Squeezed-Light Generation with an Incoherent Pump

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We report generating squeezed light via parametric down conversion of a Q-switched and frequency-doubled multi-longitudinal-mode Nd-doped yttrium-aluminum-garnet laser. A local oscillator with appropriate temporal incoherence is needed to homodyne detect the generated squeezed light. As a first approximation, we derive the local-oscillator beam from the same multimode laser whose harmonic is used to pump the parametric down-conversion process 0.8 ± 0.2 dB of squeezing is routinely observed.

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Several experiments have been reported for the generation of squeezed light since 1985.[1] All of these experiments employ a temporally coherent source, either a single-mode continuous-wave (cw) laser or a cw mode-locked pulsed laser, to pump a nonlinear medium. The resulting squeezed light is also temporally coherent. In the degenerate single-mode limit, the electric-field operator for such light can be expressed in photon units as

$$\hat{E}(t) = \hat{a}e^{i\omega_0 t} + \hat{a}^{\dagger}e^{i\omega_0 t}, \tag{1}$$

where $\hat{a}$ is the photon annihilation operator, and ω_0 is the radian frequency of light. Squeezing is said to occur when the quadrature-noise variance, $\langle\Delta\hat{a}_\theta^2\rangle \equiv (\hat{a}_\theta - \langle a_\theta\rangle)^2$ with $\hat{a}_\theta \equiv \hat{a}e^{-i\theta} + \hat{a}^{\dagger}e^{i\theta}$, falls below the level set by the coherent state $|\alpha\rangle$ of light, where $|\alpha\rangle$ is defined through the eigenvalue equation $\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$.[2] The squeeze angle θ is determined by the parameters of the experiment, in particular the pump-field phase.

It is well known, however, that a coherent pump source is not required to observe nonlinear optical processes.[3] Indeed, the very first observation of second-harmonic generation was made using a pulsed multi-longitudinal-mode ruby laser.[4] The following question, then, begs an answer: Is the requirement of a coherent pump necessary to observe quantum-optic effects, let us say squeezing in particular? The answer is no and in this Letter we report an experiment in which a temporally incoherent pump source is used to generate squeezed light. The generated squeezed light is temporally *incoherent* as well, placing stringent demands on the temporal profile of the local-oscillator (LO) beam that must be used in the homodyne setup employed for the detection of squeezing.

The concept of space-time coherence of the electromagnetic field should be differentiated from the coherent state $|\alpha\rangle$. The former expresses the spatiotemporal dependence of the electric-field operator whereas the latter is a class of states of the electromagnetic field. It is well known that an electromagnetic field with only one excited mode in a coherent state is fully coherent in the sense, as defined by Glauber,[5] that the correlation functions factorize.[6] Thus, despite the temporal incoherence, a single-mode picture can still be used to describe our experiment.[7] The positive-frequency part of the electric-field operator can be expressed as

$$\hat{E}^{(+)}(t) = \hat{a}_0\phi_0(t) + \sum_i \hat{a}_i\phi_i(t), \tag{2}$$

where $\phi_0(t)$ is the temporal profile of the field mode that is squeezed as a result of the nonlinear interaction, $\{\phi_i(t),\ i\neq 0\}$ are the remaining members of a complete set of orthonormal modes needed to describe the field over the observation time T, and $\{\hat{a}_i\}$ are the corresponding annihilation operators. It is always possible to choose $\phi_0(t)$ to be such that it represents the temporal profile of the positive-frequency part of the classical electric field. This would be the case if the modes $\{\phi_i(t),\ i\neq 0\}$ are all chosen in the vacuum state, giving $\langle\hat{E}^{(+)}(t)\rangle = \langle\hat{a}_0\rangle\phi_0(t)$. Then, once $\phi_0(t)$ has been chosen, the remaining modes $\{\phi_i(t),\ i\neq 0\}$ can be obtained via the Gramm-Schmit orthonormalization procedure.[8] The state of the electromagnetic field will then be specified completely by the (single-mode) state of $\hat{a}_0$.

In our experiment, we use the second harmonic of a multimode laser to pump a traveling-wave parametric down converter. The dual-detector balanced-homodyne detection technique is employed to measure the level of squeezing obtained.[9] A general theory of homodyne detection was first given by Yuen and Shapiro.[10] They showed that a homodyne detector measures the field operator

$$\tfrac{1}{2}\int \phi_{\rm LO}^*(t)\hat{E}^{(+)}(t)dt + \text{H.c.},$$

where H.c. stands for Hermitian conjugate, and $\phi_{\rm LO}^*(t)$ is the temporal profile of the coherent-state LO employed in the detection setup. It follows then from Eq. (2) that in order to probe the quadrature-noise properties of $\hat{a}_0$ one needs $\phi_{\rm LO}(t) = \phi_0(t)$. A coherent state of $\hat{a}_0$ is, however, not available in our experiment. Therefore, as a first approximation, we derive the LO beam from the same multimode laser whose second harmonic is used as the pump for the parametric down-conversion process. Note that $\phi_0(t)$ can have any arbitrary time dependence;[11] it can even fluctuate from pulse to pulse as it does in our experiment. Squeezing would be detectable so long as $\phi_{LO}(t) \approx \phi_0(t)$ for each pulse.

