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All-optical polarization switch in a quadratic nonlinear photonic quasicrystal

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We present an all-optical intensity-dependent polarization switch based on cascaded three-wave-mixing interactions in a quasiperiodic quadratic nonlinear photonic crystal. The polarization switching is realized by simultaneous quasiphase matching of upconversion and downconversion processes in $LiNbO_3$ and achieves three orders of magnitude better efficiency than previous devices based on cascaded cubic nonlinearities. The switch allows extending mode-cleaning and mode-locking techniques to considerably lower input power. We demonstrate experimentally that a single linearly polarized 1550 nm fundamental wave generates a new fundamental wave of orthogonal polarization. © *2009 American Institute of Physics*.
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All-optical devices such as switches, transistors, and couplers are of considerable interest today because these are essential for the realization of self controlled optical effects. These devices are mainly based on nonlinear effects such as cross phase modulation,[1] optical Kerr effect,[2–4] nonlinear phase shift based on cascaded processes,[5–7] and frequency conversion.[8]

In this work, we experimentally demonstrate a relatively low power all-optical nonlinear polarization switch based on double phase-matched cascaded processes proposed by Saltiel and Deyanova in 1999.[9] The switch is intensity dependent, i.e., at low intensity, the polarization is essentially unchanged and, as the input intensity increases, part of it is converted to the orthogonal polarization. The switch is much more efficient than similar known switches,[10,11] enabling polarization switching with significantly less power. Consequently, applications of pulse cleaning, mode locking, and switching, which were limited until now to femtosecond pulses owing to damage consideration, can be extended to the picosecond regime. The switching is obtained by cascading two three-wave-mixing processes in a quadratic nonlinear photonic quasicrystal, thereby it is extremely fast and requires a single low power input beam.

The two collinearly cascaded nonlinear second-order processes are an upconversion process followed by a downconversion process, together generating a fundamental frequency beam with the perpendicular polarization. The first process is a type I second harmonic generation (SHG) of an ordinary polarized fundamental beam, creating a second harmonic ordinary beam, i.e., $\omega_Y+\omega_Y=2\omega_Y$ using the $d_{YYY}=d_{22}$ component of the nonlinear electric tensor. The second process is a type II difference frequency generation, back converting to the fundamental frequency at an extraordinary polarization, i.e., $2\omega_Y-\omega_Y=\omega_Z$, using the $d_{YZY}=d_{24}$ component of the nonlinear tensor.

We implemented the polarization switch in $LiNbO_3$. Since the linear dispersion is different for the two polarizations, the mismatch vectors for the two processes are not equal: 0.39 μm^{-1} for the first process and 0.66 μm^{-1} for the second process. The two processes are simultaneously phase matched by a quasiperiodic modulation[12] of the nonlinear coefficient. Our design algorithm is a one-dimensional version of the so-called dual-grid method,[13] which was demonstrated to phase match arbitrary sets of nonlinear optical processes.[14,15] Feeding the required phase mismatch values into this algorithm yields a quasiperiodic sequence of two nonlinear building blocks of lengths 10.70 and 7.63 μm. By numerical optimization, we have found that the best efficiencies for the two desired processes are obtained when the 10.7 μm block is composed of two identical sub-blocks of opposite nonlinear coefficients, whereas in the 7.63 μm block, a positive nonlinear coefficient is used throughout the entire block. The conversion efficiencies for the *YYY* and *YZY* processes are determined by the value of the Fourier coefficients at the spatial frequency of the respective mismatch vector: 0.36 and 0.34, respectively. For comparison, a perfect periodic structure used for first order quasiphase matching has a Fourier coefficient of $2/\pi=0.63$ but it usually phase matches only a single process.[16]

The quasiperiodic design was implemented in a 10 mm long electric-field poled $LiNbO_3$ crystal. To enable geometrical characterization, selective chemical etching on the crystal surface was used, creating a linear diffraction pattern, which matches the bulk nonlinear modulation pattern. Illuminating the linear diffraction pattern and comparing the resulted image to the analytical Fourier transform of the structure, we received excellent agreement with the desired quasiperiodic design, as shown in Fig. 1. Next, we characterized independently the two SHG processes that are phase matched by the crystal, using a tunable cw diode laser (ANDO AQ4321D), lasing in the range of 1520–1580 nm, followed by an erbium doped fiber amplifier and a fiber polarization controller. The

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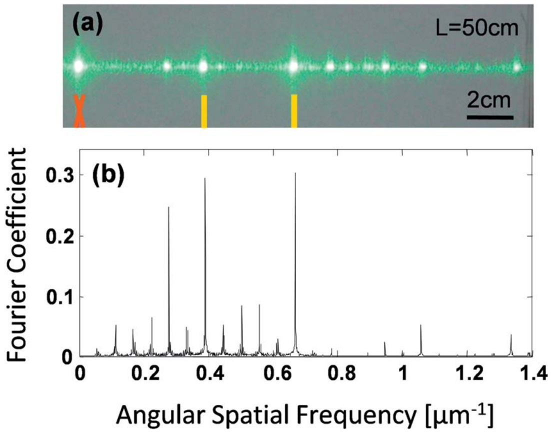

