

# Quadrature squeezing with ultrashort pulses in nonlinear-optical waveguides

Matthew E. Anderson, M. Beck,\* and M. G. Raymer

*Department of Physics and Chemical Physics Institute, University of Oregon, Eugene, Oregon 97403*

J. D. Bierlein

*Dupont Central Research and Development, Experimental Station, Wilmington, Delaware 19880-0356*

Received October 31, 1994

Using ultrashort laser pulses, we have observed quadrature squeezing and parametric gain in quasi-phase-matched  $\text{KTiOPO}_4$  waveguides. Using a local oscillator pulse that is 2.5 times shorter than the squeezed pulse, we observed noise reduction of  $12 \pm 1\%$  below the shot-noise level. Parametric amplification and deamplification of a coherent seed pulse have also been observed, with no indication of gain-induced diffraction.

From the first experimental evidence for pulsed quadrature squeezing<sup>1</sup> to the latest reports,<sup>2-5</sup> the effort has been toward increasing the degree of squeezing detected. It was pointed out that the use of ultrashort pulses, with their potential for pulse shaping, should permit optimization of the temporal mode matching between signal and local oscillator (LO) pulses, thereby increasing the detected degree of squeezing.<sup>6</sup> It was also proposed that the use of nonlinear-optical waveguides as the squeezing medium should improve the spatial mode matching between pump and signal fields<sup>7</sup> and also greatly reduce problems such as gain-induced diffraction,<sup>8</sup> both of which severely limit the obtainable squeezing. In this Letter we experimentally address both of these issues. We report on the generation of quadrature-squeezed light in quasi-phase-matched  $\chi^{(2)}$  waveguides pumped by 500-fs pulses and detected with 200-fs LO pulses, with noise variance 12% below the shot-noise level. We also report parametric gain measurements<sup>9</sup> in this system.

In a traveling-wave downconversion experiment one attempts to detect squeezed light by mixing the signal with a LO beam at a beam splitter and then detecting this mixture. There are, however, two factors that limit the amount of squeezing, i.e., temporal and spatial mode mismatch. In all previous experiments involving pulsed squeezed light the LO pulse duration has been equal to or greater than that of the squeezed signal. Temporal mode mismatch reduces the amount of detectable squeezing since the wings of the LO overlap a weakly squeezed signal. The use of pulses in the femtosecond range (in our case 200 fs) provides a means to circumvent this problem. Because we use a long doubling crystal, group-velocity walk-off between the fundamental and the second harmonic leads to a pump that is effectively temporally widened relative to the input pulse. This leads to a squeezed signal that is temporally broader than the LO. On mixing, the entire LO pulse is then able to overlap the peak of the squeezed signal, which

yields optimum mode matching for detection of broadband downconversion.<sup>6</sup>

The second consideration is spatial mode matching. In the case of downconversion in bulk crystals, in which Gaussian beams are typically used, the center portions of the squeezed signal will experience higher gains than the wings, thus distorting the spatial profile.<sup>3</sup> This gain-induced diffraction has been seen to limit the amount of attainable squeezing in bulk parametric crystals.<sup>8</sup> It may be difficult to know how best to shape the LO beam profile and phase to detect large squeezing.<sup>5</sup> In a waveguide, however, the modes are defined by the waveguide itself. Thus, using an LO that is spatially matched to the waveguide mode, we should be able to attain large amounts of squeezing.

The waveguides we used were manufactured by Dupont and are extremely effective devices for second-harmonic generation in the 800–900-nm range.<sup>10</sup> Dupont makes the devices by starting with a z-cut  $\text{KTiOPO}_4$  (KTP) crystal wafer, covering it with a waveguide mask, and immersing it in a Rb/Ba salt bath. The mask consists of a periodic train of rectangular open regions approximately 4  $\mu\text{m}$  wide and 2  $\mu\text{m}$  long. The Rb exchanges with the K, providing a higher index of refraction to permit waveguiding. The Ba also exchanges with the K and effectively flips the direction of the spontaneous polarization, thus providing quasi-phase matching. With this type of quasi-phase-matched structure the optical conversion process is able to employ the large nonlinear  $d_{33}$  coefficient of KTP. The reported conversion efficiencies are as high as 60–70%.<sup>11</sup> These particular waveguides are two-mode devices, supporting both the  $\text{TM}_{00}$  and  $\text{TM}_{01}$  modes in the fundamental, where TM refers to optical electric-field polarization normal to the surface along the length of the waveguide.