Another motivation for our experiment is provided by the pulsed squeezing experiment of Slusher *et al.*[12] Employing the second harmonic of a cw mode-locked laser as the pump source, they initially achieved 0.6 dB of squeezing via traveling-wave parametric down conversion in a second-order nonlinear medium. To obtain higher squeezing, they later made use of an optical cavity around the pump beam to increase to pump intensity in the nonlinear medium, thereby increasing the parametric gain together with the resulting squeezing. In our experiment, however, we take a different approach. We obtain higher pump intensity through Q switching of the laser. High pump intensity can be obtained either in the mode-locked Q-switched mode of operation or in the Q-switched-only mode. In our effort to demonstrate the generation of temporally incoherent squeezed light, we have chosen to run our laser in the Q-switched-only mode of operation.

The experimental setup is sketched in Fig. 1.[13] We start with a Q-switched Nd-doped yttrium-aluminum-garnet (Nd:YAlG) laser (Quantronix, Model No. 416) operating in the infrared (IR) at 1064 nm. A green beam at 532 nm, obtained by frequency doubling the fundamental IR beam in a type-II phase-matched $KTiOPO_4$ (KTP) crystal (not shown) and separated from the latter with the use of a prism, provides the pump to a traveling-wave optical parametric amplifier (OPA). Portions of the fundamental IR beam are separated using beam splitters to generate (i) an LO $\phi_{LO}(t)$ for the homodyne detection of the generated squeezed light and (ii) a test input signal to the OPA (shown as a dashed line) for the characterization of its classical response. In order to achieve the high pump intensity necessary for a large parametric gain, the multimode Nd:YAlG laser is Q switched at a repetition rate of 10 kHz. We estimate that approximately fifty longitudinal modes of the laser, separated by 100 MHz, oscillate simultaneously. The frequency-doubled green pump beam has an even broader bandwidth; it is estimated to contain approximately seventy modes. The resulting pulses are of 400- and 280-ns duration for the IR and the green beams, respectively.

Parametric down conversion of the pump beam takes place in another KTP crystal that is also oriented for type-II phase matching. The pump beam is linearly polarized along the e axis of the crystal. The down-converted IR is composed of two orthogonal linear polarization modes, called the signal and the idler modes. The IR test beam is made collinear and copolarized with the pump in order to measure the OPA gain and to facilitate the subsequent alignment of the amplified beams into the homodyne detection apparatus. The idler beam that is generated in the amplification process has a bandwidth that is even broader than the pump. We estimate that it contains approximately one hundred modes. It has a pulse duration of 200 ns, half that of the fundamental beam. The signal (S) and the idler (I) beams emerging from the KTP crystal are slightly displaced from each other because of walkoff of the beams in the birefringent KTP. To make them collinear again, for the purpose of extracting the proper squeezed mode, a separation and recombination technique is employed with use of beam-splitting polarizers (BSP) as shown in Fig. 1.

The recombined beam exhibits maximum squeezing in a mode $\phi_0(t)$ that is polarized at a 45° angle relative to both the signal- and the idler-beam polarizations. The squeezed mode is superimposed on the properly polarized LO mode $\phi_{LO}(t)$, obtained with the help of various polarizers (P) and half-wave plates (HWP), using a 50-50 beam splitter (BS) as part of the dual-detector balanced-homodyne detection configuration.[9] The homodyning mode-matching efficiency is a very strong function of the relative path lengths of the various beams because of the temporal incoherence of the pump and the

