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Generation of picosecond squeezed pulses using an all-solid-state cw mode-locked source

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We have produced squeezed states of light using a degenerate optical parametric amplifier pumped by an all-solid-state cw mode-locked laser source. The process resulted in squeezed light pulses of less than 3 ps in duration. Up to 0.7 dB of amplitude-squeezed light at 1047 nm and 0.5 dB of noise reduction in vacuum were observed directly. The inferred squeezing level in both cases, after all propagation losses in the detection system and the effects of spatial and temporal mode overlap had been taken into account, was 1.8 dB. [S1050-2947(98)03204-1]

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The optical parametric amplifier (OPA) has proved to be a very successful generator of squeezed states of light [1]. In particular, the use of pulsed lasers (resulting in high peak powers) means that relatively high parametric gains can be achieved even in a single-pass or traveling-wave amplifier. This configuration results in broadband squeezed states where the bandwidth of squeezing can be as large as the phase-matching bandwidth of the nonlinear crystal used. Pulsed squeezed light was observed by Slusher *et al.* [2] in 1987. They generated squeezed vacuum in a type-II phase-matched parametric amplifier pumped by a cw mode-locked (ML) laser that produced pulses ~140 ps in duration. Since then similar experiments have been performed by other groups using different phase-matching configurations and materials but with comparable pulse durations. Townsend and Louden [3] detected broadband quantum noise reduction using an optical source that produced 50-ps-duration pulses and Hirano and Matsuoka [4,5] reported squeezing generated by 120- and 100-ps laser pulses. This last group also performed fiber pulse compression of the fundamental light [5] and observed squeezed vacuum generated by 10-ps laser pulses.

In this paper we describe the generation of bright squeezed light and squeezed vacuum at 1047 nm. In contrast to the pulsed experiments described above, the light source we use is a diode-pumped cw ML laser that produces pulses ~3 ps in duration. This system has several advantages over a flashlamp-pumped alternative, including more compact design, greater efficiency, shorter pulse durations, and greater stability. These features make it an ideal source to investigate the effects of using squeezed light in nonlinear optical processes as it is inherently quiet, and short pulses allow one to achieve high peak powers for relatively modest average powers. These high peak powers imply that the intensity of the generated squeezed vacuum should be high enough to investigate its effect on the efficiency of nonlinear interactions.

A schematic of the experimental setup used is shown in Fig. 1. The starting point for the generation of squeezed states is a diode-pumped additive-pulse mode-locked neodymium doped lithium yttrium fluoride (Nd:YLF) laser [6] that operates at 1047 nm. The laser produces near transform-limited pulses that are 3 ps in duration at a repetition rate of 140 MHz and the average output power when mode locked is ~1 W. A small amount of the laser light was split off to form a probe and local oscillator beam. The probe beam was used to align the parametric amplifier and investigate its gain while the local oscillator (LO) propagated to a balanced homodyne detector [7] for pulsed squeezing measurements. Most of the laser output was mode matched into an external ring enhancement cavity where frequency doubling of the fundamental light, by noncritical type-I phase matching, took place in a 12-mm-long lithium triborate (LBO) crystal placed

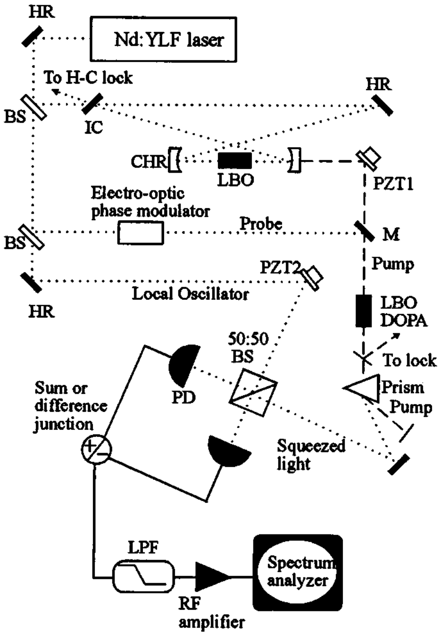

FIG. 1. Schematic of experimental setup for the generation of squeezed pulses. Dotted line, fundamental light; dashed line, second-harmonic light; BS, beamsplitter; IC, input coupler; HR, high reflector; CHR, curved high reflector at 1047 nm and high transmitter at 523.5 nm; PZT1, piezoelectrically controlled mirror to change phase between pump and probe; PZT2, mirror to change phase between LO and squeezed vacuum; M, mirror to combine pump and probe beams; PD, Ga$_x$In$_{1-x}$As photodiode; LPF, low-pass filter (dc to 20 MHz).

