Amplitude squeezing by means of quasi-phase-matched second-harmonic generation in a lithium niobate waveguide

D. K. Serkland and Prem Kumar

Department of Electrical and Computer Engineering, Northwestern University, Evanston, Illinois 60208-3118

M. A. Arbore and M. M. Fejer

E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4085

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We demonstrate that traveling-wave second-harmonic generation produces amplitude-squeezed light at both the fundamental and the harmonic frequencies. Quasi-phase-matched second-harmonic conversion efficiencies approaching 60% were obtained in a 26-mm-long single-mode $LiNbO_3$ waveguide with pulses from a mode-locked laser at 1.53 μm. The amplitude noise of the transmitted fundamental field was measured to be 0.8 dB below the shot-noise level, and the generated 0.765-μm harmonic light was measured to be amplitude squeezed by 0.35 dB. The conversion-efficiency dependence of the observed squeezing at both wavelengths agrees with theoretical predictions. Waveguide losses appear to degrade the squeezing, but the maximum observed squeezing is currently limited only by the available input power.

Second-harmonic generation (SHG) and degenerate parametric amplification in $\chi^{(2)}$ media have proved to be successful methods for generating squeezed light. Parametric deamplification of quantum noise yielded high degrees of squeezing in both resonant-cavity and traveling-wave (TW) configurations.[1] Squeezing by means of SHG, however, was limited to resonant-cavity configurations only.[2] Although evidence of squeezing at the fundamental frequency was recently observed in type II TW SHG,[3] no squeezing has yet been obtained by the conceptually simpler method of type I TW SHG, which was proposed 15 years ago.[4] The basic obstacle stems from the fact that, in bulk nonlinear crystals, hundreds of watts of peak power are typically required for significant harmonic conversion, and hence squeezing. Such squeezing is difficult to measure because the high optical power would saturate the photodiodes employed to detect the quantum noise. Waveguides in nonlinear-optical materials offer a means of substantially reducing the power requirements because of the tight mode confinement that can be maintained over long interaction lengths. Recently, waveguides in $\chi^{(2)}$ materials were employed for the generation of quadrature squeezing by means of parametric deamplification.[5,6] In this Letter we report what we believe to be the first demonstration of squeezing at both the fundamental and the second-harmonic frequencies obtained by means of TW SHG. Type I quasi-phase-matched TW SHG was implemented in a single-mode $LiNbO_3$ waveguide, and the resulting squeezing was measured by direct detection.

Recently a theory of squeezing in TW SHG was developed based on a linearization technique in which the quantum fluctuations of the electric field were assumed to be small compared with the mean fields.[7] In this theory the evolution of the fluctuations in the nonlinear medium is governed by a set of linear differential equations. In the case of perfect phase matching, the amplitude and the phase quadratures of the interacting fields decouple, and the set of equations can be solved analytically. At both frequencies the amplitude fluctuations are squeezed while the phase fluctuations are increased. The squeezing is quantified by the ratio of the mean-squared amplitude fluctuation at the output of the nonlinear medium to that at the input. For perfect phase matching, the amplitude squeezings at the two frequencies are given by[7]

$$S_1 = [(1 - \zeta \tanh \zeta)^2 + 2 \tanh^2 \zeta] \operatorname{sech}^2 \zeta \,, \qquad (1)$$

$$S_2 = 2^{-1}(\tanh \zeta + \zeta \operatorname{sech}^2 \zeta)^2 + \operatorname{sech}^4 \zeta \,, \qquad (2)$$

where the dimensionless parameter $\zeta = (\eta P_1)^{1/2}$ depends on small-signal conversion efficiency η (often expressed in percent per watt) and input power P_1. The conversion efficiency γ has the familiar form $\gamma = \tanh^2 \zeta$. One can readily extend Eqs. (1) and (2), which were obtained for a cw interaction, to describe pulsed experiments, provided that the pulses are long enough that dispersion and group-velocity mismatch can be neglected. With a mode-locked pulse source of repetition period T, one usually measures the averaged quantities

$$\overline{f} = A^{-1} \int_{-T/2}^{T/2} f[\zeta(t)] g(t) \mathrm{d}t \,, \qquad (3)$$

where $A = \int_{-T/2}^{T/2} g(t)\mathrm{d}t$, input power $P_1(t) = P_0 g(t)$, and function f indicates any of S_1, S_2, or γ.

