416) is used for both the twin-beam generation and the quantum frequency conversion. The laser is Q switched at a repetition rate of 1 kHz. The duration of the Q-switched envelopes of the resulting pulses is typically between 270 and 340 ns for the fundamental 1064-nm output and between 150 and 190 ns for the frequency-doubled 532-nm output. The mode-locked pulses underneath the Q-switched envelopes are approximately 200 and 140 ps in duration for the 1064- and 532-nm output beams, respectively. The 532-nm green output beam is used to pump a twin-beam source which is an OPA employing a type-II

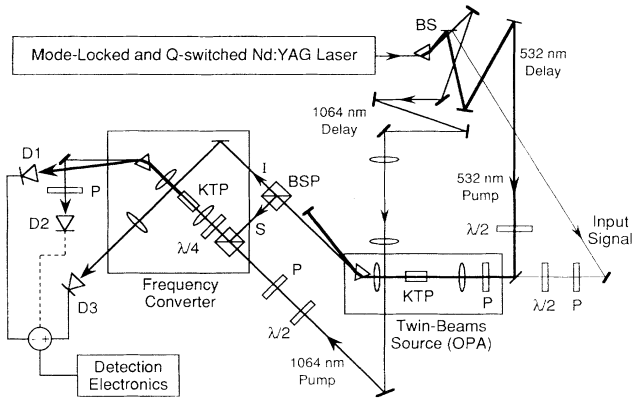

FIG. 1. A schematic of the experimental setup to demonstrate quantum frequency conversion. The second-harmonic beam from the Nd:YAG laser is used to pump the OPA whereas the fundamental beam pumps the frequency converter. The polarizers P, half-wave plates λ/2, and quarter-wave plates λ/4 are used to set the polarizations of the signal and pump beams in the type-II phase-matched KTP crystals. The delay lines are used to insure that the signal and pump pulses arrive in the KTP crystals at the same time. The detection electronics consists of a bandpass filter at 28 MHz, high-gain radio-frequency amplifiers, a radio-frequency spectrum analyzer, a boxcar averager, and a sampling oscilloscope [7].

phase-matched $KTiOPO_4$ (KTP) crystal. A portion of the 1064-nm beam is separated by a beam splitter (BS) and used as signal input to the OPA. The operation of this source and the resulting quantum correlations between the signal and idler beams at the OPA output were described in a previous Letter [7]. The gain of the OPA is varied by adjusting the power of the 532-nm pump beam. After dispersing away the green pump beam at the output of the OPA, the orthogonally polarized signal (S) and idler (I) beams are separated using a beam-splitting polarizer (BSP). The idler beam (mode $\hat{d}$) is directed to detector D3 which is an InGaAs *p-i-n* photodiode.

A second beam-splitting polarizer is used to inject the signal beam S [mode $\hat{a}_1$ in Eq. (2)] into a frequency converter which also consists of a type-II phase-matched KTP crystal that is pumped by the 1064-nm output beam from the Nd:YAG laser. The pump beam in the frequency converter is polarized along the *o* axis of the KTP crystal whereas the injected signal beam is polarized along the *e* axis. A new 532-nm light beam [mode $\hat{b}_3$ in Eq. (2)] is generated from the frequency converter that is polarized along the *e* axis of the KTP crystal because of type-II phase matching. The conversion efficiency η_f of the input signal beam into the 532-nm up-converted beam can be adjusted by varying the power of the 1064-nm pump beam into the frequency converter [9]. The up-converted 532-nm beam is separated from the 1064-nm unconverted signal (due to incomplete conversion) and pump beams with the use of a prism and directed to a silicon *p-i-n* photodiode D1. The unconverted signal beam is further separated from the pump beam using a polarizer and detected by an InGaAs *p-i-n* photodiode D2. The path lengths of the various beams are carefully adjusted using appropriate optical delay lines so that the interacting beams arrive in the KTP crystals at the same time.

The classical and quantum properties of the twin beams are measured by simply blocking the pump beam to the frequency converter and analyzing the photocurrents from detectors D2 and D3. The overall detection efficiency η_s of the signal beam is less than that of the idler beam (η_i) because the former propagates through extra optical elements that constitute the frequency converter. To measure the classical and quantum properties of the up-converted beam, the pump beam to the frequency converter is turned on and the photocurrents from detectors D1 and D3 are analyzed. Quantum-noise reduction is measured by subtracting the photocurrents of detectors D1 and D3 (D2 and D3 for the twin beams) from each other and analyzing the resulting noise process with a pulse-noise measurement scheme [10] that employs a radio-frequency spectrum analyzer, a boxcar averager, and a sampling oscilloscope. The noise measurements described in this Letter are made at a radio frequency of 28 MHz. The peak of the noise power pulses is sampled with the boxcar using a gate width of 20 ns and averaged over 10^4 pulses. To measure the noise power level at all points along the *Q*-switched 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. Calibration of the quantum limit is obtained by illuminating the three detectors with coherent-state beams from the Nd:YAG laser having the same peak powers as those from the twin-beam source and the frequency converter.