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at the intracavity focus and heated to the phase-matching temperature (~165 °C) in an oven. The second-harmonic light exited from the enhancement cavity through a dichroic mirror that was highly reflecting for the fundamental light but had 92% transmission for the doubled light. The laser light was maintained in resonance in the cavity by a Hänsch-Couillaud [8] locking technique so that the cavity, when locked, produced 0.46 W of light at 523.5 nm. This pump beam and the probe beam at 1047 nm were combined in a second 12-mm-long LBO crystal, where identical phase-matching conditions to those just described were employed to perform degenerate optical parametric amplification (DOPA).

Assuming Gaussian beam profiles, the beam parameters of the pump and probe beams were carefully modeled so that we could arrange the beam shaping optics for maximum parametric gain. Both beams were focused in the center of the LBO crystal where the beam radii at the waists were measured to be 16 μm for the pump and 22 μm for the probe. At the output of the DOPA a prism was used to separate the strong pump from the squeezed light that was sent to the homodyne detector, which consisted of a 50:50 beam-splitter (BS) and two high-efficiency $\mathrm{Ga}_x\mathrm{In}_{1-x}\mathrm{As}$ p-i-n photodiodes with an active area of 300 μm diameter (Epitaxx ETX 300T). At 1047 nm the quantum efficiency of these photodiodes was measured to be equal to 0.86 and their linearity was checked by recording the photocurrent that resulted as the incident laser power was gradually increased. We did not begin to observe any saturation effects until the laser power went above ~3 mW for a beam that was focused to a spot size that was much smaller than the active area of the detectors. Care was taken to maintain the LO power below this level during squeezing measurements. Mechanical relays were used to switch the polarity of the signal from one of the photodiodes so that the combined output from the two detectors was either their sum or difference photocurrent. This output was fed through a low-pass filter (dc to 20 MHz) to reduce the signal at the laser repetition rate, through a 52-dB amplifier (Trontech W 110B-13), and finally into a spectrum analyzer that measured the noise power. The output from the spectrum analyser (Tektronix 2710) was displayed on a digital oscilloscope that was read by a personal computer to provide data collection.

As the relative phase between the pump and probe beams was scanned, by a pump mirror mounted on a piezoelectric transducer (PZT), the probe exhibited a phase-dependent variation in intensity above and below the dc level measured when the pump was off. The classical response of two different nonlinear crystals used to perform the parametric amplification was initially investigated before deciding to use LBO. Magnesium-oxide-doped–lithium niobate ($\mathrm{MgO{:}LiNbO_3}$) and magnesium-oxide-doped–potassium niobate ($\mathrm{MgO{:}KNbO_3}$) resulted in amplification factors of 2.5 and 3, respectively, and deamplification factors of ~0.4. It was necessary to focus the pump beam to a waist with a radius of about 6 μm so that the parametric gain could be optimized in these very short lengths of crystal ($l=3$ mm for $\mathrm{MgO{:}LiNbO_3}$ and $l=2$ mm for $\mathrm{MgO{:}KNbO_3}$). These conditions resulted in extremely high green peak powers that caused thermal damage and quickly reduced the amount of gain observed; it is highly likely that the gain we measured was not at all optimized, especially in $\mathrm{MgO{:}KNbO_3}$, which is a very fragile material [9], before the crystal suffered so much damage as to be unusable. If this thermal damage problem could be overcome, perhaps by chopping the pump beam so as to reduce its average power significantly while maintaining high peak power, we predict that squeezing of greater than 4 dB should be attainable. In the experiment we performed, the 12-mm-long LBO crystal amplified the probe by a factor of 1.6 and deamplified it by a factor of 0.66 without suffering any damage due to the high pump powers used in the experiment; these gain measurements imply squeezing of up to 2 dB.

