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All-optical switching by spatial walkoff compensation and solitary-wave locking

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We demonstrate a novel approach to phase insensitive, all-optical steering and switching based on an intensity-induced change in the propagation direction of multidimensional spatial solitary waves in bulk, birefringent, quadratic nonlinear media. Our demonstration is based on second-harmonic generation in a KTP crystal. Compensation for the lateral displacements due to walkoff in SHG is observed. © 1996 American Institute of Physics. [S0003-6951(96)02011-2]

The experimental demonstration in quadratic nonlinear media of large nonlinear optical phase shifts in both bulk crystals¹ and in waveguides,² and the observation of multidimensional spatial soliton like waves³ have made possible a number of new applications such as phase-controlled transistors⁴⁻⁶ and solitary-wave dragging,⁷ both involving second-harmonic generation (SHG). These spatial solitary waves occur above a threshold power and consist of strongly coupled fundamental (FW) and second harmonic (SH) waves which propagate without diffraction and can eliminate the lateral energy displacement due to natural walk off.³ Beam steering of these spatial solitary waves has been demonstrated by controlling with interferometric precision the input phase of the SH wave relative to the FW.⁷ However, most projected applications require all-optically controlled devices which, in analogy to the Kerr intensity-dependent counterparts do not rely on inputs at different frequencies and are not sensitive to the phase relationship between them.^{8,9} Towards this end, schemes with phase-insensitive and frequency-degenerate all-optical interactions have been recently proposed¹⁰ and demonstrated¹¹ based on plane-wave propagation in type II phase-matched SHG.¹²

In this letter, we demonstrate a different approach which exploits solitary wave formation in a type II frequency degenerate interaction for phase-insensitive switching at powers above the threshold for formation of self-guided waves in a $\chi^{(2)}$ bulk crystal. We have found that the direction of propagation of two-dimensional spatial solitary waves in a birefringent bulk medium can in fact be controlled via an intensity imbalance between the two low-frequency input fields. This approach, investigated here in detail for the case of type II phase-matched SHG in KTP, appears more promising than those based on phase control.

In the paraxial ray approximation and near the collinear phase-matched geometry for a quadratic process, a three-wave interaction can be described by the equations of motion:

$$\begin{aligned} \frac{\partial E_{\omega_j}}{\partial z} - \rho_j \frac{\partial E_{\omega_j}}{\partial x} + \frac{1}{2ik_j} \left(\frac{\partial^2 E_{\omega_j}}{\partial x^2} + \frac{\partial^2 E_{\omega_j}}{\partial y^2} \right) \\ = i\Gamma E_{\omega_3} E_{\omega_{3-j}}^* \exp(i\Delta kz), \quad j=1,2, \\ \frac{\partial E_{\omega_3}}{\partial z} - \rho_3 \frac{\partial E_{\omega_3}}{\partial x} + \frac{1}{2ik_3} \left(\frac{\partial^2 E_{\omega_3}}{\partial x^2} + \frac{\partial^2 E_{\omega_3}}{\partial y^2} \right) \\ = 2iE_{\omega_1} E_{\omega_2} \exp(-ikz), \end{aligned} \quad (1)$$

with $\omega_3 = \omega_1 + \omega_2$.³ Here, z and (x, y) are the propagation and transverse directions, respectively, with the walkoff angle ρ defined in the $x-z$ plane. The k_j vectors ($j=1,2,3$) define the phase-front propagation in the birefringent crystal. The terms in parentheses in each equation model the effects of diffraction, while the second order parametric phase-matchable nonlinearity is represented by the coupling strength Γ . In KTP $\Gamma = 6 \text{ cm}^{-1}$ for an input fundamental of 1 GW/cm^2 . In our investigations we numerically launched cylindrically symmetric Gaussian beams with $E = A \times \exp[-(x^2 + y^2)/\omega_0^2] \times \exp[-i(k_x x + k_y y)]$ and solved system (1) with a split step algorithm, integrating the linear (walkoff and diffraction) and the nonlinear portions in the Fourier domain and with a Runge-Kutta routine, respectively.

