Cross-phase-modulation nonlinearities and holographic solitons in periodically poled photovoltaic photorefractives

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We show that the nonlinearity in periodically poled photovoltaic photorefractives can be solely of the cross-phase-modulation type. The effects of self-phase modulation and asymmetric energy exchange, which exist in homogeneously poled photovoltaic photorefractives, can be considerably suppressed by the periodic poling. Finally, we demonstrate numerically that periodically poled photovoltaic photorefractives can support Thirring-type ("holographic") solitons, which to our knowledge have never been observed. © 2006 Optical Society of America

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In optically nonlinear materials, the presence of light modifies the material properties. The process through which a beam is experiencing an intensity-dependent nonlinear phase shift induced by the beam itself is commonly referred to as self-phase modulation (SPM) and is accompanied by self-focusing (or defocusing) of the beam.[1] A rather different nonlinear effect is cross-phase modulation (XPM), in which the nonlinear phase shift experienced by one beam is induced by the presence of another beam, and vice versa. In optical systems, XPM has been traditionally believed to be "always accompanied by SPM."[1] Recent studies, however, have revealed optical systems that exhibit strong XPM but lack SPM altogether.[2–8] In such systems, two (or more) narrow beams that propagate jointly interact via XPM and undergo mutual focusing, whereas a single beam propagating alone experiences linear diffraction. Such systems are known from the mathematics arena to support Thirring-type solitons,[9,10] which form solely by virtue of XPM. Thus far, Thirring-type solitons have, to our knowledge, evaded experimental observation, because lossless optical systems exhibiting appreciable XPM but lacking SPM altogether are rare. In fact, such systems were demonstrated only in a highly coherent Raman medium[3] and in an atomic 4-level system under electromagnetically induced transparency conditions.[5] Common to the systems described in Refs. 3–6 is the fact that the interacting beams are at different frequencies.

Here, we suggest a scheme to produce an optical nonlinearity that is solely XPM between interacting beams at the same frequency. The scheme is based on periodically poled photovoltaic photorefractive crystals, such as periodically poled lithium niobate (PPLN). Under appropriate conditions, the periodic poling considerably suppresses the SPM nonlinearity and averages out the unidirectional energy transfer, while leaving the XPM nonlinearity unaffected. Finally, we show that such periodically poled photovoltaic photorefractives can support the hitherto unobserved holographic solitons.

Consider first the nonlinear interaction between two beams propagating in a homogeneously poled photovoltaic photorefractive crystal, such as lithium niobate [Fig. 1(a)]. The beams are mutually coherent and propagate at small angles $\pm\theta$ relative to the z-axis such that their interference intensity forms a 1D grating with a wave vector in the x direction, which is parallel to the crystalline c-axis. The beams are polarized (approximately) in the x direction, taking advantage of the typically large r_{33} electro-optic coefficient.[11] Let the joint slowly varying amplitude representing the beams be written as $\Psi(x,y,z)=A(y,z)\exp(ik_x x)+B(y,z)\exp(-ik_x x)$, where A and B are the beams' complex amplitudes and k_x is the transverse wavenumber. In this geometry, the

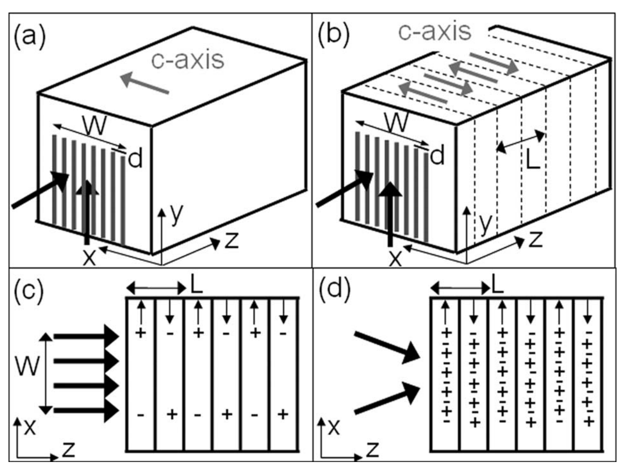

Fig. 1. Top, scheme for mutually coherent beams propagating in (a) a homogeneously poled crystal and (b) a periodically poled crystal. Bottom, scheme for photovoltaic charge separation due to (c) a uniform beam and (d) an interference pattern.