Figure 2 shows pulses of intensity noise at 28 MHz as measured, curve γ, on the signal and idler beam difference photocurrent (detector D2 minus D3) with the pump to the frequency converter blocked, and, curve δ, on the up-converted and idler beam difference photocurrent (detector D1 minus D3) with the pump to the frequency converter turned on. Noise pulses α and β are obtained by illuminating the respective detectors with coherent-state beams from the Nd:YAG laser having the same peak powers as the beams from which curves γ and δ are obtained. Therefore noise pulses α and β define the coherent-state noise levels (quantum limits) for the optical powers incident on the detectors. The vertical scale is relative to the stationary background (thermal plus amplifier) noise level. Clearly, the subtracted-noise pulses fall below the quantum limits by more than 1 dB for both the 1064-nm twin beams (dashed arrow) and the up-converted and idler beams (solid arrow), henceforth called the frequency-converted twin beams. When the background noise level is subtracted, quantum-noise reduction at the pulse peaks is 2.3 dB for the twin beams

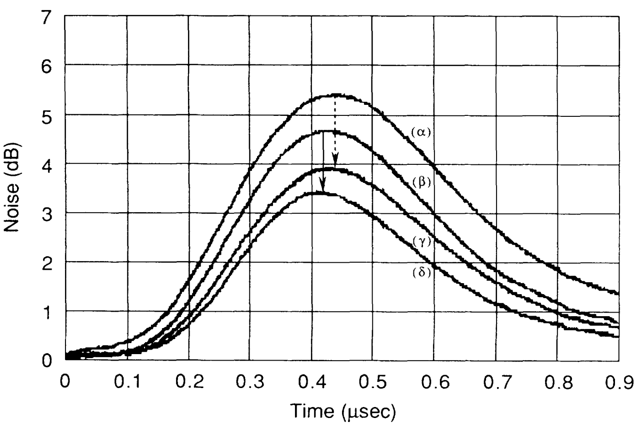

FIG. 2. Pulses of shot noise measured at 28 MHz: curve γ, on the signal and idler beam difference photocurrent with the pump to the frequency converter blocked; curve δ, on the up-converted and idler beam difference photocurrent with the pump to the frequency converter turned on. Curves α and β are the coherent-state noise levels (quantum limits) for the optical powers that are incident on the detectors in the above two cases, respectively. The vertical scale is relative to the background noise level. The dashed (solid) arrow indicates the quantum-noise reduction for the twin (frequency-converted twin) beams before the background noise level is subtracted. The OPA gain is 1.5, the spectrum analyzer resolution bandwidth is 3 MHz, and the boxcar gate width is 20 ns. The average photocurrents generated by the detectors D1, D2, and D3 at the peak of the Q-switched pulse envelopes are 2.6, 4, and 1.6 mA, respectively.

and 2.1 dB for the frequency-converted twin beams.

The observed noise reduction for the twin beams and the frequency-converted twin beams can be compared with the quantum theory of an OPA and QFC. Following the calculation in Ref. [7], when the idler beam detection efficiency at the OPA output is different from that of the signal beam, the following expression for the quantum-noise reduction R observable upon direct differenced detection of the twin beams is obtained:

$$R=\frac{\eta_i^2-\eta_i\,\delta\eta\, g+2(\delta\eta)^2 g(g-1)}{\eta_i(2g-1)-\delta\eta\, g}+1-\eta_i\,, \qquad (3)$$

where $\delta\eta\equiv\eta_i-\eta_s$ is the extra inefficiency in the detection of the signal beam over that of the idler beam, and g is the OPA gain.

When the frequency conversion process is incomplete, an efficiency $\eta_f\equiv\sin^2\chi L$ can be defined, which allows Eq. (1) to be rewritten as

$$\hat{b}_1=(1-\eta_f)^{1/2}\hat{a}_1-\eta_f^{1/2}\hat{a}_3,\quad \hat{b}_3=\eta_f^{1/2}\hat{a}_1+(1-\eta_f)^{1/2}\hat{a}_3\,. \qquad (4)$$

The quantum state in our experiment is such that $\hat{a}_3|\Psi\rangle=0$. This is because there is no input to the frequency converter at ω_3. Equation (4) then simply states that, if the conversion is incomplete, the up-converted output can be treated as if after complete conversion the output has passed through a beam splitter of transmissivity η_f. Therefore, the quantum-noise reduction observable upon direct differenced detection of the frequency-converted twin beams is also given by Eq. (3) with $\delta\eta$ replaced by $\delta\eta_c=\eta_i-\eta_f\eta_g$, where η_g is the total detection efficiency of the 532-nm up-converted beam.