Figure 1 shows a schematic of our experimental setup for generating amplitude-squeezed (sub-Poissonian) light by means of TW SHG. The 1.53-μm fundamental light was generated by a cw mode-locked $KCl{:}Tl^+$ color-center laser (synchronously pumped at 100 MHz), which was wavelength tuned with an intracavity birefringent filter. Autocorrelation measurements indicated 21-ps (FWHM) $g(t) = \operatorname{sech}^2(t/\tau_1)$ output pulses. We reduced the duty cycle by chopping the laser beam with an acousto-optic modulator (AOM)

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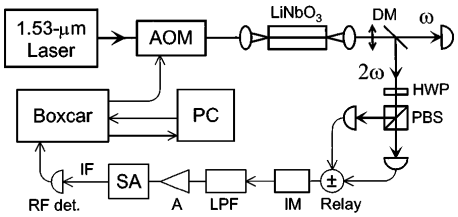

Fig. 1. Schematic of the experiment, configured for measurement of noise at the harmonic frequency by direct detection. The amplitude noise of the transmitted fundamental was measured similarly with a separate resonant detector (not shown).

to minimize photorefractive effects in the $LiNbO_3$ waveguide. The AOM deflected a 15-μs pulse train into the waveguide every 0.95 ms.

The waveguide, which was single moded at 1.53 μm, was fabricated by annealed proton exchange through a 4.5-μm-wide channel opening in a thin-film SiO_2 mask on an electric-field-poled $LiNbO_3$ substrate.[8] The 14-μm poling period resulted in quasi-phase-matched SHG for an input wavelength of 1530.5 nm, with the fields at both wavelengths polarized parallel to the $LiNbO_3$ z axis. The 26-mm-long waveguide yielded 50% average conversion efficiency ($\overline{\gamma} = 0.5$) with a pulse-train-averaged input power of 2.6 mW (pulse energy of 26 pJ), which implies that $\eta = 120\%/\text{W}$. The conversion efficiency was determined as the ratio of the generated second-harmonic power to the fundamental power that would have been transmitted in the absence of SHG (i.e., the incident fundamental power times the linear power-transmission coefficient). Such a definition is independent of the coupling efficiency and waveguide losses and provides a reasonable approximation for comparison with the theoretical predictions that assume a lossless interaction. The waveguide was independently characterized with a tunable cw 1.53-μm laser and found to have a phase-matching bandwidth of 0.6 nm (FWHM) and a peak normalized conversion in agreement with the pulsed result.

After the generated second-harmonic light exited the waveguide, a dichroic mirror (DM) separated it from the fundamental (p polarized), as shown in Fig. 1. A single photodiode measured the mean field at one wavelength, and a balanced pair of photodiodes monitored noise at the other wavelength. The half-wave plate (HWP) was rotated so that the polarization beam splitter (PBS) directed an equal mean field to each photodiode. Setting the relay to add the currents from the two photodiodes (equivalent to direct detection with a single photodiode) resulted in a measurement of the squeezed amplitude noise. We calibrated the shot-noise level by setting the relay to subtract the two photocurrents. Fundamentally, this shot-noise calibration results from mixing of the large mean field with the fluctuation in one quadrature of the orthogonally polarized vacuum state. The impedance-matching (IM) section following the relay consisted of a tapped $\approx$1-μH inductor in parallel with the capacitances of the two photodiodes, thereby forming a tank circuit that is resonant at 43 MHz. The additional sensitivity provided by the resonant detectors[6] was needed for accurate measurement of the squeezing, since the average transmitted powers were frequently less than 1 mW. A 50-MHz low-pass filter (LPF) prevented the coherent spikes at multiples of 100 MHz, the pulse-repetition rate, from saturating the low-noise amplifier (A; Miteq Model AU-1263; 45-dB gain, 1.2-dB noise figure). The spectrum analyzer (SA) detected noise within a 1-MHz resolution bandwidth centered at 43 MHz. However, to achieve better noise-power resolution, we bypassed the internal logarithmic amplifier and detector of the spectrum analyzer, and we externally detected the 10-MHz intermediate-frequency (IF) output with a linear-response power detector having a 0.4-μs rise time.