steady-state nonlinear index change is given by[12–14]

$$\Delta n = -\frac{1}{2}{n_0}^3 r_{33} \frac{E_{\mathrm{PV}} I + E_D \mathrm{d}I/\mathrm{d}x}{|A|^2 + |B|^2 + I_{\mathrm{dark}}}, \tag{1}$$

where n_0 is the linear index of refraction; E_D and E_{PV} are the diffusion and photovoltaic fields, respectively; and I_{dark} is the dark irradiance. Inserting $I=|\Psi|^2 =|A|^2+|B|^2+AB^* \exp(2ik_x x)+A^* B \exp(-2ik_x x)$ into Eq. (1) leads to

$$\Delta n = -\frac{1}{2}{n_0}^3 \frac{\delta_1 + \delta_2 + \delta_3}{|A|^2 + |B|^2 + I_{\mathrm{dark}}}. \tag{2}$$

The term $\delta_1=r_{33}E_{\mathrm{PV}}(|A|^2+|B|^2)$ arises from the photovoltaic space-charge field produced by the transversally averaged intensity pattern, and it gives rise to equal SPM and XPM nonlinearities. The terms δ_2 and δ_3, on the other hand, both involve a grating. The term $\delta_2=r_{33}E_{\mathrm{PV}}[AB^* \exp(2ik_x x)+c.c.]$ represents an induced index grating that is in phase (or π out of phase) with respect to the intensity grating in I; this term leads to a solely XPM (holographic) nonlinearity.[2,15,16] The last term, $\delta_3 =2ik_x r_{33}E_D[AB^* \exp(2ik_x x)-c.c.]$, results from the diffusion space-charge field, and it represents an index grating that is $\pm\pi/2$ phase shifted relative to the intensity grating. Consequently, this term yields a unidirectional energy exchange between the beams.[17,18]

Consider now two beams interacting in the same configuration but propagating in a periodically poled photovoltaic crystal (e.g., PPLN), as shown schematically in Fig. 1(b). Assume also that the periodic poling is at a 50% duty cycle, with a wave vector along z and periodicity L, where L is much larger than the period of the intensity grating, $L \gg d$, and much smaller than the transverse width of the beam in the x direction, $W \gg L$. For example, possible values are $d \approx 2$ μm, $L \approx 50$ μm, and $W=3$ mm. It is well established, both theoretically and experimentally, that under these conditions the effect of δ_1 is significantly suppressed[12,19–21] and the effect of δ_3 is averaged out,[12,20] while at the same time the solely cross-phase-modulated holographic nonlinearity arising from δ_2 remains practically unaffected by the periodic poling.[12,19–21] Below, we give a qualitative explanation for these effects.

We first elucidate the effect of the periodic poling on the photovoltaic nonlinearity (δ_1 and δ_2). The direction of the photovoltaic field depends on the crystalline c-axis, and hence it has opposite signs at adjacent domains and vanishes in the interfaces.[12,21] The relevant steady-state photovoltaic field is associated with charge separation along the $c \| x$-axis. The distance that the charges are separated is comparable to the length scale of the relevant intensity variations. In the case of δ_1, the relevant length is the width of the beam, which is much larger than the poling periodicity ($W \gg L$). Hence, the photovoltaic field, and consequently the photovoltaic–photorefractive effect (manifested in δ_1), is considerably suppressed by the rapid sign alternation of charges at the beam boundary [Fig. 1(c)]. In δ_2, on the other hand, the relevant length scale is the periodicity of the intensity grating, which is much smaller than the poling periodicity ($d \ll L$). Hence, the photovoltaic field is suppressed only in narrow regions near the domain interfaces, while within the domains its absolute value is practically unaffected [Fig. 1(d)].[12,19–21] Moreover, the sign of δ_2 does not depend on the poling direction, because the signs of both the photovoltaic field and the electro-optic coefficient, r_{33}, are opposite in antiparallel domains. Thus, δ_2 is practically unaffected by the poling periodicity.[12,19–21] The absolute value of δ_3 is independent of the poling direction, yet its sign is opposite in antiparallel domains (because the diffusion field is independent of the crystalline axes, hence the sign of δ_3 follows the sign alternation of r_{33}). Consequently, the effect caused by δ_3 (asymmetric energy exchange, e.g., from A to B) is averaged out throughout propagation, because energy is transferred in opposite directions in antiparallel domains.[12,20]

