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Pulsed Squeezed Light

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Squeezed light in the form of a train of pulses, each approximately 100 ps in width, has been generated by parametric down-conversion in $KTiOPO_4$ crystals. The measured noise reduction in the quiet quadrature of the field is 0.6 dB below the shot-noise limit. The quadrature noise components are measured with a balanced homodyne detector using a pulse train for the local oscillator. The noise reduction extends over a broad spectrum and has important implications for precision measurement at very short time scales.

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New quantum states of light called squeezed states have recently[1] been generated by parametric amplification and deamplification of vacuum fluctuations. Parametric deamplification of one quadrature phase of the vacuum fluctuation field allows a reduction in measured quantum noise for the squeezed light to a level below the shot-noise limit (SNL) usually encountered in photodetection experiments. Nonlinear optical materials presently available, pumped by common cw laser sources, have parametric gains which are marginally adequate for producing large squeezed noise reduction. For example, the most spectacular result obtained to date[2] is a 4.3-dB noise reduction below the SNL which required buildup of the pump light *and* the parametrically generated squeezed light in an optical cavity. In this case the cavity resonance width restricts to a few megahertz the frequency bandwidth of the two-mode squeezed states which are generated. Noncavity experiments in optical fibers[3] allow wide-bandwidth squeezed light but long lengths of fiber are required in order to obtain large parametric gain. In contrast to the cw laser pumps, high peak powers can be obtained from pulsed lasers over a wide range of wavelengths throughout the infrared and visible. This makes it possible to obtain the high parametric gain required for large squeezing in a wide range of nonlinear optical materials without the use of resonant optical cavities. Sufficient pulsed parametric gain can be obtained in short lengths of nonlinear materials so that the linear loss can be less than a few percent. This low loss is always required for the generation of squeezed light, since random absorption of single photons will degrade the squeezed noise reduction by decorrelating the quantum-correlated pairs which comprise the squeezed light. Short lengths of nonlinear material also allow phase matching over large frequency bandwidths. The experiment described here demonstrates that squeezed light can be generated and detected by pulsed parametric amplification and homodyne detection with a strobed local oscillator. Pulsed-squeezed-light sources similar to those described here can be used to enhance the sensitivity of short–time-scale measurements and extend the range for squeezed-light sources throughout the visible and ir regions of the spectrum.

Pulsed generation of squeezed light proceeds in a similar way to the cw parametric amplification methods already demonstrated, except that the time variation in the nonlinear phase shifts of the pulse-pumped parametric amplifier must be taken into account. An analysis[4] of the pulsed generation shows that the two-mode squeezed light produced can extend over the entire range of frequencies allowed by phase matching of the pump at frequency $2\omega_0$ and the parametrically generated signal and idler waves at $\omega_0+\omega$. Nonlinear materials typically used for parametric down-conversion have phase-matching bandwidths greater than 100 GHz (depending on the crystal length). This frequency width allows squeezed-light pulse widths τ of the order of 10 ps or less to be generated. Phase-sensitive detection of these short light pulses at the quantum noise level is easily achieved by the use of periodic pulse trains characteristic of mode-locked lasers. A small portion of the parametric pump pulse train can be used as the local oscillator (LO) for a homodyne detector to measure a chosen quadrature component of the squeezed pulse. In this case the spectrum of photocurrent noise in the homodyne detector output is predicted[4] to be at the SNL for the average photocurrent for the pulse train. This small noise level is more easily measured if a large fraction of photocurrent pulse train is canceled by use of a balanced detector. The remaining imbalanced pulsed photocurrents appear only at multiples of the reciprocal of the pulse train period T. An example of the expected noise spectrum for homodyne detected pulsed squeezed light is shown in Fig. 1. For the optimally squeezed quadrature, the noise (normalized to the vacuum fluctuation level or SNL) is reduced below unity over a range of frequencies out to the limit imposed by phase matching, f_{pm}. In practice the detector frequency response (typically $\lesssim 1$ GHz) limits the range of observed squeezed frequencies. This squeezed noise spectrum is interrupted only by spikes caused by imbalance in the photocurrents at intervals of $1/T$ over a range of $1/\tau$. If the local-oscillator pulse