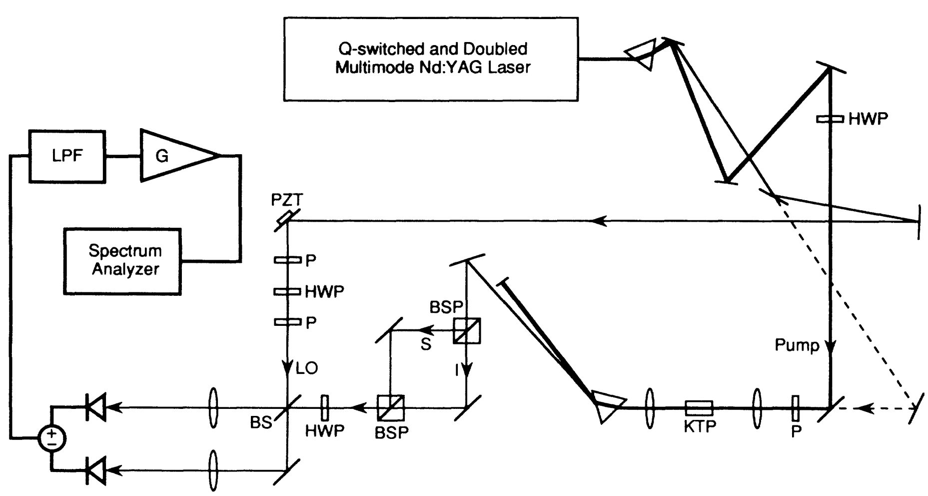

FIG. 1. Schematic of the experimental setup.

LO beams. In order to obtain the best mode-matching efficiency, the path lengths of the various beams from the Nd:YAlG laser to the photodetectors are made equal to within a few millimeters.

The output beams from the 50-50 beam splitter are detected with InGaAs *p-i-n* photodiodes having high quantum efficiencies at 1064 nm. The dynamic range of the photodetectors is limited by the applied reverse bias voltage, dictating a minimum duty cycle that must be attained on the pulsed LO beam. The average LO power must be sufficient enough for the associated shot noise to overcome the front-end thermal noise of the subsequent electronics, whereas the peak power must remain low in order not to saturate the detectors. On the other hand, we need high peak power for a high parametric gain because both the pump beam to the OPA and the LO beam to the homodyne detector are derived from the same laser. Photocurrents from the two detectors are subtracted from each other to cancel any excess noise on the LO beam,[9] and furthermore, to avoid saturation of the amplifying electronics from the high peak power associated with the pulsed LO. A low-pass filter (LPF) with a cutoff frequency of 80 MHz is used to suppress the longitudinal-mode beats even further. The difference photocurrent is amplified and fed to a spectrum analyzer (SA) for spectral analysis. The gain of the amplifiers (G) is chosen large enough for the difference-photocurrent noise power to exceed the SA noise floor up to about 80 MHz. One mirror in the LO path is mounted on a piezoelectric transducer (PZT) to sweep the phase of the LO beam with respect to that of the squeezed mode. No attempt is made to stabilize the relative phases of the various beams.

When the pump beam is blocked, the noise level observed on the spectrum analyzer corresponds to the sum of the vacuum-state noise (shot noise) N_S and the background thermal noise N_T. With 0.6 mW average LO power on each detector, at 23 MHz, this noise level is 4.5 dB higher than the background thermal noise in accordance with our calculations.[14] However, when the pump beam is turned on, the measured noise is found to be a function of the phase of the LO beam, as shown in Fig. 2. In typical measurements, when the LO beam is in phase with the field quadrature whose noise is deamplified, a decrease (ΔN_-) of 0.5 ± 0.1 dB in the noise level is observed. Similarly, an increase (ΔN_+) in the noise level of 0.8 dB is observed for the other field quadrature. These changes are related to the measured deamplification (squeezing) and amplification of the vacuum-state noise level by

$$\Delta N_{\pm} = \frac{S^m_{\pm} N_S + N_T}{N_S + N_T}, \qquad (3)$$

where $S^m_{\pm}$ represents the measured degree of squeezing. Since, in our measurements, $(N_S + N_T)/N_T = 4.5$ dB, the vacuum-state noise level $N_S = 1.8 N_T$. From this we find that, with the pump beam on, the relative decrease (S^m_-)

