Polarization switching as a result of cascading of two simultaneously phase-matched quadratic processes

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A method of intensity-dependent polarization switching is proposed. The effect is based on simultaneous action of two phase-matched second-order processes in a quadratic medium. Using analytical and numerical techniques, we demonstrate that a single linearly polarized fundamental wave, when it is propagating in such a medium, can efficiently generate a new fundamental wave of orthogonal polarization. The polarization switching is explained by an effective four-wave-mixing process that is performed through second-order cascading. © 1999 Optical Society of America

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There is substantial interest in the use of second-order cascading effects for construction of all-optical switching devices (Ref. 1 and references therein). Polarization switching (PS) is one of the methods used to realize all-optical switching. Efficient low-power PS of a probe wave controlled by the intensity of a gate wave was reported in Refs. 2 and 3. Intensity-dependent polarization rotation was predicted and observed when a single wave (divided into extraordinary and ordinary waves in a crystal) was involved in type I (Refs. 4 and 5) or type II (Refs. 6–8) second-harmonic generation (SHG). The polarization rotation that was described in these studies was a result of different accumulation of nonlinear phase shift by the extraordinary and the ordinary beams. This method of PS requires the use of additional elements for compensation of the linear phase-shift difference that results from the natural birefringence. The common characteristic of all these PS schemes is that two input waves are required, and the cascading effect is a result of interaction between waves connected by a single phase-matched process.

All-optical processing in a medium that is simultaneously phase matched for two or more second-order processes was recently investigated.[9–13] Two possibilities were treated: (i) when all interacting waves had the same polarization (an examples is third-harmonic multistep cascading[13]) and (ii) when the two allowed polarization states at the fundamental or the second-harmonic frequency, $E(\omega) = [A(\omega), B(\omega)]$ and $E(2\omega) = [S(2\omega), T(2\omega)]$, are involved.[9–12] Interactions of the second type are called vectorial processes. The possibility of PS at the fundamental frequency in a single-input wave geometry was not considered in any of these studies. For example, the PS that was predicted in Ref. 9 requires seeding of the other orthogonal component and a specific phase difference between the two fundamental field components.

Here we analyze a new PS scheme based on simultaneous action of one upconversion and one downconversion $\chi^{(2)}$ process. This double-phase-matched cascading scheme can lead to efficient generation of the orthogonal polarization component of the input fundamental wave. To the best of our knowledge, this is the first prediction of efficient nonlinear optical energy transfer from one orthogonal component to the other in a nonseeded geometry.

The idea of double-phase-matched cascading is shown in Fig. 1(a). The polarization plane of the fundamental input wave A is oriented in the direction in which in the linear regime the wave will remain linearly polarized inside the crystal. The cascading process starts with generation of S by type I SHG process AA–S. By a second phase-matched process, difference-frequency mixing (SA–B), wave B is generated at fundamental frequency ω, with the polarization plane orthogonal to that of wave A. Further, the generated waves S and B take part in chains (cascades) of interactions that reconstruct the depleted fundamental wave A, and as a consequence wave A accumulates a strong nonlinear phase shift. Here we concentrate on the effect of strong energy transfer between the two fundamental orthogonal components.

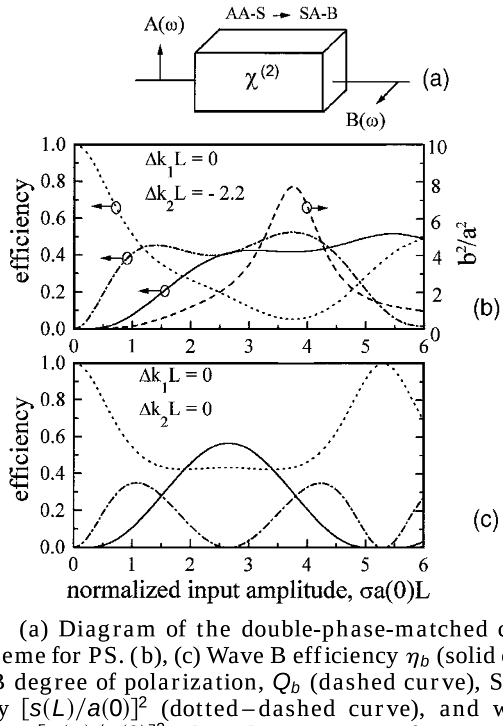

Fig. 1. (a) Diagram of the double-phase-matched cascading scheme for PS. (b), (c) Wave B efficiency η_b (solid curve), wave B degree of polarization, Q_b (dashed curve), SHG efficiency $[s(L)/a(0)]^2$ (dotted–dashed curve), and wave A depletion $[a(L)/a(0)]^2$ (dotted curve) as a function of the normalized input amplitude $\sigma a(0)L$.