Figure 1 shows a schematic of our experimental apparatus. We use a Ti:sapphire-based chirped-pulse regenerative amplifier to generate 200-fs 2- $\mu\text{J}$  830-nm pulses at a repetition rate of 3 kHz. This

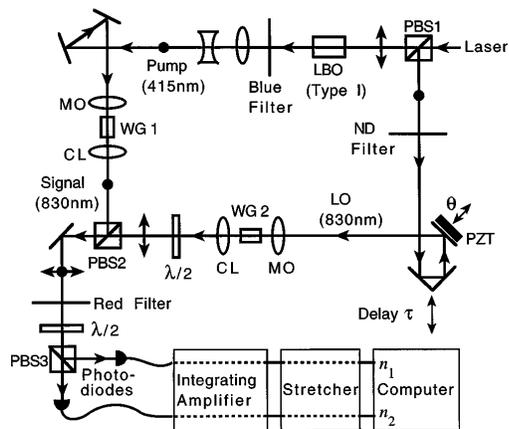


Fig. 1. Experimental apparatus for waveguide squeezing. ND, neutral-density; PZT, piezoelectric translator;  $\lambda/2$ 's, half-wave plates.

beam is then split at the first polarizing beam splitter (PBS1) into the signal arm (upper) and the LO arm (lower). In the signal arm the fundamental (830 nm) is type I doubled (with loose focus) in a 5-mm-long lithium borate crystal (LBO), generating 500-fs (up to 200 nJ) pulses at 415 nm. The residual fundamental is blocked with a blue filter. After collimating and attenuating this pump light, we coupled it into the 1-mm-long KTP waveguide (WG 1) with a  $20\times$  microscope objective (MO). The downconverted light generated in the waveguide at 830 nm (signal) is coupled out with a low-loss laser-diode collimating lens (CL). The parametric process in the waveguide is type I, which occurs in this waveguide when the polarizations of both the pump and the signal are TM. Waveguide losses are negligible<sup>11</sup> (0.5 dB/cm), and other downstream optical losses are small ( $<5\%$ ). Dispersion in the waveguide does not significantly broaden the pump,<sup>11</sup> but temporal walk-off (500 fs/0.36 mm) tends to lengthen the downconverted pulse.

In the LO arm a small portion of the fundamental is attenuated by a neutral-density filter to yield light levels of  $2.3 \times 10^6$  photons/pulse. It then passes through an optical delay  $\tau$  to overlap temporally the signal and LO pulses and reflects from a mirror mounted on a piezoelectric translator to adjust the phase ( $\theta$ ) of the LO relative to the signal. The LO is coupled through an identical waveguide (WG 2) with identical optics in an effort to mode match spatially the LO to the signal.

From PBS2 the LO and the signal propagate collinearly with orthogonal polarizations. They pass through a red filter to remove any residual pump light, a half-wave plate to rotate both polarizations by  $45^\circ$ , and PBS3 to split and balance precisely the energies of the beams at the Si photodiodes used for detection (Hamamatsu S-2216, 85% quantum efficiency). The current pulses from the two photodiodes are integrated and amplified in low-noise charge-sensitive preamplifiers,<sup>12</sup> shaped and stretched,<sup>13</sup> and sampled by the computer through two 16-bit analog-to-digital channels to yield photoelectron numbers  $n_1$  and  $n_2$  from each detector. The electronic-noise standard deviation in each integration channel is  $\Delta n_{\text{elec}} = 294$ . The calibration of the overall responsivity of the de-

tection channels is accurate to better than a few percent.

Since the two channels  $n_1$  and  $n_2$  are separate into the computer we are able to calculate statistics of sum and difference quantities, including the variance  $\langle(n_1 - n_2)^2\rangle$  of the difference number, where the fences indicate an ensemble average over many laser pulses. The shot-noise level (SNL) is simply the total mean photon number:

$$\text{SNL} = \langle n_1 + n_2 \rangle. \quad (1)$$

The quadrature noise variance of the detected field is

$$\langle(n_1 - n_2)^2\rangle - 2(\Delta n_{\text{elec}})^2, \quad (2)$$

where we have corrected for the electronic noise.

