Large nonlinear phase modulation in quasi-phase-matched KTP waveguides as a result of cascaded second-order processes

M. L. Sundheimer, Ch. Bosshard, E. W. Van Stryland, and G. I. Stegeman

Center for Research in Electro-Optics and Lasers, University of Central Florida, 12424 Research Parkway, Orlando, Florida 32826

J. D. Bierlein

Central Research and Development, Experimental Station, E. I. DuPont de Nemours & Company, Wilmington, Delaware 19880

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Nonlinear spectral modulation and broadening have been observed in quasi-phase-matched KTP waveguides near 850 nm, indicative of self-phase modulation that is due to cascaded second-order processes. Numerical beam-propagation simulations indicate nonlinear peak phase shifts larger than π for 600 W of peak power in a 2.8-mm-long guide.

It has been known for many years that a nonlinear phase shift can occur with non-phase-matched second-harmonic generation in particular and with parametric processes in general.[1,2] Frequently it is an undesirable factor that leads to instabilities in parametric oscillators. Such a nonlinear phase shift has been measured experimentally in bulk KTP at 1.06 μm with Z-scan techniques,[3] which measure the phase distortion directly, and earlier in bulk cesium dihydrogen arsenate by observation of the temporal modulation on the pulses.[4] Spectral modulation of the fundamental has also been reported in bulk samples.[5] In general, the effective third-order nonlinearities have been small (10^{-14} cm^2/W), and the required powers have been large (kilowatts to megawatts). However, with the development of quasi-phase-matching (QPM) techniques, which allow large second-order nonlinear coefficients to be phase matched in waveguide geometries, large nonlinear phase shifts are potentially possible at relatively low powers. It has recently been shown theoretically that such phase shifts could prove useful for low-power all-optical switching in waveguides at watt power levels, provided that phase shifts of π or more can be obtained.[6] However, to our knowledge no measurements of this nonlinear phase shift have been performed in waveguides. In this Letter we report the measurement of large nonlinear phase shifts ($>\pi$), using 3-ps pulses at 850 nm in KTP quasi-phase-matched channel waveguides.

Experiments were performed in a $-Z$-cut sample of hydrothermally grown KTP with segmented, domain-inverted waveguides formed by ion exchange.[7] Ion exchange was performed in a 95 mol.% $RbNO_3$/5 mol.% $Ba(NO_3)_2$ molten salt bath for 45 min at 325 °C. The y-propagating waveguides are 2.8 mm long, with an asymmetric QPM period of 4 μm consisting of 2.7-μm exchanged regions followed by 1.3 μm of bulk material. The waveguides used had 5-μm widths and effective depths of approximately 4 μm. These guides support at least two modes at the fundamental wavelength and several modes at the second harmonic. However, the input coupling conditions could be adjusted to excite predominantly the fundamental TM_{00} mode. Calculations based on the Sellmeier formula for KTP and this segmentation geometry predict that the first-order phase match for TM polarization [$TM_{00}(\omega) + TM_{00}(\omega) \rightarrow TM_{00}(2\omega)$] should occur at 846 nm with a FWHM bandwidth of 0.3 nm for this waveguide length.[8] The mode of the generated second harmonic is determined by phase-matching considerations. A low-power cw wavelength scan with a Ti:sapphire laser (Fig. 1) determined that the $TM_{00}(\omega)$-to-$TM_{00}(2\omega)$ phase match occurs at 852.2 nm with a bandwidth of 0.34 nm, in excellent agreement with the Sellmeier calculations considering that bulk refractive indices were used rather than mode effective indices. There is also a phase match for $TM_{00}(\omega)$-to-$TM_{01}(2\omega)$ conversion (less efficient) at 844.1 nm, and phase matching to higher-order modes occurs at shorter wavelengths. Use of TM modes exploits d_{33}, which at 18.5 pm/V is the highest coefficient in KTP.[9] Waveguide

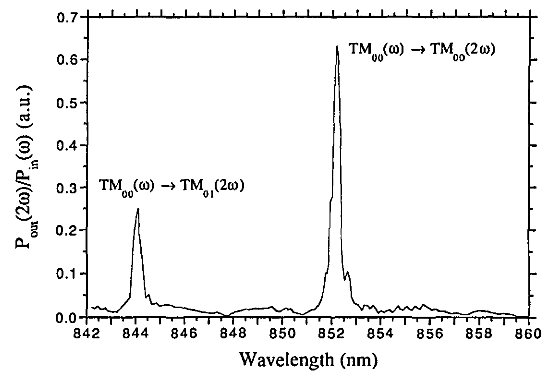

Fig. 1. Low-power cw wavelength scan in KTP QPM waveguide showing prominent phase-match locations.