FIG. 1. (Color online) (a) The diffraction pattern photograph of the quasiperiodic nonlinear photonic crystal where the two relevant Fourier frequencies are marked. The dc component is marked with a red cross. (b) Fourier transform of the theoretical quasiperiodic design.

pump beam was chopped at a frequency of 1.3 kHz and focused to a 30 μm waist. The resulting second harmonic processes were measured using a calibrated silicon photodiode, followed by a lock-in amplifier. The results were compared with a simulation employing a split step Fourier method,[17] in which a Gaussian beam was used as a pump. Both measured processes exhibit good agreement with the simulations, when applying a temperature shift of -10 °C or a wavelength shift of 5 nm, possibly due to the inaccuracy of the Sellmeier equation for ordinary polarized waves in $LiNbO_3$.[18] By measuring the second harmonic power as a function of the pump power, we have deduced an internal conversion efficiency coefficients of $10^{-4}\%\ W^{-1}$ and $10^{-3}\%\ W^{-1}$ for the *YYY* and *YZY* processes, respectively, which is in reasonable agreement to the simulation results [$3.8\times10^{-4}\%\ W^{-1}$ and $1.1\times10^{-3}\%\ W^{-1}$, respectively, assuming $d_{22}=1.1$ pm/V (Ref. 19) and $d_{31}=4.3$ pm/V]. As shown in Fig. 2, the curves of phase-matched wavelength versus crystal temperature of the two processes intersect at temperature of 136 °C and at wavelength of 1550 nm, giving the operating parameters for cascading the two processes.

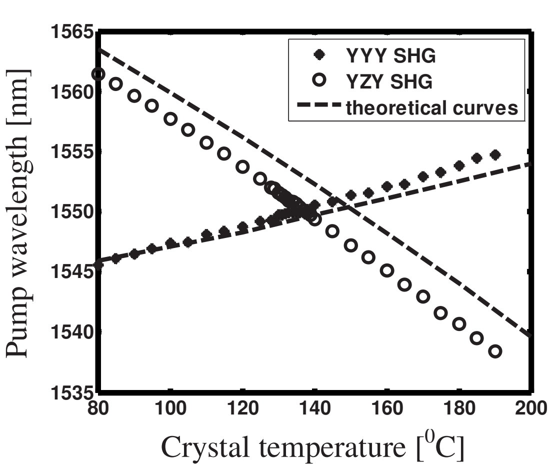

FIG. 2. Experimental results and theoretical curves of the two SHG interactions, showing the phase-matched wavelength dependence on temperature for the type I *YYY* and type II *YZY* processes. The intersection points of the measured and theoretical processes are different due to inaccuracies of the Sellmeier equation for ordinary polarization.

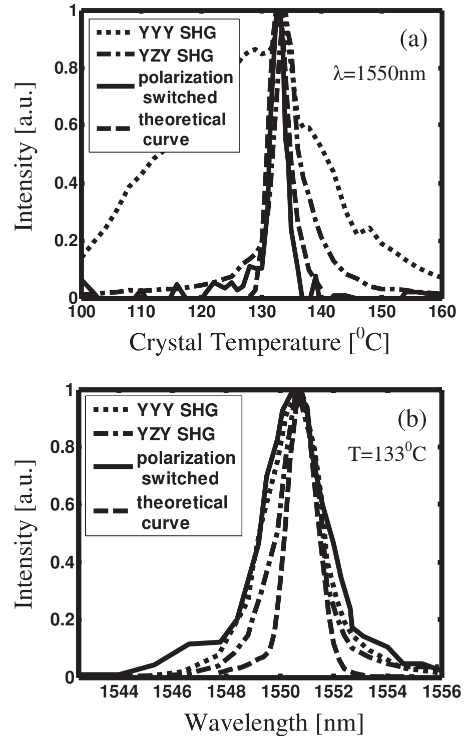

FIG. 3. Measurements of the polarization switched intensity (solid curves) as a function of temperature at a constant wavelength (a) and as a function of wavelength at constant temperature (b), together with the two SHG processes it is based upon (dotted and dot-dash curves), along with the theoretical polarization switched curve (dashed curves). The 3° shift in the intersection temperature is due to change in experimental conditions from cw to pulsed OPO setup.

