Nonlinear directional coupler in periodically poled lithium niobate

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Nonlinear wave propagation was investigated experimentally in coupled waveguides by means of the cascaded nonlinearity in quasi-phase-matched second-harmonic generation. With a specially designed wave-vector-mismatch distribution along the propagation axis, cascading was optimized for low fundamental depletion. High-contrast, ultrafast all-optical switching with switching powers of tens of watts was observed.

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Soon after the proposal for using cascaded quadratic (instead of third-order) dielectric nonlinearity for intensity-dependent light propagation, typical all-optical effects such as soliton propagation and all-optical switching based on cascading were demonstrated experimentally.[1] Most previous experiments with the cascaded nonlinearity were performed in quasi-cw operation with relatively long-duration laser pulses. Our first experiments with waveguides relied on cascading in birefringent phase-matched second-harmonic generation (SHG) in lithium niobate ($LiNbO_3$).[2,3] To decrease the power that is necessary for observing all-optical effects[4,5] and to use more-flexible phase-matching conditions, we are performing our next generation of experiments with cascading in quasi-phase-matched (QPM) $LiNbO_3$ waveguides[6] with the largest second-order susceptibility tensor element in $LiNbO_3$, d_{33}. Furthermore, the new experiments are operated with laser pulses ranging from a few hundreds of femtoseconds to a few picoseconds in samples a few centimeters long, so the pulse propagation can no longer be considered quasi cw and the specific temporal behavior of cascading can be explored. Here we report the first results on all-optical switching in nonlinear directional couplers (NLDC's) in periodically poled $LiNbO_3$.

To generate large intensity-dependent phase shifts and nonlinear propagation for the fundamental (FD) with cascading, we implemented type I wavelength-tunable QPM SHG from the TM_{00} mode at the FD wavelength λ_F near 1550 nm to the second-harmonic (SH) TM_{00} mode with $\lambda_{SH} = \lambda_F/2$. Both single channels and pairs of linearly coupled channel waveguides were fabricated by proton exchange in three groups on a 35-mm-long Z-cut $LiNbO_3$ crystal for propagation along the crystallographic X axis. The end faces were polished for end-fire coupling. All waveguides were 7.6 μm wide, with a proton exchange depth of 0.71 μm. The sample was annealed at 328 °C for 25 h. The design is noncritical in width, such that the phase-matching wavelength is insensitive to variations in waveguide width that arise from lithographic defects. Multiple FD transverse modes are supported in these waveguides. To permit efficient coupling to the FD TM_{00} mode only, adiabatic tapers and mode filters were used at the input and the output of the sample.[6] The coupled waveguides were separated by spacings of 6.3 to 7.1 μm. The couplers with a separation of 6.3 μm are half-beat-length couplers with a linear coupling length of 35 mm for the FD.

Each of the three waveguide groups was situated in an electric-field-poled 30-mm-long QPM grating section.[7] One type had a uniform period of 14.96 μm for QPM SHG between the FD TM_{00} and the SH TM_{00} modes of a single waveguide with the phase-matching FD wavelength $\lambda_{PM} = 1545$ nm at room temperature. The other two had QPM gratings in three sections. In the central section the same uniform period of 14.96 μm was used. The outer sections had a wave-vector mismatch $\Delta\beta L$ that either increased (positive grating) or decreased (negative grating) toward the ends. The wave-vector-mismatch distribution and a corresponding grating period for the positive grating are plotted in Fig. 1. The calculated cw wavelength dependence of the SH and the FD depletion in this QPM grating for a single waveguide are plotted in Fig. 2. Also shown is the nonlinear phase shift Φ_{NL} of the FD at the waveguide output. Φ_{NL} is the phase difference between a high- and low-power FD TM_{00} mode. The characteristic strong asymmetry of the tuning curve with its large and only weakly dispersive nonlinear phase shift in the low FD depletion regime for $\lambda_F > \lambda_{PM}$ was well pronounced.[2] For a negative grating with grating periods increasing toward the sample ends, a low-dispersive negative nonlinear phase shift in the low depletion range for $\lambda_F < \lambda_{PM}$ was calculated.

Because of the finite resolution of the mask writer it was not possible to realize the required wave-vector-mismatch distribution by smoothly and continuously

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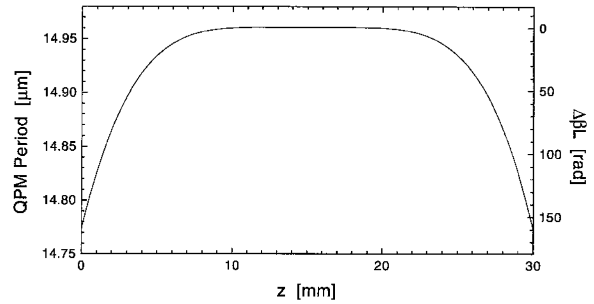

Fig. 1. Distribution of the wave-vector mismatch and a corresponding QPM grating period along a 30-mm-long positive grating.

