All-optical deflection and splitting by second-order cascading

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We describe a novel type of second-order cascading by which the signal that is cross polarized to the pump can be split with an efficiency of more than 100%. The process requires the simultaneous phase matching of two second-order parametric interactions, whcih can easily be achieved with recently fabricated two-dimensional nonlinear photonic crystals.

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Two major types of second-order cascading can be achieved in nonlinear optical media with quadratic response. The first type is based on a single second-order process, such as second-harmonic generation (SHG),[1] and it is governed by a single phase-matching parameter. The second type, called multistep second-order cascading, involves at least two different second-order processes, each of which is characterized by an independent phase-matching parameter. Multistep cascading can be described, in some respects, as an effective third-order process. A famous example of such a process is third-harmonic generation in a single quadratic crystal.[2,3]

Recent studies of multistep second-order cascading led to the prediction of many interesting effects based on self- and cross-phase modulation that include the accumulation of a nonlinear phase shift,[4] multicolor parametric optical solitons,[5,6] and parametric generation of cross-polarized waves in a single quadratic crystal.[7,8] Another important example of the multistep cascading processes is the frequency shifting effect in quasi-phase-matched (QPM) structures,[9–11] which may find applications in optical communications.

In this Letter we propose a spatial analog of the frequency shifting effect: a multistep second-order process, based on a double-phase-matched parametric interaction, that permits splitting of the input signal into two or three channels (see Fig. 1) and the simultaneous amplification of the split signals with respect to the input signal.

The process of beam deflection, which can be based on double phase matching in two-dimensional nonlinear photonic crystals,[12] is shown in Figs. 1(a), 2(b), and 2(c). The input pump and signal are at the same frequency and are cross polarized. The first process [Figs. 2(b)] is the collinear generation of the second-harmonic (SH) wave by the pump beam based on the fundamental vector $\mathbf{K}_a$ of the reciprocal lattice [Fig. 2(a)], $\mathbf{k}_2 + M\mathbf{K}_a = 2\mathbf{k}_{1p}$, where integer M indicates the order of the parametric interaction.[12] As the second process [Fig. 2(c)], the SH wave generated by the pump interacts with the cross-polarized input signal beam and is downconverted into a new wave with the same frequency and polarization but with a deviation by angle θ from the propagation direction. The phase-matching condition for the second step, $\mathbf{k}_{1s'} + \mathbf{k}_{1s} + N\mathbf{K}_b = \mathbf{k}_2$, can be satisfied by the use of another fundamental vector, $\mathbf{K}_b$ [Fig. 2(a)]. If the propagation direction is chosen such that a symmetric reciprocal lattice vector is situated on each side of the pump direction [as shown in Figs. 2(d) and 2(e)], two deflected beams will be generated: one at angle θ and the other one at the angle $-\theta$. The polarizers shown in Fig. 1 are used to block the pump beam.

The important condition for such a cascading process to occur is the double-phase-matching parametric interaction that can be achieved by periodic modulation of the quadratic susceptibility in one-dimensional QPM structures,[13] and, as was shown in Refs. 12 and 14, in the recently fabricated two-dimensional nonlinear photonic crystals (2DNPCs).[15]

To develop the theory of the cascaded processes shown in Fig. 1 we assumed that x is the propagation direction, the subscripts p, s, and s' stand for the pump, the transmitted signal, and the deflected signal, respectively, with the additional subscripts 1 and 2 that mark the fundamental and the second-harmonic waves, and that y and z stand for the polarization directions of the interacting waves. The processes involved in these parametric interactions can then be formally presented as two possible chains: (a) $z_{1p}z_{1p} - z_{2p}$, $z_{2p}y_{1s} - y_{1s'}$, and *(b) $y_{1p}y_{1p} - z_{2p}$, $z_{2p}z_{1s} - z_{1s'}$. In both cases