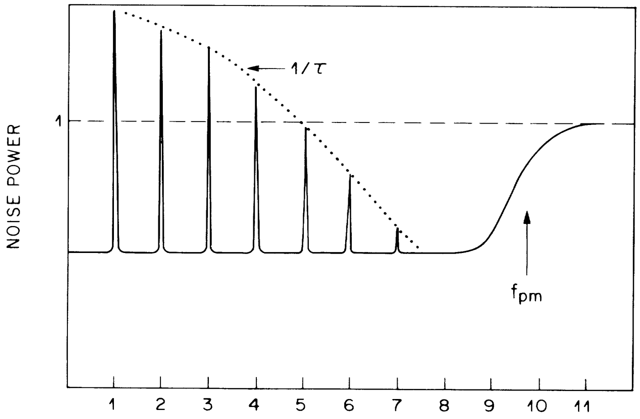

FIG. 1. Noise spectrum expected for pulsed squeezed light as a function of frequency in units of the reciprocal pulse train period T. The noise power is normalized with respect to the shot-noise level indicated by the dashed line. Noise reduction below the SNL, interrupted only by sharp spikes at intervals of $1/T$, extends out to the frequency limit f_{pm} imposed by phase matching of the parametric pump, signal, and idler waves.

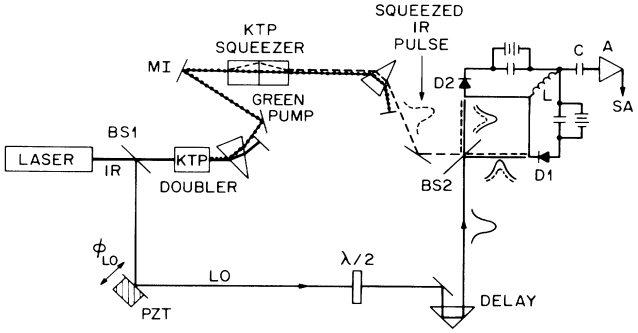

FIG. 2. Schematic diagram of the experimental apparatus used to generate and detect pulsed squeezed light. A mode-locked neodymium-doped yttrium aluminum garnet laser is doubled by a KTP crystal to form a green pump pulse train for the KTP squeezer used to generate squeezed light pulses. A portion of the initial ir pulsed train is phase shifted and delayed to overlap the squeezed pulses and serve as the local oscillator for the balanced homodyne detectors D1 and D2. The λ/2 plate in the LO beam is rotated so that the polarization of the squeezed and LO pulses are aligned. The LC circuit in the input of the detector balancing network is tuned to a frequency of 60 MHz with a Q of 2 to provide improved shot-noise to amplifier-noise ratio over a range from 50 to 100 MHz and attenuate the spikes in photocurrent at 200-MHz intervals. The signal is amplified by a low-input-noise, high-output-saturation amplifier A (Trontech model W40F) and recorded on spectrum analyzer SA.

width τ_{LO} is much less than τ, the maximum squeezing at the peak of the pulse is measured. Otherwise, the measured squeezing is degraded (only 5% in the present experiments) by a convolution[4] of the local oscillator and squeezed pulses.