The data obtained for the waveguide squeezing with a 0.63-nJ pump are shown in Fig. 2. The dashed curve indicates the SNL calculated from Eq. (1), the filled diamonds show the quadrature noise calculated from the data by use of expression (2), and the solid curve is data obtained with just the LO (signal arm blocked), again by use of expression (2). This no-signal method agrees with the SNL from Eq. (1) to within 1%. We ensemble average over 5000 measurements at each phase angle and then step the LO phase uniformly 30 times through nearly a  $2\pi$  cycle. The amount of quadrature squeezing observed is  $12 \pm 1\%$ . Analysis of the minimum and maximum variance indicates an overall detection efficiency of 15% and a squeezing gain of 5.2 (7.2 dB). The low efficiency is the reason for the low squeezing levels and prevents the state from being that of minimum uncertainty. A possible cause of low efficiency is imprecise optical alignment. We have performed similar measurements with a bulk  $\beta$ -BaB<sub>2</sub>O<sub>4</sub> crystal in place of WG 1 (and WG 2 removed); this yielded a noise reduction of  $6 \pm 1\%$ .

We also measured the amplification (and deamplification) of a coherent input pulse at 830 nm in these waveguides. The experiment consists of injecting both a 415-nm pump pulse and an 830-nm  $\sim 1$ -pJ seed pulse into the waveguide simultaneously, both with TM polarization. The relative phase between the two pulses determines the amplification (or deamplification) of the seed. Figure 3 shows the resulting amplification factor  $A_{\pm}$  ( $A_{\pm} = \text{seed}$

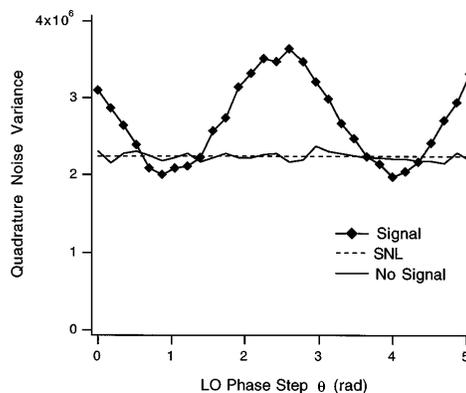


Fig. 2. Quadrature noise variance versus LO phase.

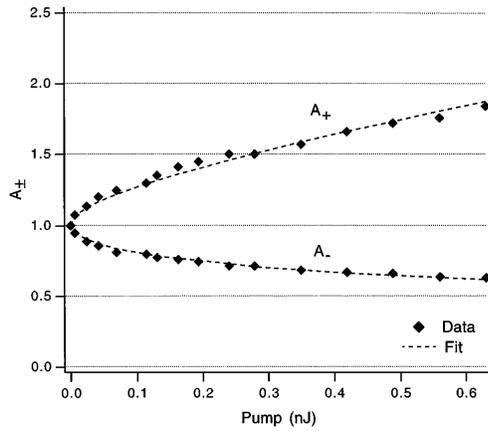


Fig. 3. Amplification factors  $A_{\pm}$  of a seed pulse versus pump pulse energy. The dashed curve is obtained by use of Eq. (3).

energy output/seed energy input). Simple mode-matching considerations permit us to estimate the mode-matching efficiency  $\eta$  between pump and signal of the parametric amplification process<sup>4</sup>:

$$A_{\pm} = 1 - \eta + \eta \exp(\pm\sqrt{\alpha P}), \quad (3)$$

where  $\alpha$  is a gain factor and  $P$  is the pump-pulse energy. In the waveguides, we found that  $\alpha = 1.0/\text{nJ}$  and  $\eta = 0.70$ , a considerable improvement over the bulk-crystal case for which our best result was  $\eta = 0.20$ . [A change in  $\eta$  of  $\pm 0.10$  led to fairly convincing fits as well. Also, this  $\alpha$  is ten times larger than that found in our second-harmonic-generation measurements with 200-fs pulses, a matter that is currently unresolved (see *Note added in proof* below).] The same value for  $\eta$  and  $\alpha$  gave good fits to both  $A_+$  and  $A_-$ . We did not find such global agreement in the bulk case. Furthermore we found no indication of gain-induced diffraction with pumping levels as high as 0.63 nJ, which is near the waveguide damage threshold.