Having elucidated that $\delta_1 \sim 0$ and $\langle\delta_3\rangle_z=0$, we now show that the remaining δ_2 term indeed gives rise to a solely XPM interaction between the beams. The paraxial time-independent propagation of the joint slowly varying amplitude is described by the following (2+1)D equation:

$$i\frac{\partial \Psi}{\partial z} + \frac{1}{2k}\nabla_\perp^2 \Psi + \frac{k\Delta n}{n_0}\Psi = 0, \tag{3}$$

where $k=2\pi n_0/\lambda$ with λ being the wavelength at vacuum. Inserting Ψ and Δn into Eq. (3) and selecting only synchronous terms leads to

$$i\frac{\partial A}{\partial z} + \frac{1}{2k}\frac{\partial^2 A}{\partial y^2} + \Delta n_0 \frac{|B|^2}{|A|^2 + |B|^2 + I_{\mathrm{Dark}}} A = 0,$$

$$i\frac{\partial B}{\partial z} + \frac{1}{2k}\frac{\partial^2 B}{\partial y^2} + \Delta n_0 \frac{|A|^2}{|A|^2 + |B|^2 + I_{\mathrm{Dark}}} B = 0, \tag{4}$$

where $\Delta n_0=-\pi {n_0}^3 r_{33}E_{\mathrm{PV}}/\lambda$. Clearly, the nonlinearity is saturable and is solely XPM. Hence, if the beams are narrow in y, then both beams experience mutual focusing–defocusing in y. The focusing results from the induced grating (hologram), which is periodic in the direction perpendicular to the focusing direction and hence was termed holographic focusing.[15,16] Moreover, for such a set of equations, holographic solitons[2] [stationary mutually trapped solutions of Eq. (4)], as well as more complex structures such as multimode[7] and dissipative holographic solitons,[22] are known to exist.

Next, we demonstrate a numerically bright holographic soliton in our system. Having in mind PPLN, we use the following experimental parameter values: $n_0=2.2$, $\lambda=0.5$ μm, $d=2$ μm ($\theta\sim\pm 6.5°$), $L=50$ μm, $|r_{33}|=30$ pm/V, $E_D=0.8$ kV/cm, and $|E_{\mathrm{PV}}|=20$ kV/cm. We simulate Eq. (3) with initial excitation $\Psi(x,y,z=0)=U(y)\cos(k_x x)$ (i.e., setting $A=B=U/2$), where U is the solution (wave function) found for the bright holographic soliton.[2] The nonlinearity is given by Eq.

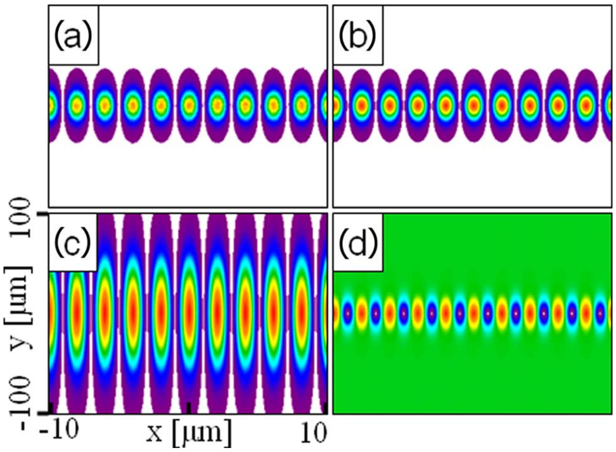

Fig. 2. (Color online) Holographic soliton in a periodically poled phovoltaic photorefractive crystal. (a) Intensity of the beam launched into the medium in the presence of 10% noise. (b), (c) Output intensity after $z=2$ cm: (b) nonlinear and (c) linear propagation. (d) Index structure induced by the holographic soliton beam.

(2) with $\delta_1=0$, and the signs of r_{33} and E_{PV} alternate every $L/2$. As an example, Fig. 2 presents a holographic soliton with $U(0)=\sqrt{I_{\text{Dark}}}/4$ having FWHM $=22$ μm. To test the stability of these solitons, we simulate the propagation of holographic solitons in such a PPLN system in the presence of noise, launching the soliton waveform embedded in noise at the level of 10% of the peak intensity. The noisy intensity at $z=0$ is shown in Fig. 2(a). We observe that the noise radiates away after ~1 mm propagation, after which the beam demonstrates stationary propagation. The intensities of the soliton beam and the linearly propagating beam (which experience diffraction broadening) at $z=2$ cm are shown in Figs. 2(b) and 2(c), respectively. Finally, Fig. 2(d) shows the induced index change (with $\delta_3=0$) displaying the shape of a grating mediated waveguide of the first type.[23]