The experimental apparatus used to demonstrate pulsed squeezing is shown in Fig. 2. The parametric amplifier pump is the frequency-doubled output (532-nm wavelength) of a mode-locked neodymium-doped yttrium-aluminum-garnet laser. The peak green pump power is 50 W and the pulse duration is approximately 100 ps. A portion of the initial 1.064-μm pulse train from the mode-locked laser is split off and delayed to form the local-oscillator pulse train with pulses 140 ps in width spaced at intervals $T=5$ ns. Parametric down-conversion from the green to the infrared is obtained in a pair of $KTiOPO_4$ (KTP) crystals[5] oriented for type-II phase matching.[6] In this case the green polarization is horizontal relative to the vertical z axis of the crystal. For the quantum correlated photon pairs at $\omega_0+\omega$ which form the squeezed pulse, one component of the pair is polarized along the green light and the other is polarized at 90° along the KTP z axis. Linearly polarized squeezed light is formed from a superposition of these photon pairs polarized at an angle of 45° with respect to the z axis at the crystal output. Because of the refractive-index variation with incident angle, the squeezed-light component with polarization along the green pump light (the extraordinary signal beam) propagates at an angle with respect to the idler component polarized along the z axis. This "walkoff" between signal and idler beams is compensated by the use of two KTP crystals of equal length (5 mm) oriented so that the net walkoff is zero at the output of the pair of crystals. The squeezed pulse is combined with the local oscillator at a beam splitter (BS2 in Fig. 2) where their spatial and time forms as well as their phase fronts are matched. Balancing of the InGaAs photodiodes D1 and D2 is accomplished before amplification in order to avoid amplifier saturation. Even after being balanced by 20 dB, the spikes at $1/T$ intervals shown in Fig. 1 are nearly 80 dB above the SNL which is attained at frequencies between the spikes. The shot noise is measured to be at the level expected for the average LO power to within a few percent as predicted by our analysis.[4] Possible errors in the measurement of pulsed LO shot-noise level are avoided and checked by our measuring it to be equal to the cw shot-noise level obtained for the same average photocurrent. The average LO photocurrent is maintained at less than 0.5 mA in order to avoid saturation of the photodiodes caused by the LO pulses. This average photocurrent level results in shot noise which is 9.3 dB above the amplifier noise so that the amplifier output, displayed on a spectrum analyzer, is predominantly associated with quantum noise fluctuations of the squeezed light pulses. It is a pleasant surprise to measure quantum-limited noise for the mode-locked laser pulse train at all frequencies except those within less than a megahertz of the sharp spikes at intervals of 200 MHz.

An alignment of the optical system and a calibration of the parametric gain is accomplished by the introduction of a weak probe beam through mirror MI along the direction of the squeezed light. Typical classical parametric gains of ± 1.35 dB are obtained in agreement with the nonlinear susceptibility of KTP and the incident green pump intensity of 2 MW/cm^2 with use of a beam waist of 30 μm. This gain corresponds to a nonlinear phase shift of 0.15. These modest gains are limited at present by the available green pump power.

Squeezed noise reduction below the SNL is evident in Fig. 3, where the noise power measured on a spectrum analyzer is shown as a function of the local-oscillator phase ϕ_{LO} and time. The measured noise reduction is 0.6 dB below the combined amplifier and SNL and the noise increase is 0.8 dB with a period of π in ϕ_{LO} as expected for the phase dependence of parametric down-conversion. The average photocurrent remains unchanged (± 0.1 dB) for the two traces in Fig. 3, eliminating any possible interpretation of noise reduction as due to optical interference. The squeezed noise levels are consistent with the analysis[4] using the measured parametric gain of ± 1.35 dB, net losses of $\eta_{\mathrm{eff}}=0.58$, amplifier noise 9.3 dB below the SNL, convolution of the temporal profiles of the squeezed and local-oscillator pulses, and $\pm 20°$ of phase jitter caused by vibrations on the optical table. The losses include the detector quantum efficiency $\eta_d=0.9$, phase-matching efficiency $\eta_{\mathrm{het}}=0.85$, and losses in the propagation optics $\eta_{\mathrm{op}}=0.9$. Squeezing is observed throughout the frequency range between 30 and 170 MHz. This bandwidth is limited in these experiments by the resonant balancing circuit in the detector shown in Fig. 2 as well as by the detector and amplifier bandwidths. Detection systems presently available combined with notch filters for the imbalanced photocurrent spikes at intervals of 200 MHz should allow observation of the noise reduction out to 1 GHz.