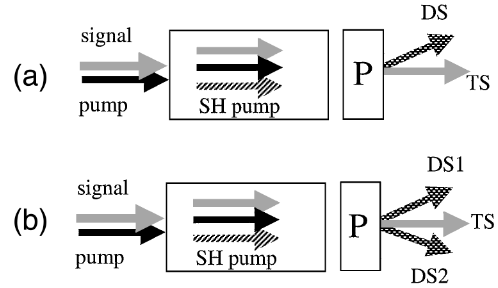

Fig. 1. Schematic of the suggested cascading interaction for (a) deflection and (b) splitting. Signal and pump are cross polarized. TS, transmitted signal; DS, DS1, DS2, deflected signals; P's, polarizers.

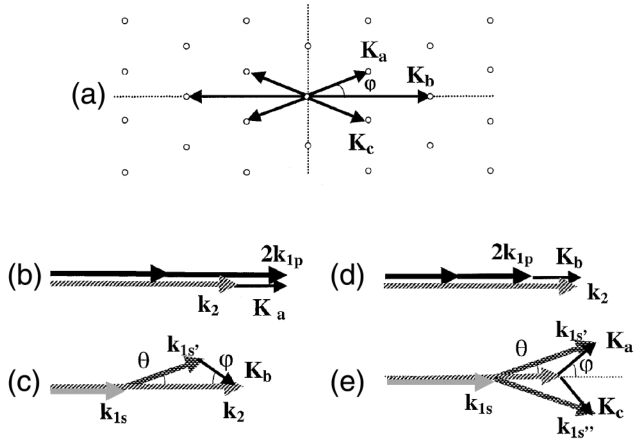

Fig. 2. (a) Reciprocal lattice and the main reciprocal vectors of a 2DNLC structure. Phase matching for (b) the first and (c) the second steps of the process, $z_{1p}z_{1p} - z_{2p}$ and $z_{2p}y_{1s} - y_{1s'}$. Phase matching for (d) the first and (e) the second steps of the process, $y_{1p}y_{1p} - z_{2p}$, $z_{2p}z_{1s} - z_{1s'}$. Drawings correspond to $n_{1z} < n_{2z} < n_{1y}$.

the pump and the input signal are cross polarized; the difference between them lies in which of the subprocesses (SHG or difference-frequency mixing) will profit from the use of second-order nonlinearity with a larger value. For the crystals that permit modulation of the second-order susceptibility (such as $LiNbO_3$, $LiTaO_3$, $KTiOPO_4$, and $KNbO_3$), tensor component $d_{33}^{(2)}$ is several times larger than component $d_{32}^{(2)}$. Moreover, the second-order nonlinearity that governs the two steps of the proposed process has an electronic origin, and therefore the deflection (splitting) process should be instantaneous. The overall parametric cascading interaction resembles an effective totally degenerate four-wave mixing process with the combined phase-matching condition $\mathbf{k}_{1s} + \mathbf{k}_{1s'} + (M\mathbf{K}_a + N\mathbf{K}_b) = 2\mathbf{k}_{1p}$.

It is important to note that the deflection and splitting described here are optically addressable processes; i.e., splitting (deflection) occurs only when a pump is provided. The suggested parametric process can be analyzed by use of equations similar to those that describe the frequency shifting effect.[10] If we neglect, for simplicity, the effect of walk-off, temporal pulse profiles, and losses at the fundamental and SH frequencies, we can obtain the following system of equations for the parametric processes shown in Fig. 1(a):

$$i\,\frac{\mathrm{d}A_{1p}}{\mathrm{d}x} = \sigma_1 A_{1p}{}^* A_2 \exp(-i\Delta k_1 x)\,,$$

$$i\,\frac{\mathrm{d}A_2}{\mathrm{d}x} = \sigma_1 A_{1p}{}^2 \exp(i\Delta k_1 x) + 2\sigma_2 A_{1s} A_{1s'} \exp(i\Delta k_2 x)\,,$$

$$i\,\frac{\mathrm{d}A_{1s}}{\mathrm{d}x} = \sigma_2 A_2 A_{1s'}{}^* \exp(-i\Delta k_2 x)\,,$$

$$i\,\frac{\mathrm{d}A_{1s'}}{\mathrm{d}x} = \sigma_2 A_2 A_{1s}{}^* \exp(-i\Delta k_2 x)\,. \qquad (1)$$