Bright squeezing measurements were made using the balanced homodyne detector where the second input to the 50:50 BS was the vacuum state. Before it entered the DOPA the probe was electro-optically phase modulated at 80 MHz and a small portion of the DOPA output was detected with a fast photodiode. The generated ac photocurrent was mixed with the modulation signal to create an error signal for the feedback to a servo loop that controlled the relative phase between the pump and probe beams. In this way the phase of the pump field could be stabilized to produce maximum parametric amplification, resulting in phase-squeezed light, or deamplification, which resulted in amplitude-squeezed light. An additional small amount of the DOPA output was split off to monitor the stability of the lock as the quadrature-phase noise of the pulsed squeezed light was being recorded. The total average power of the bright squeezed beam was 0.3 mW and the beam waists at the $\mathrm{Ga}_x\mathrm{In}_{1-x}\mathrm{As}$ detectors were of the order of 80 μm; this low power and loose focusing ensured no saturation of the photodiodes. As mentioned previously, the separate outputs from the photodiodes could be combined to give either their sum (I_+) or difference (I_-) photocurrents and so the spectrum analyzer could measure the noise power $P(I_+)$ or $P(I_-)$. A measurement of $P(I_+)$ is proportional to the noise properties of the beam while $P(I_-)$ measures the shot-noise level (SNL). When the pump beam was blocked, so that no parametric amplification could take place, a measurement of $P(I_+)$ and $P(I_-)$ yielded the same value to within 0.1 dB, behavior expected for classical light with Poissonian statistics at frequencies away from dc. Amplitude-squeezed light should have $P(I_+)$ less than $P(I_-)$ with the opposite expected for phase-squeezed or antisqueezed light. For maximum pump power incident on the LBO crystal we observed 0.7 dB of amplitude squeezing when the system was locked to deamplification and 0.95 dB of antisqueezing with the system locked to amplification. Noise power measurements as a function of the DOPA gain at 4 MHz are shown in Fig. 2, where the electronic background level has been subtracted from all of the results given.

In order to take into account the losses in propagation and detection processes, the experimental data points were fitted by $G_{\mathrm{obs}}=\eta G+(1-\eta)$ [10] to correct for the overall quantum efficiency of the system when measuring the noise reduction associated with a parametric gain G. There are several factors that go into the total quantum efficiency η, which is given by the product of the individual components $\eta=\eta_d\eta_p\eta_t$. Here $\eta_d=0.86$ is the $\mathrm{Ga}_x\mathrm{In}_{1-x}\mathrm{As}$ detector quantum efficiency, while $\eta_p=0.7$ is due to propagation losses in various beam-shaping optics and use of some signal for lock-

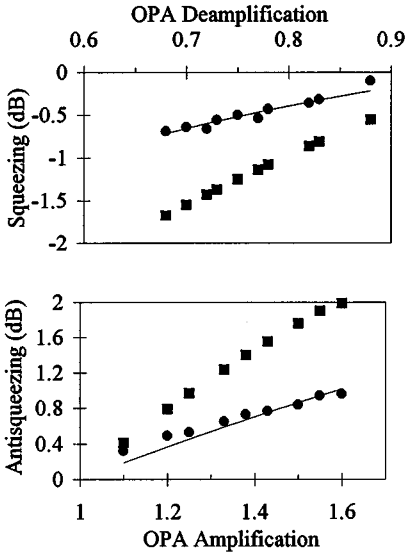

FIG. 2. Noise power measurements as a function of LBO DOPA gain at a detection frequency of 4 MHz. Circles represent directly observed squeezing (antisqueezing), squares represent inferred squeezing (antisqueezing) for unity detection efficiency, and the solid lines are theoretical fits (details described in the text) to the data where the actual detection efficiency is a free parameter.

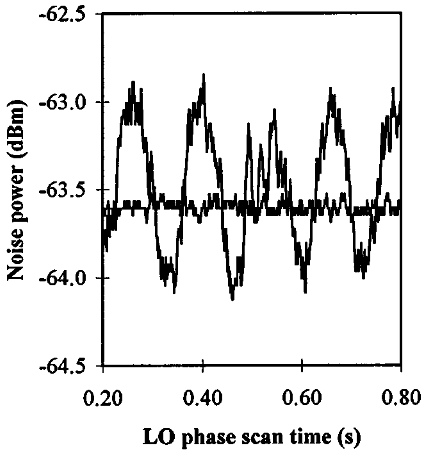

FIG. 3. Detection of squeezed vacuum at a fixed frequency of 2 MHz as the LO phase is scanned slowly. The flat line at −63.6 dBm is the SNL, while the squeezed vacuum exhibits a phase-dependent noise power. The discontinuity in the squeezed vacuum at ~0.5 s indicates a reversal in the direction of the LO phase sweep.