The above equations show that in a parametric interaction the two input fields need not be coherent (phase locked) to generate a higher frequency wave. The latter, in turn, back converts into the fundamentals through down conversion. This process has been shown previously to lead to "solitary wave locking" above a threshold intensity.³ For type II SHG ($\omega_1 = \omega_2$), in crystals with walkoff and for equal intensity fundamental inputs below the locking threshold, walkoff and diffraction of the interacting beams occurred. The beam directions were governed by the usual linear optics. Above the SW threshold, all three fields can be locked in space, coalescing into a single direction and beating diffraction and walkoff. The key condition is that the parametric gain length be shorter than both the diffraction and the walkoff length. In this letter, we show that an intensity imbalance between the low-frequency inputs can be used to control the SW propagation direction at and above locking threshold. Experimentally, we used a half-wave plate to detune the input polarization from the standard equal input condition for type II SHG.

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FIG. 1. (a) Calculated propagation in a 1 cm long KTP crystal is shown for three different sets of fundamental input intensities (units are GW/cm^2). (a) $I_o = 20$, $I_e = 20.5$; (b) $I_o = 20$, $I_e = 19.5$, and (c) $I_o = 20$, $I_e = 18.5$, for an input beam waist of $20 \mu\text{m}$. (b) Output beam profile measured for a 1 cm long KTP crystal, for a phase mismatch of $+3\pi$ and an input fundamental beam waist of $12 \mu\text{m}$ corresponding to 20 diffraction lengths inside of the crystal and an input peak intensity of $80 \text{ GW}/\text{cm}^2$.

By using appropriately placed apertures the mutual trapping and dragging of the three fields in space can be used for all-optical switching and demonstrate walkoff compensation.

We now make the calculations and experiments specific to type II SHG in KTP. The two input fields, I_o and I_e are orthogonally polarized where “o” and “e” refer to the ordinary and extraordinary polarized fundamental beam components along the Z axis and in the X-Y plane of KTP (X, Y, Z are the principal axes), respectively. At low intensities, the propagation of the “o” field is not affected by walkoff while the “e” fundamental as well as the SHG in KTP exhibit walkoff angles of 0.18° and 0.28° , respectively. Figures 1(a)–1(b) clearly show that, above the SW threshold, a small imbalance in the fundamental input intensities results in power dependent steering of the mutually locked solitary wave beams which does not depend on the relative phase of the input beams. When the “e” beam has an input intensity larger than the “o” beam, the SW is dragged toward the (“e”) walkoff direction in the x-y plane. Conversely for an input imbalance towards the “o” wave, the mutually trapped beams propagate parallel to the z-axis (orthogonal to the input plane), compensating for the lateral displacement induced by spatial walkoff. At intermediate imbalances and large enough input intensities breakup of the SW into two solitary beams is observed [Figs 1(a) and 1(b)]. Indeed, if the strength in both input polarizations is more than twice the SW locking threshold, diffraction is compensated and two separate solitary waves are created. This effect was repro-

FIG. 2. (a) Numerically evaluated transmission of the FW through a $30 \mu\text{m}$ diam aperture at the output fundamental of a 1 cm KTP crystal for $I_o = 20 \text{ GW}/\text{cm}^2$ vs the input peak intensity imbalance for the “e”-polarized fundamental field. The dashed line refers to the transverse position of the SW peak. (b) Experimentally measured transmission through an aperture for an input intensity of $80 \text{ GW}/\text{cm}^2$ and a fundamental beam waist of $12 \mu\text{m}$, corresponding to 20 diffraction lengths in the 1 cm long KTP crystal. A modulation depth of 10 is experimentally achieved.

duced experimentally with the same setup used previously,³ with the simple addition of a half-wave plate which rotates the input fundamental polarization, changing the projection on both extraordinary and ordinary planes of polarization. In a brief summary, a 1064 nm pulse, 35 ps long was focused to a $20 \mu\text{m}$ spot at the entrance face of a 1 cm long KTP crystal and the output from the crystal was filtered to isolate either 1064 or 532 nm radiation imaged onto a camera. Figure 1(b) shows experimental verification of the three cases predicted numerically in Fig 1(a). The inset in Fig. 1(b) indicates the angular rotation of the wave plate from the equal intensity position.