In the system of Eqs. (1) the functions A_{1p}, A_2, A_{1s}, and $A_{1s'}$ are the complex envelopes of the pump wave, the SH wave generated by the pump, and nondeflected and deflected signals, respectively. Here $\sigma_1 = 2\pi f_1 d_{\mathrm{I}}/(\lambda_1 n_1)$ and $\sigma_2 = 2\pi f_2 d_{\mathrm{II}}/(\lambda_1 n_1)$ are the coefficients that characterize the two parametric processes, SHG and difference-frequency mixing, respectively. The numerical coefficients f_1 and f_2 depend on the parameters of the 2DNPC (see, e.g., Ref. 16). If the input pump's polarization is directed along the crystallographic z axis, $d_{\mathrm{I}} = d_{33}^{(2)}$, then $d_{\mathrm{II}} = d_{32}^{(2)}$ and, for the input pump polarization perpendicular to the crystallographic z axis, $d_{\mathrm{I}} = d_{32}^{(2)}$ and $d_{\mathrm{II}} = d_{33}^{(2)}$.

To find analytical solutions of Eqs. (1) we assume that the pump intensity is much larger than the input and output signal intensities. Using the well-known solution for SHG, $A_2 = -iA_0 \tanh(\sigma_1 A_0 x)$, we reduce the system of Eqs. (1) to the equations for A_{1s} and $A_{1s'}$ and obtain, for $\Delta\mathbf{k}_2 = 0$, the intensity conversion efficiency of the output signals:

$$\eta_1(\eta_{1s'}) = 1/4\,\{[\mathrm{sech}(\sigma_1 A_0 L)]^\rho \pm [\cosh(\sigma_1 A_0 L)]^\rho\}^2, \quad (2)$$

where $\eta_j = [A_j(L)/A_s(0)]^2$, A_0 is the input pump's amplitude, $A_s(0)$ is the input signal's amplitude, L is the crystal length, and $\rho = |\sigma_2/\sigma_1|$; + and − correspond to nondeflected and deflected output signals, respectively.

In Fig. 3 we show the dependence of the intensity amplification of the deflected (solid curves) and nondeflected (dashed curves) signal waves for the deflection process with the ratio $\rho = |\sigma_2/\sigma_1|$ equal to 6 (thick curves) and 1/6 (thin curves). Thus the suggested multistep cascading processes can be used for simultaneous splitting and amplification of the input signal, and the first effect is more efficient.

Amplification for the scheme that results in threefold splitting [Figs. 1(b), 2(d), and 2(e)] is described by

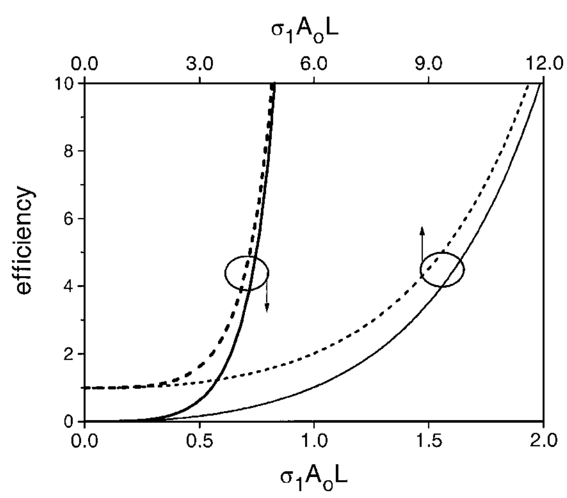

Fig. 3. Efficiency of the deflected (solid curves) and nondeflected (dashed curves) signals relative to normalized input pump amplitude, as given by the result [Eq. (2)] for the deflection scheme and for two values of the ratio ρ, namely, $\rho = 6$, shown by thick curves (lower scale), and $\rho = 1/6$, shown by thin curves (upper scale).

the same solution [Eq. (2)], the conversion efficiency of the transmitted wave is equal to η_{1s} and the conversion efficiency of each deflected wave (DS1 and DS2; Fig. 1) is 2 orders of magnitude less than $\eta_{1s'}$.