Figure 3 shows plots of the quantum-noise reduction measured at the peak of the noise pulses for various values of the peak OPA gain. Solid diamonds are the data points for the quantum-noise reduction on the twin beams and open diamonds are those for the frequency-converted twin beams. Also included are theoretical curves of Eq. (3). The solid curve is for $\eta_i=0.78$, $\delta\eta=0.05$ and the dashed curve is for $\eta_i=0.78$, $\delta\eta_c=0.48$. The experimental data points follow the theoretical curves closely. In fact η_i, $\delta\eta$, and $\delta\eta_c$ were used as adjustable parameters to fit the theoretical curves to the data. Independent measurements of propagation losses and detector quantum efficiencies confirmed the above values. For the data in Fig. 3, η_f was measured [9] to be 0.8 which gives $\eta_g=0.38$. The main contributor to the poor detection efficiency of the up-converted beam is the detector D1 which was measured to have a quantum efficiency of only 50% at 532 nm.

In the case of the up-converted twin beams, the observed quantum-noise reduction acquires a maximum value and then decreases as the OPA gain is increased. This is due to unequal detection efficiencies for the two beams as noted above. The photocurrents from the two detectors become increasingly unbalanced as the OPA gain increases. This, however, is a drawback of the detec-

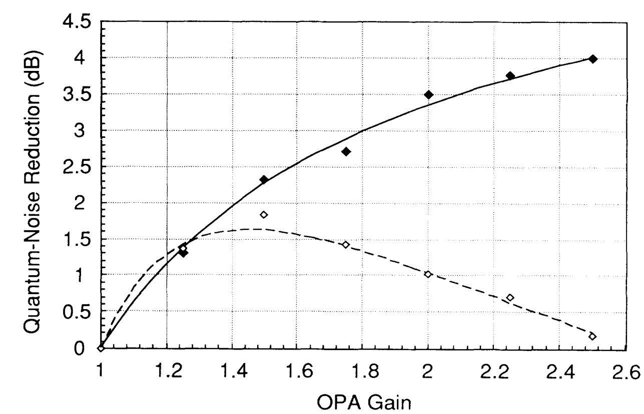

FIG. 3. Quantum-noise reduction R at the peak of the noise pulses as a function of the peak OPA gain g. Solid diamonds: data points for the twin beams; open diamonds: data points for the frequency-converted twin beams; solid curve: plot of Eq. (3) for $\eta_i=0.78$ and $\delta\eta=0.05$; dashed curve: plot of Eq. (3) for $\eta_i=0.78$ and $\delta\eta_c=0.48$. The emergence of an optimum gain for maximum quantum-noise reduction, very pronounced in the case of the frequency-converted twin beams, is due to unequal detection efficiencies of the two beams.

tion electronics that we employ [7] and can be overcome by amplifying the two photocurrents by differing amounts before subtracting them [11].

In conclusion, we have demonstrated quantum frequency conversion with pulsed twin beams of light. The experimental results are in agreement with the quantum theory of optical parametric amplification and quantum frequency conversion. This experimental demonstration opens the door for the development of tunable sources of novel quantum states of light. For example, a tunable laserlike beam of light whose intensity is quantum correlated with the fixed-frequency idler beam can be generated by employing a tunable laser, such as a dye laser, to pump the frequency converter.

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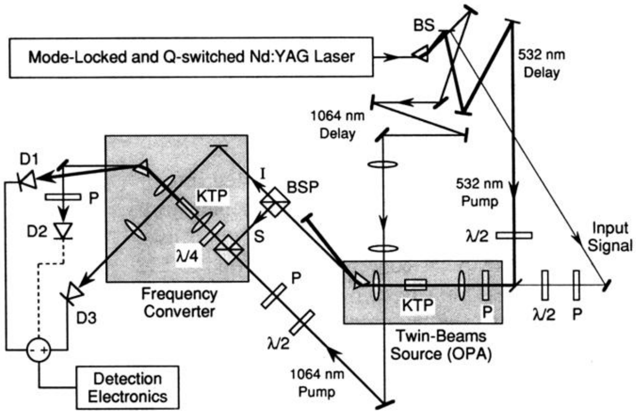
[11] *Note added.*—After completing the experiments described in this Letter, we have implemented such an improvement in our detection electronics. The quantum-noise reduction no longer decreases as the OPA gain is increased.



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