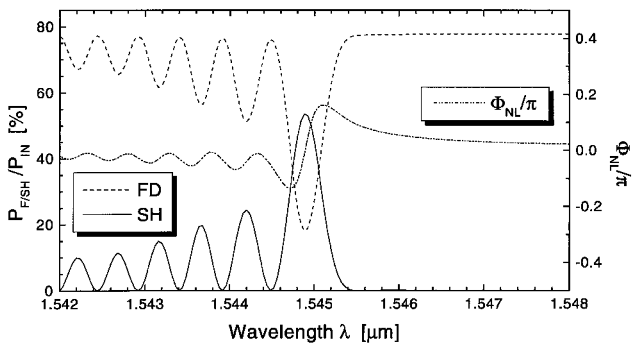

Fig. 2. Calculated SHG, FD depletion, and nonlinear phase shift Φ_{NL}/π at the output of a waveguide with the QPM grating of Fig. 1 for room-temperature, cw FD input $P_{IN} = 1$ W.

varying the QPM grating period. An equivalent result was obtained with a 125-nm resolution mask writer by an appropriate spatial distribution of only three or four different grating periods chosen such that the spatially averaged grating period profile matched that in Fig. 1. The calculated QPM SHG performance was indistinguishable from the one shown in Fig. 2.

All simulations were based on a cw coupled-mode theory. Losses of 0.3 dB/cm for the FD and 0.6 dB/cm for the SH modes were taken into account. The normalized SHG efficiency for the waveguide design should be 60%/W cm^2 in the uniform grating.

The measurements were performed with a tunable, pulsed NaCl color-center laser near $\lambda = 1550$ nm. The transform-limited pulses had a FWHM duration of 8 ps and a repetition rate of 76 MHz. Peak powers of as much as 140 W were available at the waveguide input. Although photorefractive effects were not observed for averaged input powers below 40 mW, a chopper reduced the maximum average power to 5 mW.

The quality of the QPM gratings was checked with SHG tuning curve measurements of single waveguides for each grating distribution. A cw wavelength-tunable laser diode gave low-power tuning curves with true zeros between the SH maxima and smoothly decaying SH for wavelengths below (above) and above (below) λ_{PM} for a positive (negative) grating, respectively, in agreement with the theoretical predictions. SHG tuning curves measured with the color-center laser were temperature tuned for convenience. A typical low-depletion tuning curve in the positive QPM grating measured with pulsed input is shown in Fig. 3. For operation at a fixed wavelength, negligible SH output occurred for temperatures below the phase-matching temperature. The width of the SHG resonance and the temperature difference between the SH maxima corresponded well to the temperature-dependent shift of the phase-matching wavelength by 1 nm/10 K. The room-temperature phase-matching wavelength was only 5 nm larger than the 1545 nm expected from the design. The most obvious deviation from the cw tuning curves was the absence of zeros between the SH maxima, which indicated that SHG with our pulsed excitation could no longer be considered a quasi-cw process. The FWHM bandwidth of 0.44 nm for the 8-ps input pulses was no longer small compared with the SHG acceptance bandwidth of the 30-mm-long QPM interaction length (see Fig. 2). Therefore the pulsed response was a convolution of the cw response with the finite laser spectrum, which resulted in a broadening of all spectral features and a loss of fine features such as zeros. In fact, the linear part of the frequency-dependent variation of the phase-matching conditions for different frequencies within a pulse's spectrum is well known as the cause of SH walk-off, and the tuning curve in Fig. 3 is evidence of SH walk-off in our waveguides.

For a FD input power of 60 W the simulations show a nonlinear phase shift of the nondepleted FD mode of 2π near the resonance. This nonlinear phase shift is sufficient to detune a directional coupler.[3] Figure 4 shows images of the output facet of a directional coupler for different powers input into the bar channel. The half-beat-length coupler was operated at a wavelength $\lambda_{PM} + 1$ nm, near phase matching but still in the low FD depletion regime of the positive QPM grating. Compared with that for a single channel, the phase-matching wavelength at room temperature for a coupler was increased by 5 nm because of the presence of the second arm. At low power, i.e., with no nonlinear phase shift, all the light coupled completely to the second cross channel and exited from it at the output. For higher input power the coupling was detuned and the light stayed in the bar arm. The averaged output power from both coupler channels, shown in Fig. 5, was measured versus input peak power with photodetectors. It exhibited the switching behavior quantitatively with a switching power of