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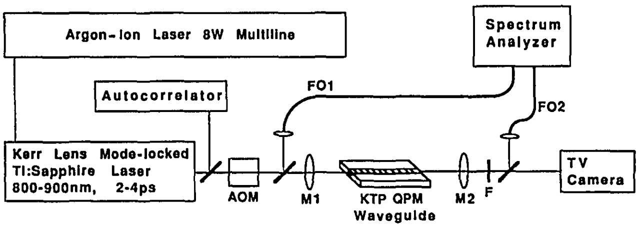


Fig. 2. Experimental setup for spectral modulation measurements: AOM, acousto-optic modulator; M1, M2, 20× microscope objectives; FO1, FO2, multimode fiber-optic cables; F, filter to block the second harmonic.

quality is excellent, with typical overall throughputs (measured from before the input objective to after the output objective) of 30–40%. Waveguide losses are so low that they are difficult to measure and are estimated to be less than 0.5 dB/cm for the fundamental and less than 1 dB/cm for the second harmonic.

We evaluated the nonlinear phase shifts that are due to cascading by measuring the spectral modulation obtained on transmission through the KTP waveguides. The experiments were performed with a Kerr lens mode-locked Ti:sapphire laser that produces transform-limited pulses with autocorrelation pulse widths from 2 to 4 ps. Owing to the solitonlike nature of this laser, a sech^2 pulse shape is assumed, and typical measured time–bandwidth products are 0.315 to 0.320. The experimental apparatus is shown in Fig. 2. Continuous monitoring of the pulse autocorrelation and input spectrum ensured that the pulses remained transform limited. Because the input spectrum was taken just before the beam was focused into the waveguide, we verified that none of the optical elements before the waveguide distorted the spectrum. The acousto-optic modulator is used to adjust the input power into the waveguide without steering the beam and affecting waveguide coupling. The spectrometer (Instrument Systems Spectro 320) consists of a slowly scanned grating and a calibrated detector and has a resolution of less than 0.07 nm. Multimode fiber cables provide the optical input to the spectrometer, and tests were done to ensure that the fiber coupling conditions and the fibers themselves did not distort the spectra.

Large amounts of spectral broadening and modulation were observed slightly off phase matching in the 854–857-nm range, with a typical power-dependent result shown in Fig. 3. This clearly shows the greater-than-threefold increase in spectral width and three-lobed modulation at high guided intensities relative to low intensities. The low-intensity KTP waveguide transmission spectrum is indistinguishable from the input spectrum. No phase matching is obtained when TE-polarized light is used, and the output spectrum remains unchanged even at the highest powers. With 30% throughput, correcting for Fresnel reflection at the output face and taking an effective mode area of 20 μm^2, we estimate the peak intensity in the guide for 300 mW of average incident power and 3.4 ps FWHM autocorrelation width to be 3 GW/cm^2. Large amounts of second-harmonic conversion are required for this effect to be seen, as evidenced by the 60–70% average fundamental depletion observed where the phase modulation is largest. If it were compared with self-phase modulation in fibers, the three-lobed modulation would correspond to a peak nonlinear phase shift of 2.5π.[10] In our case, however, the second-harmonic-generation process can lead to additional spectral structure unrelated to pure self-phase modulation. Our theoretical simulations (see below) indicate phase shifts of the order of π to 2π. The natural third-order n_2 of KTP at 1.06 μm is 2.4×10^{-15} cm^2/W, which gives a phase shift almost 2 orders of magnitude less than that inferred here.[3]

We modeled short-pulse second-harmonic generation to compare calculated and experimental spectra. This problem has been studied extensively over the years, but many of these studies generally neglected pump depletion and/or dispersive effects such as temporal walk-off, group-velocity dispersion, and spectral bandwidth limitations to phase matching.[1,11–13] These studies also tended to neglect the phase distortion and spectrum of the fundamental. Eckardt and Reintjes[14] and Bakker *et al.*[15] did include these effects, and their theoretical treatments formed the basis of our modeling. The appropriate coupled time-domain equations governing pulsed second-harmonic generation in a dispersive medium are[14]

$$\frac{\partial}{\partial \xi}A_1 - \frac{1}{2}\frac{\partial}{\partial \tau}A_1 - i\frac{k_1''L_w}{2T_0^2}\frac{\partial^2}{\partial \tau^2}A_1 = i\kappa L_w A_2 A_1^* \exp(i\Delta k \xi L_w) - \frac{\alpha_1 L_w}{2}A_1, \quad (1)$$

$$\frac{\partial}{\partial \xi}A_2 + \frac{1}{2}\frac{\partial}{\partial \tau}A_2 - i\frac{k_2''L_w}{2T_0^2}\frac{\partial^2}{\partial \tau^2}A_2 = i\kappa L_w A_1 A_1 \exp(-i\Delta k \xi L_w) - \frac{\alpha_2 L_w}{2}A_2, \quad (2)$$

where κ is the second-harmonic nonlinear coefficient, defined by $\kappa = 2\omega d_{\text{eff}}/(2n_\omega^2 n_{2\omega}\epsilon_0 c^3)^{1/2}$, Δk is the detuning from the quasi-phase match, α_i are the absorption coefficients of the fundamental and the second harmonic, and A_i are the field amplitude envelopes normalized such that $|A|^2$ is the guided intensity in megawatts per square centimeter. For QPM, κ must be reduced by a factor of $2\sin(\pi D)/\pi$, where D is the duty cycle of the grating (0.675 in our case).[16] Following the method of Eckardt and Reint-