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The reduced-amplitude equations in the slowly varying envelope approximation that describe the simultaneous action of type I and type II processes for SHG in lossless quadratic media when they are written for linearly polarized plane waves are

$$\mathrm{d}S/\mathrm{d}z = -\,i\sigma_1 A^2 \exp(i\Delta k_1 z) - 2i\sigma_2 AB \times \exp(i\Delta k_2 z)\,, \tag{1a}$$

$$\mathrm{d}A/\mathrm{d}z = -\,i\sigma_1 SA^* \exp(-i\Delta k_1 z) - i\sigma_2 SB^* \times \exp(-i\Delta k_2 z)\,, \tag{1b}$$

$$\mathrm{d}B/\mathrm{d}z = -\,i\sigma_2 SA^* \exp(-i\Delta k_2 z)\,, \tag{1c}$$

where S denotes the complex amplitude of the second-harmonic wave and A and B are the complex amplitudes of the two orthogonally polarized fundamental waves; $A = a\exp(i\varphi_a)$, $B = b\exp(i\varphi_b)$, and $S = s\exp(i\varphi_s)$. σ_1 and σ_2 are the nonlinear coupling coefficients, and the wave-vector mismatches are $\Delta k_1 = k_s - 2k_a + G_1$ and $\Delta k_2 = k_s - k_a - k_b + G_2$, where G_1 and G_2 are the quasi-phase-matching (QPM) grating constants.[14,15] The other possible interactions that are responsible for generation of higher harmonics and the interaction BB–S are neglected because of the large wave-vector mismatch or the negligible $\chi^{(2)}$ tensor component that is responsible for the process.

First, it is noted that the results for the amplitudes and phases of the three waves are symmetrical and antisymmetrical functions with respect to the vector $\mathbf{m} = (\Delta k_1, \Delta k_2)$. For any of the waves it is valid that $r(\Delta k_1, \Delta k_2) = r(-\Delta k_1, -\Delta k_2)$ and $\varphi_r(\Delta k_1, \Delta k_2) = -\varphi_r(-\Delta k_1, -\Delta k_2)$, where r replaces a, b, or s.

Both the efficiency of generation of wave B, $\eta_b = [b(L)/a(0)]^2$, and its degree of polarization, $Q_b = [b(L)/a(L)]^2$, were investigated by numerical solution of the system of equations (1) for the conditions $\sigma_1 = \sigma_2$ and no seeding of the B and the S waves. Figures 1(b) and 1(c) show the dependence of these two parameters on the input amplitude of wave A. For normalized input amplitude $\sigma a(0)L = 2.7$ and $(\Delta k_1 L, \Delta k_2 L) = (0, 0)$ the efficiency of the generated component B reaches 58%. At $\sigma a(0)L = 3.7$ and $(\Delta k_1 L, \Delta k_2 L) = (0, -2.2)$ the output beam at the fundamental frequency is almost linearly polarized, and the polarization plane is oriented perpendicularly to the input one [see the dashed curve in Fig. 1(b)]. This is the point where wave A has the maximum depletion. Figure 2 illustrates the dependence of the degree of polarization of wave B on the mismatch difference $(\Delta k_1 - \Delta k_2)L$. It can be seen that by proper choice of Δk_1 and Δk_2 one can achieve a higher value of Q_b but with less efficiency. This effect is in fact intensity-dependent 90° rotation of the polarization plane of the input wave A. Unlike the previous PS devices based on two-step $\chi^{(2)}$ cascading,[4–8] the PS scheme that is proposed here does not need birefringence correction, which will make devices based on this idea more simple and less expensive. The required input intensity that corresponds to $\sigma a(0)L = 2.7$ is $I \approx 1.45\ \mathrm{GW/cm^2}$ [$\lambda_1 = 1.55\ \mu$m, $n = 2.15$, $L = 1$ cm, and $d^{(2)} \approx 2$ pm/V is the QPM value of the $LiNbO_3$ yyy and yzy components[16]]. This switching intensity is approximately the same as that reported in Ref. 6

The dependence of the efficiency of generation of wave B, η_b, and the depletion of wave A, $\eta_a = |a(L)/a(0)|^2$, on the values of $\Delta k_1 L$ and $\Delta k_2 L$ are presented in contour-map form (Fig. 3). The areas of strongest depletion of wave A are suitable for observation of intensity- dependent 90° rotation.

An approximate analytical formula for amplitude B can be derived for the case in which the process AA–S is relatively far from the exact phase-matching condition. By using the substitutions $S = \tilde{S}\exp(i\Delta k_1 z)$ and $B = \tilde{B}\exp[i(\Delta k_1 - \Delta k_2)z]$ and requiring that $|\Delta k_1|L \gg 1$, we can reduce the system of equations (1) to a new system that describes the coupling of the two orthogonal polarization states, A and B:

$$\frac{\mathrm{d}A}{\mathrm{d}z} - \frac{i}{\Delta k_1}(\sigma_1{}^2|A|^2 + 2\sigma_2{}^2|B|^2)A - \frac{i\sigma_1\sigma_2}{\Delta k_1}(2A^*\tilde{B} + A\tilde{B}^*)A = 0\,, \tag{2a}$$