ing the system and monitoring the stability of this lock. The final efficiency factor η_t is due to the temporal mismatch between the pump and probe pulses. As the pump pulse is obtained from the laser pulse by second-harmonic generation it is expected to be shorter by about 30%; this should result in amplified (deamplified) pulses that are shorter (longer) in duration than the original laser pulses. We checked that this is indeed the case by performing second-harmonic autocorrelations of the squeezed and antisqueezed pulses with the system locked to deamplification and amplification. The imperfect temporal overlap between the pump and probe beams in the DOPA causes a decrease, by a factor of $\eta_t = 0.6$ [11], in the amount of squeezing produced. The experimental data points are fitted by $\eta = 0.38$ for squeezed light and $\eta = 0.44$ for antisqueezed light. These numbers, especially for amplitude squeezing, agree quite well with the total detection efficiency of the system, which we estimated to be $\eta = 0.37$ by measuring the individual components as described above. From our direct observation of 0.7 dB of amplitude squeezing at 1047 nm, we infer 1.8 dB of bright squeezing generated in the experiment.

When the input to the DOPA is the vacuum state, rather than a probe beam at 1047 nm, the process of parametric amplification produces squeezed vacuum [12]. The noise properties of the squeezed vacuum were investigated by interfering it with the LO at the laser frequency and measuring the fluctuations associated with the difference photocurrent I_-. In the experiment the average LO power was ~2.5 mW, resulting in a photocurrent in each $\mathrm{Ga}_x\mathrm{In}_{1-x}\mathrm{As}$ detector of 1 mA, which was well below the level where saturation of the photodiodes may start to occur. Figure 3 shows a typical spectrum analyzer scan recorded by sitting at a single measurement frequency as the LO phase was scanned slowly. The resolution bandwidth of the spectrum analyzer was 300 kHz and the video filter was 30 Hz. The SNL was obtained by blocking the output from the DOPA to the homodyne detector and, for the LO power used, this level lay ~9 dB above the amplifier noise. The detector photocurrents were typically balanced to 20–30 dB at detection frequencies of several megahertz, but we found the best balance at around 2 MHz. At this detection frequency we observed directly quantum fluctuations in the vacuum level that were reduced by 0.5 dB below the SNL.

As was the case for the bright squeezed pulses, the observed vacuum noise reduction is degraded by the imperfect detection efficiency of the system. In addition to the detector quantum efficiency and the propagation losses (now $\eta_p = 0.8$), we must also consider the spatiotemporal mismatch that exists between the LO and squeezed vacuum pulses. Efficient detection of the squeezed vacuum relies very heavily on a high degree of spatial wave-front matching, described by an efficiency η_s between it and the LO field. We estimated the value of this parameter to be ~0.8 by measuring the fringe visibility in an interference experiment between the LO and probe beams. It was predicted by Yurke *et al.* [13] that to maximize the amount of detected squeezing, the LO pulse duration should be of the same order as the pump pulse or shorter; this would allow one to sample the amount of squeezing along the pulse envelope. It was later realized [14] that the optimum LO pulse duration for finite squeezing bandwidths was one with a duration less than that of the pump but that had a spectrum narrower than that of the squeezed field. Deviations of the LO pulse width from this preferred range results in observed squeezing levels that can be much less than those inferred from parametric gain measurements. It is estimated that the squeezed vacuum pulses may be as much as 40% shorter than the LO pulses derived from the same laser [11] because the process of parametric amplification is an interaction between the laser pulse and its second harmonic. For detection of squeezed vacuum we expect this temporal mismatch to contribute an efficiency factor of $\eta_t \sim 0.5$ and so the total efficiency of the system when all of the contributions mentioned above are considered was calculated to be $\eta=0.28$. Given a deamplification factor of 0.66, we therefore expect to measure about 0.54 dB of squeezing, a number that agrees almost exactly with what we actually observed.

In conclusion, we have generated squeezed light pulses of less than 3 ps in duration in a LBO traveling-wave parametric amplifier pumped by an all-solid-state cw mode-locked source. Amplitude squeezing of up to 0.7 dB below the SNL was measured on a weak probe beam at the fundamental wavelength. We also observed directly squeezed vacuum with quantum fluctuations that were reduced by up to 0.5 dB below the SNL. The amounts of squeezing measured in both cases agreed very well with the expected values predicted by the detection efficiency of the system and, in our experiment, more than 1.8 dB of squeezing was inferred. We are presently modifying the system to investigate the effects of using a superposition of squeezed vacuum and coherent light in nonlinear optical processes.

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