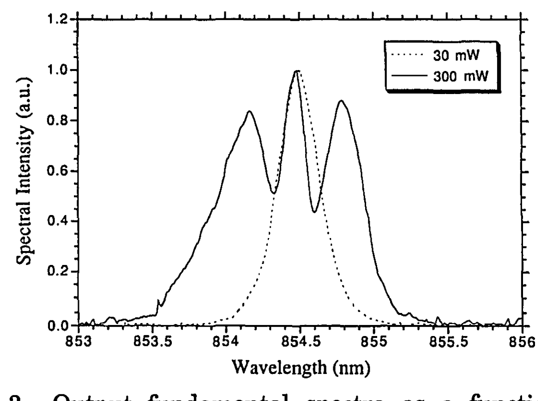
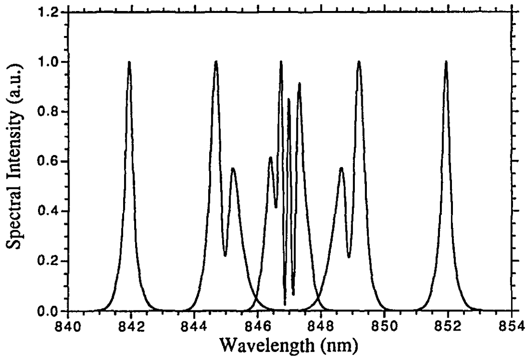
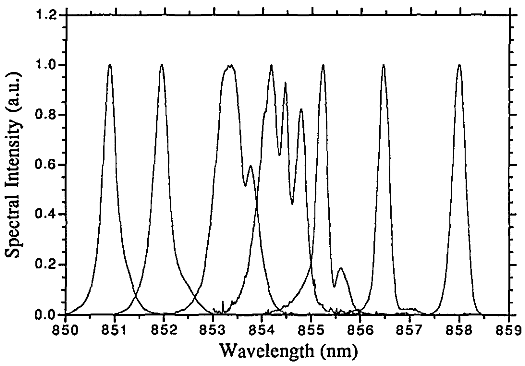


Fig. 3. Output fundamental spectra as a function of incident power.



(a)



(b)

Fig. 4. Output fundamental spectra at 3 GW/cm^2 guided intensity as a function of wavelength: (a) numerical simulation, (b) experimental results.

jes, we use a reduced time that averages the group velocities of the fundamental and second harmonic and normalize the time and space coordinates to the pulse width and the walk-off length, respectively. The walk-off length is defined by $L_w = T_0/(k_2' - k_1')$, where T_0 is the intensity FWHM pulse width and $k_{1,2}'$ are the first frequency derivatives of the fundamental and the second-harmonic wave vectors. Likewise, the wave vectors with double primes are the second derivatives that represent group-velocity dispersion. Calculations for KTP at 850 nm based on the Sellmeier equation give $L_w = 1.5$ mm for a 2-ps pulse, implying that walk-off must be considered for the 2.8-mm samples. Group-velocity dispersion is much less important over these lengths. A symmetric split-step fast-Fourier-transform beam-propagation program, with a third-order Runge–Kutta routine to evaluate the nonlinearity over each distance increment, was written to evaluate the coupled second-harmonic equations numerically and model the experiments. This approach gives energy conservation to within 10^{-5}. Extensive numerical modeling of these equations was performed for QPM in KTP, and Fig. 4(a) shows the wavelength dependence of the modulation of the spectrum.

We measured the variation in the spectral broadening (and hence in nonlinear phase shift) as a function of detuning from phase matching in order to test further the predictions of the cascading calculations. Figure 4(b) shows the evolution of the spectral modulation as the wavelength is tuned through the phase match. Care was taken to keep the input power and pulse width the same for every wavelength in the scan. No phase modulation was observed in this experiment on the short-wavelength side of phase matching, perhaps as a result of competition from the TM_{01} phase match, which would give a phase shift of opposite sign. There is good qualitative agreement between experiment and theory considering that the modeling was done for QPM in bulk KTP and not for waveguides and thus does not consider contributions and competition from several phase-matching interactions [i.e., $TM_{00}(\omega) \rightarrow TM_{01}(2\omega)$, $TM_{01}(\omega) \rightarrow TM_{01}(2\omega)$]. We plan further interferometric studies of the tuning behavior of the second-order phase shift to determine accurately the magnitude and sign of the phase shift near these resonances.

In conclusion, peak nonlinear phase shifts larger than π have been observed in KTP QPM waveguides through novel use of the phase distortion associated with second-harmonic generation. The demonstration of such large phase shifts at relatively low powers and in short samples is promising for all-optical photonic switching applications.

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