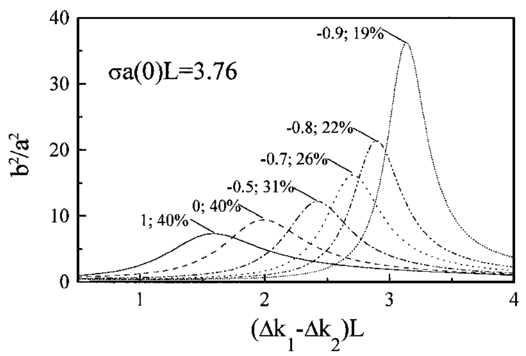

Fig. 2. Degree of polarization of wave B versus wave-vector mismatch difference $(\Delta k_1 - \Delta k_2)L$ for fixed normalized input amplitude. The two numbers assigned to each curve correspond to the wave-vector mismatch $\Delta k_1 L$ and to the efficiency $[b(L)/a(0)]^2$ of generation of wave B at the maximum of the curve.

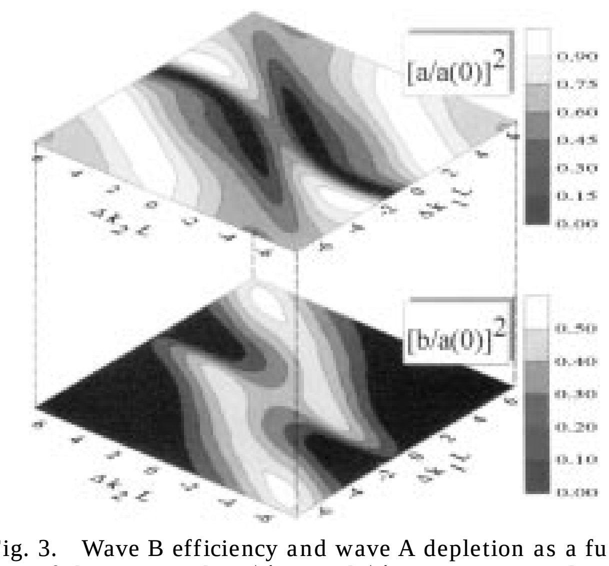

Fig. 3. Wave B efficiency and wave A depletion as a function of the mismatches $\Delta k_1 L$ and $\Delta k_2 L$. Input amplitude, $\sigma a(0)L = 3.7$.

$$\frac{d\tilde{B}}{dz} + i(\Delta k_1 - \Delta k_2)\tilde{B} - \frac{i2\sigma_2{}^2}{\Delta k_1}|A|^2\tilde{B} - \frac{i\sigma_1\sigma_2}{\Delta k_1}|A|^2 A = 0\,. \tag{2b}$$

The last left-hand-side terms in Eqs. (2a) and (2b) are usually neglected when cross-phase modulation in centrosymmetric media is considered (see, e.g., Ref. 17). In our case, however, these terms have comparable contributions because of the double-phase-matching condition. They are responsible for the observed strong energy exchange between the two fundamental polarization components. The magnitudes of the crossed terms are determined by effective cubic coupling coefficients of the type $\gamma = \sigma\sigma/\Delta k_1$. The structure of these coefficients reflects the fact that the strong coupling between the two polarization components is a result of cascading of two second-order processes: AA–S and SA–B.

With the approximation of negligible depletion of wave A, the following expression for amplitude B can be found:

$$B = \frac{\sigma_1\sigma_2}{\Delta k_1}|A|^2 AL\,\mathrm{sinc}(DL/2) \times \exp\left\{i\left[\frac{\pi}{2} - \frac{DL}{2} + (\Delta k_1 - \Delta k_2)L\right]\right\}, \tag{3}$$

where $D = \Delta k_1 - \Delta k_2 - 2\sigma_2{}^2|A|^2/\Delta k_1$. Equation (3) indicates that the generation of component B can be described by phase-matched four-wave mixing of the type AAA–B, governed by $\chi^{(2)} : \chi^{(2)}$ cascading cubic nonlinearity.

The problem of obtaining simultaneous phase matching of two nonlinear processes in crystals has a history of more than 30 years.[18] Several approaches have been tested. One approach is the combination of birefringence phase-matching and QPM techniques.[19] In a second approach, both processes are phase matched by use of different orders of QPM.[9,15,20,21] Finally, in Ref. 22 a different approach that uses Fibonacci gratings was described. With it, any two processes can be simultaneously phase matched. $LiNbO_3$ is one example of a suitable crystal for the realization of the single-input-wave PS effect. One can achieve type I and type II SHG by phase matching the processes yy–y and yz–y, respectively. Calculations based on dispersion equations[23] show that these two processes can be phase matched by a single grating with period $\Lambda = 30.5\ \mu$m ($\lambda_1 = 1.55\ \mu$m).

In conclusion, we have proposed a new double-phase-matched cascading scheme that allows all-optical intensity-dependent polarization switching. We believe that devices based on the idea described here will find applications in the all-optical-processing domain[1] and in intracavity mode locking.[24–26] Additionally, this kind of double-phase-matched process should support new types of soliton waves.[27]

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