In conclusion, we have shown that periodically poled photovoltaic photorefractives can exhibit a nonlinearity involving solely XPM between two beams. The conditions for such solely XPM conditions are that the poling periodicity is much smaller than the width of the interacting beams but much larger than the period of the interference grating they form, i.e., $W \gg L \gg d$. We expect that relaxing this condition will lead to continuous control of the ratio between the SPM and the XPM nonlinearities. Finally, we numerically demonstrated that this nonlinearity in periodically poled crystals gives rise to stable holographic solitons. We believe that Thirring-type holographic solitons will soon be demonstrated. A potentially important property of these solitons is their ability to facilitate instantaneous switching in a slow response nonlinearity.[2]

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References

1. G. P. Agrawal, *Nonlinear Fiber Optics*, 2nd ed. (Academic, 1995), Chap. 7.
2. O. Cohen, T. Carmon, M. Segev, and S. Odoulov, Opt. Lett. **27**, 2033 (2002).
3. D. R. Walker, D. D. Yavuz, M. Y. Sheverdin, G. Y. Yin, A. V. Sokolov, and S. E. Harris, Opt. Lett. **27**, 2094 (2002).
4. D. D. Yavuz, D. R. Walker, and M. Y. Sheverdin, Phys. Rev. A **67**, 041803(R) (2003).
5. H. Kang and Y. Zhu, Phys. Rev. Lett. **91**, 093601 (2003).
6. I. Friedler, G. Kurizki, O. Cohen, and M. Segev, Opt. Lett. **30**, 3374 (2005).
7. J. R. Salgueiro, A. A. Sukhorukov, and Y. S. Kivshar, Opt. Lett. **28**, 1457 (2003).
8. Note the similarity between the two beam interaction in the solely XPM system and three-wave parametric interactions in quadratic media in the limit of large phase mismatch, as pointed out in Refs. 2 and 7.
9. W. Thirring, Ann. Phys. (N.Y.) **3**, 91 (1958).
10. A. V. Mikhailov, JETP Lett. **23**, 320 (1976).
11. In lithium niobate r_{51} is comparable to r_{33}. However, its contribution to the nonlinearity is negligible because (a) $G_{23}=0$, hence there is no photovoltaic field in the y and z directions, and (b) $\mathrm{d}I/\mathrm{d}z$, $\mathrm{d}I/\mathrm{d}y \ll \mathrm{d}I/\mathrm{d}x$.
12. G. C. Valley, M. Segev, B. Crosignani, A. Yariv, M. Fejer, and M. Bashaw, Phys. Rev. A **50**, R4457 (1994).
13. M. Taya, M. C. Bashaw, and M. M. Fejer, Opt. Lett. **21**, 857 (1996).
14. M. Segev, M. C. Bashaw, G. C. Valley, M. M. Fejer, and M. Taya, J. Opt. Soc. Am. A **14**, 1772 (1997).
15. O. Cohen, R. Uzdin, T. Carmon, J. W. Fleischer, M. Segev, and S. Odoulov, Phys. Rev. Lett. **89**, 133901 (2002).
16. O. Cohen, S. Lan, T. Carmon, J. A. Giordmaine, and M. Segev, Opt. Lett. **27**, 2013 (2002).
17. B. I. Sturman and V. M. Fridkin, *The Photovoltaic and Photorefractive Effect in Noncentrosymmetric Materials* (Gordon & Breach, 1992).
18. L. Solymar, D. J. Webb, and A. Grunnet-Jepsen, *The Physics and Applications of Photorefractive Materials* (Oxford U. Press, 1996).
19. B. Sturman, M. Aguilar, F. A. Lopez, V. Pruneri, P. G. Kazansky, and D. C. Hanna, Appl. Phys. Lett. **69**, 1349 (1996).
20. S. Odoulov, T. Tarabrova, A. Shumelyuk, I. I. Naumova, and T. O. Chaplina, Phys. Rev. Lett. **84**, 3294 (2000).
21. B. Sturman, M. Aguilar, F. A. Lopez, V. Pruneri, and P. G. Kazansky, J. Opt. Soc. Am. B **14**, 2641 (1997).
22. J. S. Liu, Opt. Lett. **28**, 2237 (2003).
23. O. Cohen, B. Freedman, J. W. Fleischer, M. Segev, and D. N. Christodoulides, Phys. Rev. Lett. **93**, 103902 (2004).