Figure 2 elucidates the above-mentioned effect in more detail. Figure 2(a) shows the integrated transmission through a $30 \mu\text{m}$ aperture centered at the exit (i.e., the transverse location for maximum output of a purely “o” wave input) of a 1 cm long KTP crystal close to the SW-locking threshold. As expected, when no “e” beam is launched [i.e., $(I_e - I_o)/I_o = -1$] no SHG takes place and the fundamental “o” field diffracts freely resulting in a residual 20% transmission through the aperture. As the input “e” field strength increases, SW locking becomes more efficient, eventually forming a diffractionless SW along the walkoff free “o” polarization direction. Above a minimum I_e (slightly lower than I_o), the extraordinary field dominates the evolution of the mutually trapped waves, the SW is smoothly shifted side-

ways to the position where the “*e*” would propagate at low intensities and the device turns “off”, i.e., the throughput through the aperture falls. Notice the quasidigital behavior of the imbalance SW-locking process. In this case a modulation ratio of ~ 20 is anticipated, limited only by losses due to nonsolitary-like radiation (a longer crystal could efficiently take care of the residual light). The dashed line in Fig. 2(a) shows the transverse location of the SW peak, with a double peaked profile in the sharp switch-on/switch-off region (see Fig. 1). In a similar fashion, we experimentally measured the transmission through an aperture leading to the characteristic switching transmission shown in Fig. 2(b). Note that experimentally a modulation of less than 20% resulted in an output modulation exceeding 10, in good agreement with our numerical investigation. The measured response is not as sharp as the calculated cw one, at least partially due to the use of pulses in the experiment.

Finally, to further improve the switching, it is conceptually possible to introduce an input tilt to both input fundamental components. While our previous examples dealt with lateral displacements induced by the natural walkoff in a KTP crystal, an “artificial” walkoff can be induced by an input phase front tilt. This results in an increased/decreased SW lateral shift depending upon the relative sign of the “natural” and “artificial” walkoff in the x - z plane. An important consequence is the possibility to also counteract the lateral displacement induced by walkoff with an input “*e*” wave tilt opposite in sign to birefringent walkoff. In this case an “*o*” input more intense than the “*e*” polarization will ensure no displacement. On the other hand, in order to avoid the need for a longer crystal in the case of Fig. 2, the lateral shift can be enhanced by the introduction of an angular tilt in the same direction as the natural walkoff for the fundamental “*e*” field. Switching between the “*e*” and “*o*” output positions can be achieved with higher contrast ratios at the expense of a larger imbalance between the input beams. It is worth emphasizing, however, that the input tilt needs not be restricted to the x - y plane, and this might be relevant in 2D transverse reconfigurable interconnects. Such phase front tilts, in fact, could be introduced by a double stack of liquid-crystal electronically controlled phase modulators.

In conclusion, we have demonstrated efficient, digital like switching in a quadratic medium in the solitary-wave-

locking regime. Optical modulation with a contrast in excess of 10 are demonstrated for relative imbalances in fundamental inputs of less than 20%. This phenomenon can also be interpreted as all-optical amplification, potentially leading to efficient all-optical-transistor action with soliton like waves. Finally, we have demonstrated that a small imbalance between the “*o*” and “*e*” input fundamental beams can compensate for the lateral displacement experienced by the “*e*” beams in the parametric process. We believe that such a compensation will impact on the design of novel quadratic parametric devices.

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