These results indicate that, in the waveguide, mode control is improved over the bulk-crystal case. The  $\alpha$  reported above is smaller than the inferred squeezing gain by a factor of 2, possibly owing to limitations in the model. The squeezing inferred from  $\alpha$ , however, is fairly consistent with the measurements, as a result of the low detection efficiency.

Interestingly, in second-harmonic generation both the  $\text{TM}_{00}$  and  $\text{TM}_{01}$  modes in the fundamental were found to produce a  $\text{TM}_{00}$  mode in the second harmonic. (This is also seen with cw lasers.<sup>14</sup>) The reverse process in downconversion is a possible reason for the low detection efficiency; i.e., if the squeezed light is produced in a linear combination of the two modes (as in a type II process), it will be difficult to mode match with the LO to obtain the full amount of squeezing. For this reason, higher squeezing levels might be obtained with a single-mode device.

In conclusion, we have observed squeezing and parametric amplification in waveguides, with both results indicating improvement over the bulk-crystal case. The increase in mode-matching efficiency for parametric amplification is particularly encouraging. Also, the absence of gain-induced diffraction removes the squeezing limit found in bulk crystals. Further improvements in spatial mode matching will likely improve the squeezing levels, particularly with a single-mode waveguide.

We thank Dan F. McAlister and Deepak Bogavarapu for their assistance in the experiments. This study was supported by a grant from the National Science Foundation.

\*Present address, Department of Physics, Reed College, Portland, Oregon 97202.

*Note added in proof:* After the experiments a possible calibration error was found in the pump energy measurement. Correction of this error could lead to  $\alpha$  values up to 2.5 times smaller than reported above.

## References

1. R. E. Slusher, P. Grangier, A. LaPorta, B. Yurke, and M. J. Potasek, *Phys. Rev. Lett.* **59**, 2566 (1987).
2. P. Kumar, O. Aytür, and J. Huang, *Phys. Rev. Lett.* **64**, 1015 (1990); T. Hirano and M. Matsuoka, *Opt. Lett.* **15**, 1153 (1990); M. Rosenbluh and R. M. Shelby, *Phys. Rev. Lett.* **66**, 153 (1991); K. Bergman and H. A. Haus, *Opt. Lett.* **16**, 663 (1991); D. T. Smithey, M. Beck, M. G. Raymer, and A. Faridani, *Phys. Rev. Lett.* **70**, 1244 (1993).
3. A. LaPorta and R. E. Slusher, *Phys. Rev. A* **44**, 2013 (1991).
4. P. D. Townsend and R. Loudon, *Phys. Rev. A* **45**, 458 (1992).
5. C. Kim and P. Kumar, *Phys. Rev. Lett.* **73**, 1605 (1994).
6. B. Yurke, P. Grangier, R. E. Slusher, and M. J. Potasek, *Phys. Rev. A* **35**, 3586 (1987); M. J. Werner, "Travelling-wave parametric amplifiers," Ph.D. dissertation (University of Queensland, Queensland, Australia, 1994).
7. P. Kumar, in *Squeezed and Nonclassical Light*, P. Tombesi and E. R. Pike, eds. (Plenum, New York, 1989), pp. 175–183.
8. C. Kim, R.-D. Li, and P. Kumar, *Opt. Lett.* **19**, 132 (1994).
9. W. Sohler and H. Suche, *Appl. Phys. Lett.* **37**, 255 (1980).
10. J. D. Bierlein, in *Guided Wave Nonlinear Optics*, D. B. Ostrowsky and R. Reinisch, eds. (Kluwer, Dordrecht, The Netherlands, 1992), p. 49.
11. M. L. Sundheimer, Ch. Bosshard, E. W. Van Stryland, G. I. Stegeman, and J. D. Bierlein, *Opt. Lett.* **18**, 1397 (1993).
12. D. T. Smithey, M. Beck, J. Cooper, and M. G. Raymer, *Phys. Scr.* **T48**, 35 (1993).
13. J. Guena, Ph. Jacquier, M. Lintz, L. Pottier, M. A. Bouchiat, and A. Hrisoho, *Opt. Commun.* **71**, 6 (1989).
14. M. G. Roelofs, A. Suna, W. Bindloss, and J. D. Bierlein, *J. Appl. Phys.* **76**, 4999 (1994).