The entire squeezing measurement was controlled by a personal computer (PC) that triggered the boxcar circuit every 0.95 ms. The boxcar circuit opened the AOM shutter for 15 μs and then integrated the intermediate-frequency detector voltage, which is proportional to the noise power at 43 MHz, during a 10-μs gate centered on the 15-μs noise window. The result of each integration was digitized and stored in the computer. The mean and the variance of 420 consecutive integrations were calculated and saved as a single data point. The inset of Fig. 2 shows the mean data points versus time for a complete squeezing scan. The computer first set the relay to add the photocurrents and recorded 25 amplitude-noise data points. The computer then switched the relay to subtract the photocurrents and recorded 25 shot-noise data points. Finally, the computer held the AOM off (shutter closed) while it recorded 25 more data points to determine the noise added by the electronics.

Figure 2 shows the measured squeezing at the fundamental frequency versus the conversion efficiency. Each data point in the figure resulted from a squeezing scan such as the one shown in the inset (for the data point with the most squeezing). The Fano factor was calculated as the ratio of the amplitude noise (photocurrents added) to the shot noise (photocurrents subtracted), after the mean electronic-noise contribution

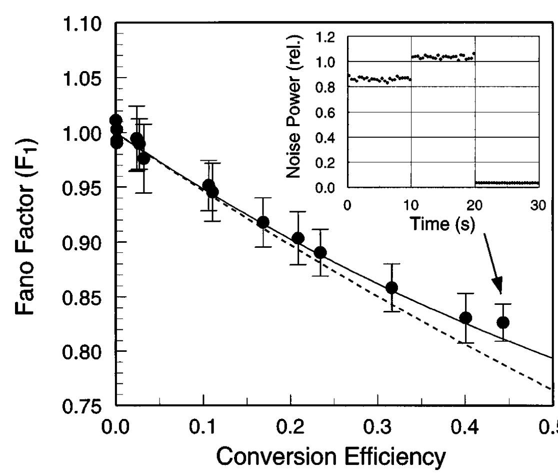

Fig. 2. Fundamental squeezing versus conversion efficiency. Theoretical predictions for cw (dashed curve) and pulsed (solid curve) squeezing are shown for $\eta_1^{\text{eff}} = 0.55$. The inset shows the detected noise at 43 MHz versus time during a complete squeezing scan, where amplitude, shot, and electronic noise are each measured for 10 s.

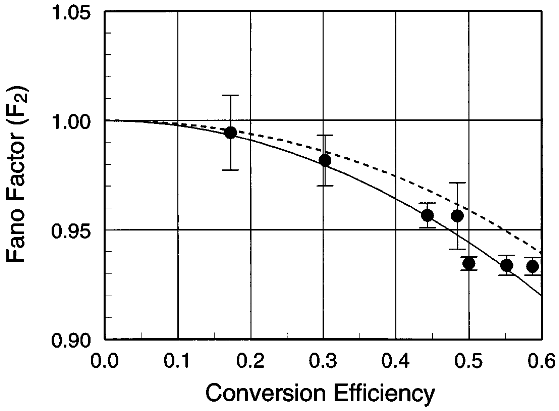

Fig. 3. Second-harmonic squeezing versus conversion efficiency. Theoretical predictions for cw (dashed curve) and pulsed (solid curve) squeezing are shown for $\eta_2^{\mathrm{eff}} = 0.45$.