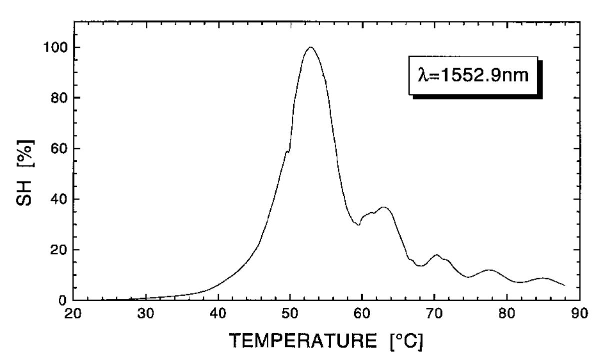

Fig. 3. Measured, temperature-tuned SHG in a single-channel waveguide in a positive nonuniform QPM grating, pulsed input, low depletion limit.

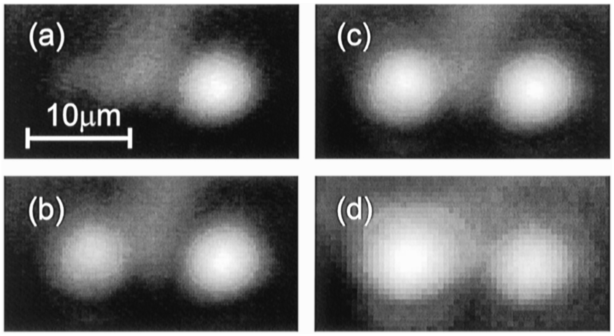

Fig. 4. Normalized power-dependent mode pattern at the NLDC output facet: (a) 6.3-W, (b) 32-W, (c) 44-W, (d) 126-W peak power fundamental input. The waveguide output surface was imaged with a 10× microscope objective into a vidicon camera. Left, bar channel and right, cross-channel, low-FD depletion for $\lambda_{PM} + 1$ nm.

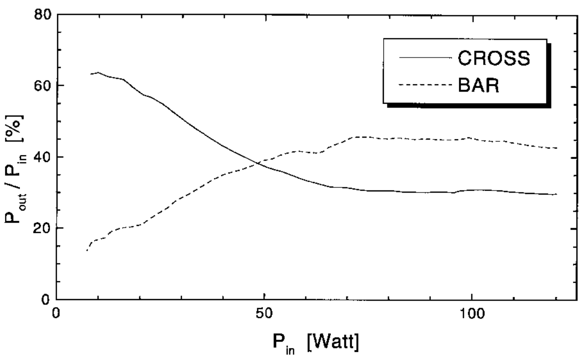

Fig. 5. Measured switching curve of a NLDC in a positive nonuniform QPM grating close to phase matching but still in the low-FD depletion regime for $\lambda_{PM} + 1$ nm.

50 W. The pulse breakup that was due to incomplete switching in the pulse wings reduced the switching ratio to the theoretical maximum of 65%. It is noteworthy that the measured switching characteristic did not show any degradation (compared with the temporal averaged switching curves with quasi-cw pulsed excitation[3]), owing to the broad spectral width of the pulses and the SH walk-off. In fact, calculations show that the electric field of the SH that is responsible for the FD phase shift does not walk away from the fundamental pulse. As long as no significant SH is generated, the experiments show that cascading acts just like a local $\chi^{(3)}$ process.

All-optical switching was also observed in couplers with the other QPM gratings. The tuning curve for negative gratings had secondary SH maxima on the low-temperature side, and the tuning curve in the uniform grating was symmetric about phase matching. Correspondingly, clean switching was observed without SHG because of a negative nonlinear phase shift for $\lambda < \lambda_{PM}$ in the negative grating and degraded switching with SHG on both sides of phase matching in the uniform grating.[8]

In conclusion, the switching power in NLDC's based on cascading was reduced from the 2000 W in our previous experiments[3] with birefringent phase-matched SHG to 50 W in waveguides with QPM SHG. QPM gratings were designed and fabricated to provide large nonlinear phase shifts in regions with low fundamental depletion, so the nonlinearly propagating fundamental is not depleted as a result of losses into the SH. With more-careful tuning closer to phase matching it should be possible to reduce the switching power further, to 20 W, with negligible losses to the SH. Using shorter pulse lengths, down to 200 fs, we intend to investigate in more detail the degradation of cascading as a result of broadband excitation. A first experimental proof has been found that SH walk-off does not necessarily limit the application of the cascaded nonlinearity.

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