To find the exact phase-matching conditions we take the example of a 2DNPC made from a planar hexagonally polled $LiNbO_3$ structure for which z is the direction of the poling axis. The reciprocal lattice of the 2DNLC structure is shown in Fig. 2(a). As was done in the research reported in Ref. 16, we select the reciprocal lattice basis vectors $\mathbf{K}_a = k_0(\cos\phi, \sin\phi)$ and $\mathbf{K}_b = k_0(2\cos\phi, 0)$, with $k_0 = 2\pi/d$. First we consider the case of Fig. 1(a) with the pump polarized in the xy plane, signals polarized along the z axis, and vector $\mathbf{K}_a$ selected to phase match the SH process directed along the direction of pump propagation. Then the following equations define the parameters of the 2DNPC [Figs. 2(b) and 2(c): $k_2 = 2k_{1p} - Mk_0$, $k_2 = k_{1s}(1 + \cos\theta) + 2Mk_0\cos^2\phi$, and $k_{1s}\sin\theta = Mk_0\sin(2\phi)$. Solutions of these equations are $k_0 = (2k_{1p} - k_2)/M$, $\cos^2\phi = [(Nk_0)^2 + w^2 - k_{1s}^2]/(2wNk_0)$, and $\sin\theta = [Nk_0\sin(2\phi)]/k_{1s}$, where $w = k_2 - Nk_0 - k_s$. Similar analytical solutions can be obtained for the second case, which is presented in Figs. 1(b), 2(d), and 2(e).

Taking the fundamental wavelength $\lambda = 1.53\ \mu$m and the refractive indices $n_{1z} = 2.141645$, $n_{1y} = 2.21227$, and $n_{2z} = 2.18377$ from Ref. 17 for $T = 100\ °$C and the deflection geometry shown in Fig. 1(a), we obtain (for $M = N = 1$) $d = 26.84\ \mu$m, $\phi = 30.38°$, and $\theta = 1.33°$. For the second process of the splitting geometry [Figs. 1(b), 2(d), and 2(e)] the corresponding results are $d = 5.53\ \mu$m, $\phi = 67.8°$, and $\theta = 6.64°$.

So far, we have discussed collinear SH generation as the first process in multistep cascading. However, both deflection and splitting can be achieved with noncollinear SH generation. In such a case a single QPM structure can be employed to provide the phase matching of both the parametric interactions. Additionally, the so-called two-pass QPM geometry (previously suggested in the context of the frequency shifting experiments[10]) can also be applied for beam deflection and splitting by means of second-order cascading.

Finally we should point out that the proposed scheme could also be used for the generation of a cross-polarized wave. Indeed, if only a pump wave enters a nonlinear medium and the corresponding double-phase-matching conditions are satisfied, the generation of a pair of cross-polarized signals starts from quantum fluctuations in the nonlinear medium or from some source of depolarization of the pump (e.g., surface depolarization), leading to the generation of two or three waves of the fundamental frequency propagating in different directions and polarized perpendicularly to the pump wave.

In conclusion, we have suggested a new type of second-order cascading interaction for the simultaneous generation, amplification, deflection, and splitting of waves that are cross-polarized to the pump by means of a double-phase-matching parametric interaction. We believe that the basic ideas presented in this Letter can be useful in the construction of all-optical devices for communications networks based on the properties of nonlinear photonic crystals as well as of different devices, such as interferometers and ellipsometers, for which beam splitting and recombination are required.

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