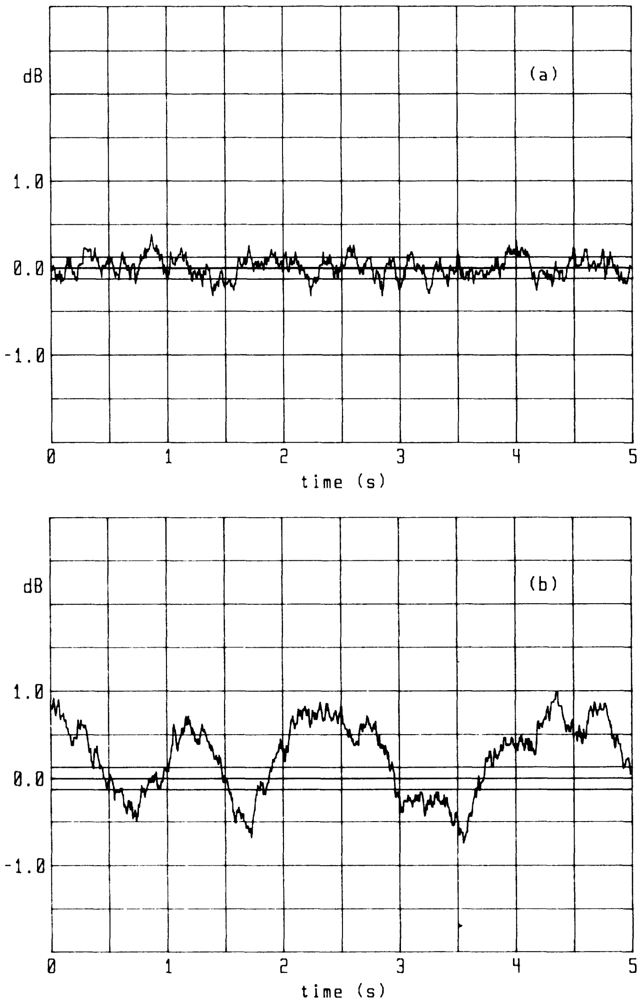

FIG. 2. Time trace of the noise measured on the spectrum analyzer at 23 MHz (a) when the squeezed mode is blocked, and (b) when it is unblocked. The phase of the LO beam is being scanned in both cases. The three horizontal lines are drawn at noise levels that correspond to the mean (-98.03 dBm, middle line) and mean $\pm$ 1 standard deviation (0.12 dB) of the phase-insensitive shot plus background noise level. At least 0.5 dB of squeezing is clearly observed. The resolution and video bandwidth settings on the spectrum analyzer were 10 kHz and 3 Hz, respectively. The vertical scale is 0.5 dB/div and the horizontal scale is 0.5 s/div.

and the increase (S^m_+) from the vacuum-state noise level are 0.83 and 1.31, respectively. This corresponds to 0.8 dB (17%) of observed squeezing. With some effort, when the setup is aligned well, we are able to measure up to 1.0 dB (20%) of squeezing. A higher value of squeezing is expected with an increase in the pump beam power. For the data presented above, the peak power density of the green pump pulses in the down-converting KTP crystal was 30 MW/cm^2. However, since the laser in the present experiment is operated in the *Q*-switched-only mode, there are large exponential intensity fluctuations underneath the Q-switched pulse profile due to random beating of the longitudinal modes.[15] When the peak power density of the pump pulses is increased beyond approximately 40 MW/cm^2, these exponential intensity fluctuations tend to damage the KTP crystal, thereby limiting the amount of observable squeezing. Although the data presented above were taken at 23 MHz, where extensive noise measurements were made, squeezing was observable at many other radio-frequency settings of the spectrum analyzer from about 10 to 75 MHz. The lower limit is due to the presence of low-frequency Fourier components of the Q-switched LO pulses,[14] whereas the upper limit is due to the low-pass filter introduced in the detection electronics to suppress the signal components at multiples of 100 MHz arising from the beating of the various longitudinal modes of the laser.

The generated squeezed light encounters many loss mechanisms in propagation from the nonlinear medium to the detection apparatus. The squeezing level generated by the down-conversion process is thus better than that observed. Major causes of loss are spatiotemporal (mostly temporal) mode mismatch in homodyne detection with $\eta_m = 0.5$, reflection losses at various optical surfaces with $\eta_r = 0.9$, and less than unity quantum efficiencies of the photodetectors with $\eta_d = 0.9$. These give a total detection efficiency $\eta = \eta_m \eta_r \eta_d$ of 0.4. The measured quantities $S^m_\pm$ are related to those generated in the down-conversion process by

$$S^m_\pm = \eta S^i_\pm + 1 - \eta \,, \tag{4}$$

with S^i_- representing the inferred degree of squeezing. From this the vacuum-noise deamplification (squeezing) and amplification are inferred to be 2.4 dB (42%) and 2.5 dB, respectively.

It has been shown by Wu *et al.*[16] that the parametric amplification of vacuum noise generates a minimum-uncertainty squeezed state. To see whether such is the case in our pulsed experiment, we can compute $S^i_\pm$ from the measured parametric gain μ^2 using

$$S^i_\pm = [\mu \pm (\mu^2 - 1)^{1/2}]^2 \,. \tag{5}$$

In our experiment, μ^2 is typically 1.15. This predicts 3.3 dB of deamplification and amplification which is in reasonable agreement with our noise measurements.

In conclusion, we have generated squeezed light by parametric down conversion of a pump laser that is temporally incoherent. The resulting squeezed light is also temporally *incoherent* because an incoherent local oscillator is needed for its detection. The experimentally observed beam-path matching requirement implies a coherence length of about 1 cm. The light generated in our experiment is of direct use in applications which require that the first-order coherence be washed out.[17] In our experiment 0.8 ± 0.2 dB of squeezing is routinely observed. At present, the maximum amount of observed squeezing is limited primarily by the temporal mismatch that exists between the local-oscillator mode $\phi_{LO}(t)$ and the squeezed mode $\phi_0(t)$ that is generated by the parametric down converter.

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