Finally, we characterized the polarization state of the fundamental beam that was controlled by the cascaded processes. In order to increase the conversion efficiency, a neodymium doped yttrium aluminuim garnet pumped periodically poled $LiNbO_3$ optical parametric oscillator (OPO) was used. The pulses generated by the OPO are about 6 ns duration, 15 μJ energy, and 1.5 nm spectral width. The OPO signal beam was coupled to the crystal in the ordinary (Y) polarization, and the intensity of the fundamental wavelength that was generated at the extraordinary (Z) polarization was measured as a function of both wavelength and temperature around the intersection parameters of the two SHG processes, as shown in Figs. 3(a) and 3(b), after two consecutive polarizers (a CVI Glan Laser polarizer and Newport linear precision polarizer, with extinction ratios of 10^{-6} and 10^{-5}, respectively). The alignment was checked by verifying the absence of a birefringence signal. If the incident beam is not on the principle axis of the trigonal 3m crystal, the birefringence effect generates a rotated polarization radiation with sinusoidal dependence on wavelength and temperature. We verified in our experiment that we do not have a birefringence effect, meaning that the incident beam is on the principle axis of the $LiNbO_3$ crystal. As predicted, the efficiency of the fundamental polarization switching is strongly correlated with the two cascaded processes it is based upon, thereby verifying the operation of the switch.

The measured performance of the polarization switched fundamental beam is compared to a split-step Fourier beam propagation method (BPM) simulation[17] as well as with an analytical calculation.[20] The temperature and wavelength de-

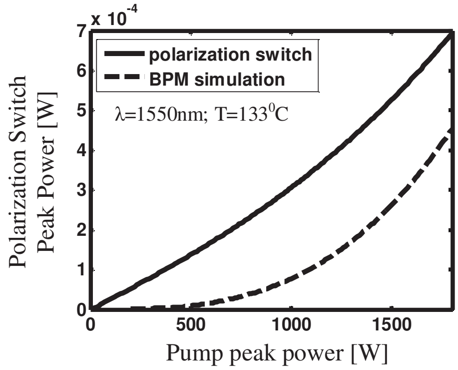

FIG. 4. The polarization switched peak power as a function of the pump peak power.

pendence of the measured signal are in good agreement to the simulated outcomes, as can be seen in Figs. 3(a) and 3(b). However, the efficiency of the polarization switch is larger than expected and in a relatively small pump power it is dominated by a linear dependence instead of the expected cubic dependence, as can be seen in Fig. 4. The measured crossed polarized signal was fitted to a third order polynomial: $P_{XP}=3.01\times10^{-14}\cdot P_{\text{pump}}^3+1.46\times10^{-13}\cdot P_{\text{pump}}^2+2.61\times10^{-7}\cdot P_{\text{pump}}-3.69\times10^{-7}$, where P_{XP} and P_{pump} are the crossed polarized and input fundamental beams in Watts, respectively. When examining the polynomial, we see that at the highest power of 1.8 kW, the offset and quadratic parts are negligible, with magnitude of $\sim10^{-7}$ W, whereas the linear and cubic parts are comparable, with magnitude of $\sim10^{-4}$ W. Possibly, at higher power, the cubic part will dominate, as expected from the theoretical analysis. The third order coefficient gives an efficiency of $3\times10^{-12}\%$ W^{-2}. This efficiency is lower than the theoretical efficiency of $10^{-9}\%$ W due to pulsed laser measurements and narrow bandwidth response. This efficiency is nine orders of magnitude higher than the previously reported $4.5\times10^{-21}\%$ W^{-2} efficiency of an all-optical polarization rotation switch based on cascaded second order nonlinear interactions where only one of the two processes was phase matched.[10] Polarization switches based on cascaded cubic nonlinearity are three orders of magnitude less efficient with a maximum efficiency of $4.63\times10^{-15}\%$ W^{-2}.[11] The effective nonlinearity of the two cascaded $\chi^{(2)}:\chi^{(2)}$ processes in a 10 mm long $LiNbO_3$ is four orders of magnitude higher than the pure $\chi^{(3)}$ nonlinearity of BaF_2,[21] which is a common material for third order nonlinear processes. This improvement in efficiency opens the possibility to use lower power pulses. Moreover, it enables to use longer pulses without damaging the crystal.

In conclusion, we experimentally investigated an all-optical intensity-dependent polarization switch in a quadratic nonlinear media, shown to be considerably more efficient than similar devices, based on either phase-matched cubic nonlinearity or on partly phase-matched quadratic nonlinearity. By enabling two cascaded three wave mixing processes, we converted an ordinary polarized beam to the orthogonal polarization. The advantages of a nonlinear polarization switch are that it can be tuned by changing phase matching conditions, e.g., wavelength or temperature, and can be all-optically controlled. This polarization switch can be used in all-optical processing applications, soliton formation[22] and for construction of intracavity nonlinear optical devices for mode locking.[23,24]

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