from each was removed. The error bars in Fig. 2 represent the standard deviation resulting from the variance of the 25 data points during each segment of the squeezing scan. We obtained the data points at the lowest conversion efficiency by tweaking the laser to increase the pulse width and thereby lower the conversion. Also shown in Fig. 2 are the theoretical predictions for the detected squeezing $F_1 = \eta_1^{\mathrm{eff}}(S_1 - 1) + 1$, where an effective detection efficiency η_1^{eff} of 0.55 was chosen to fit the data. The dashed curve corresponds to S_1, as given by Eq. (1), versus γ. The solid curve corresponds to $\overline{S_1}$ versus $\overline{\gamma}$, calculated according to Eq. (3). Note that the solid curve depends on the pulse shape but not on the pulse width. The detection efficiency from the end of the waveguide was determined to be $\eta_1^{\mathrm{det}} = 0.71$, which includes the 14% Fresnel reflection at the output end of the waveguide, the 4% loss in propagating to the photodiodes, and the 86% quantum efficiencies of the InGaAs photodiodes (Epitaxx Model ETX-300). Correcting for this nonideal detection efficiency, we infer that 1.2 dB of squeezing at the fundamental frequency was produced within the waveguide. We presume that the difference between η_1^{det} and η_1^{eff} is a consequence of the waveguide losses, which are estimated to be $\approx 7\%/\mathrm{cm}$.[8] We are pursuing a theoretical study to determine the effects of the waveguide losses.

A demonstration of squeezing at the second-harmonic frequency is considerably more challenging, since it requires substantial conversion. Without chopping, photorefractive effects limited the conversion to less than 40%, which sufficed only to demonstrate squeezing at the fundamental frequency.[9] Chopping with the AOM permitted conversion of as much as 60% (limited only by the available input power) and yielded unambiguous squeezing at the harmonic frequency, as shown in Fig. 3. Also shown in the figure are the theoretical predictions for the detected squeezing $F_2 = \eta_2^{\mathrm{eff}}(S_2 - 1) + 1$, where we chose an effective detection efficiency η_2^{eff} of 0.45 to fit the data. The dashed curve corresponds to S_2 versus γ (cw light), and the solid curve corresponds to $\overline{S_2}$ versus $\overline{\gamma}$ (pulsed light). To measure more accurately the harmonic-light squeezing, we performed four (or more) squeezing scans at each conversion-efficiency value and averaged the results to obtain the data shown in Fig. 3. The error bars indicate a 90% confidence interval based on the spread in the data points that were averaged. The disparity between the data points near 50% conversion efficiency probably arises from a systematic drift in the phase-matching wavelength with temperature. The detection efficiency at 0.765 μm, including the 14% Fresnel reflection at the output end of the waveguide, the 4% loss in propagating to the photodiodes, and the 85% quantum efficiencies (boosted with retroreflecting mirrors) of the Si photodiodes (EG&G Model CA30971E), was determined to be $\eta_2^{\mathrm{det}} = 0.7$. As in the case of squeezing at the fundamental frequency, the difference between η_2^{det} and η_2^{eff} is likely due to the losses in the waveguide. We note that light scattering is the dominant loss mechanism, which is expected to be more significant at shorter wavelengths.

In conclusion, we have observed squeezing by means of type I TW SHG at both the fundamental and the second-harmonic frequencies. The maximum measured amplitude-noise reduction was 0.8 dB at 1.53 μm and 0.35 dB at 0.765 μm. The dependence of the measured squeezing on conversion efficiency agrees reasonably well with the theoretical predictions, if we assume that the waveguide losses reduce the effective detection efficiency. Determining the ultimate limits of squeezing by means of TW SHG requires further investigation of the effects of the waveguide losses and imperfect phase matching.

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