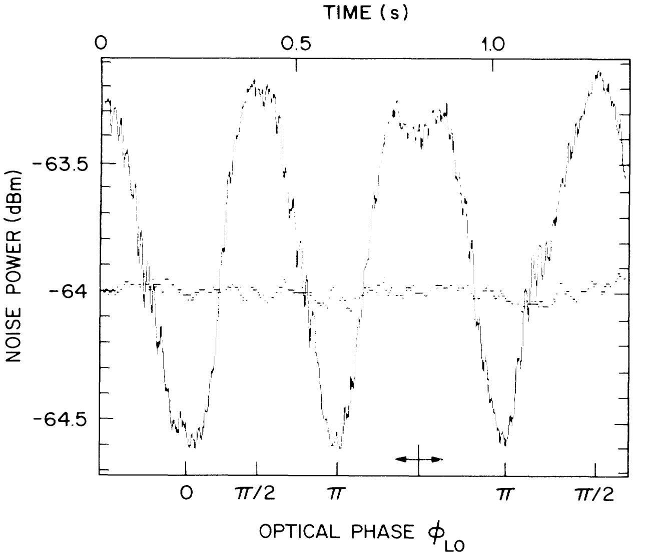

FIG. 3. Noise power for shot noise (dotted line) and pulsed squeezed light (solid line) as a function of homodyne detector local-oscillator phase ϕ_{LO} and time. Noise at $\phi_{\mathrm{LO}}=\pi/2$, $3\pi/2$, etc., drops as much as 0.6 dB below the combined shot-noise and amplifier level (0.7 dB below SNL when amplifier noise is accounted for). The center frequency is 53 MHz, the radio-frequency bandwidth is 1 MHz, and the video averaging bandwidth is 10 Hz. Phase jitter of the LO relative to the squeezed pulse of $\pm 20°$ at a frequency of 56 Hz (optical table resonance excited by laser cooling-water turbulence) is evident in the solid data and degrades the observed noise reduction. The double arrow indicates a reversal in the direction of the ϕ_{LO} sweep.

The pulsed techniques described here to generate squeezed light should extend the range of wavelengths and nonlinear interactions which can be used to generate states of light. For example, the pulsed ac Stark effect in semiconductors[7] can be used to generate large nonlinear phase shifts with fast response times. Intense, tunable pulsed lasers, e.g., free-electron or dye lasers and their harmonics, can be used to tune the parametric pump to spectral regions where resonant nonlinearities[8,9] should result in very large parametric gains.

In combination with the recently demonstrated increases in interferometric measurement sensitivity obtained with squeezed light,[10,11] pulsed squeezed light can be used to enhance measurements of small phase shifts on time scales of the order of picoseconds. The sensitivity of recently developed electro-optic techniques[12,13] for measurement of small charge and voltage fluctuations is limited by shot noise. Pulsed squeezed light can be directly used in these measurements to increase the measurement sensitivity level or decrease the time interval required to make a measurement. There are also pulsed phenomena where interesting quantum noise effects are predicted, e.g., quantum noise on soliton light pulses in optic fibers,[14] where the pulsed detection techniques described here could be employed. Finally, optical computation and communication involve pulsed sequences where the noise can be dominated by quantum effects. One can envision optical quantum computers where pulsed squeezed light will play an important role in the information processing.

In conclusion, an experiment demonstrating generation and detection of pulse trains of squeezed light has achieved noise reduction 0.6 dB below the shot-noise limit in agreement with an earlier analysis.[4] The techniques used in this experimental demonstration can be used to extend the wavelength range and nonlinear processes used for squeezed-light generation. These sources combined with interferometric measurements can increase the sensitivity for picosecond time-scale measurements of optical phase shifts produced, for example, by variations of the dielectric constant induced by nonlinear optical phenomena or small electric field fluctuations measured by electro-optic techniques.[12]

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