Spatial vector solitons consisting of counterpropagating fields

Oren Cohen

Department of Physics and Solid State Institute, Technion, Haifa 32000, Israel

Song Lan

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

Tal Carmon

Department of Physics and Solid State Institute, Technion, Haifa 32000, Israel

J. A. Giordmaine

Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544, and NEC Research Institute, Princeton, New Jersey 08540

Mordechai Segev

Department of Physics and Solid State Institute, Technion, Haifa 32000, Israel, and Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544

Received May 16, 2002

We present the experimental observation of a spatial vector soliton formed by counterpropagation of coherent optical fields. This is to our knowledge the first observation of a vector soliton in which the induced waveguide (potential) is periodic in the propagation direction. This vector soliton induces a waveguide and a thick grating within the waveguide, which can be used as a tunable optical waveguide filter.

OCIS codes: 260.5950, 190.4420.

Vector solitons are solitons that consist of two (or more) components that jointly self-trap in a nonlinear medium.[1] Thus far, all experimental observations of spatial vector solitons have displayed a multicomponent localized wave packet whose intensity induces a waveguide that is nonvarying in the propagation direction and whose field components properly populate the guided modes of the induced waveguide.[2] To meet these two requirements, several techniques were proposed and demonstrated.[3–9] These techniques share one common feature: The induced waveguide (potential) is not affected by interference between different field components. The first method employs orthogonally polarized components.[3–5] In the second, each field component is at a different frequency, and the frequency difference between components is either wide enough that the components propagate in an asynchronous fashion[6,7] or much larger than τ^{-1}, where τ is the response time of the nonlinearity. In the third method the components are incoherent with one another; that is, the relative phases between the components vary much faster than τ, hence averaging out the contributions of interference terms.[8,9] Thus far, all experimentally observed vector solitons have consisted of field components that propagate in the same direction. All the techniques mentioned above rely on components that interact (bind to form solitons) only through the sum of their intensities; therefore, vector solitons consist of counterpropagating components (for which interference terms do not contribute) can be trivially constructed as well. In contrast to these, a completely different kind of vector soliton, a vector soliton consisting of interfering counterpropagating fields, has been suggested.[10] Reference 10 showed theoretically that two counterpropagating field components that interfere and form a grating in a Kerr medium, thereby inducing an index change that is stationary in the transverse direction but periodic along the propagation axis, can jointly form a vector soliton. It is a vector soliton that is conceptually different from all those observed thus far.[3–9]

Here we present the experimental observation of a spatial vector soliton formed by counterpropagating coherent optical fields. This is to our knowledge the first vector soliton in which the induced waveguide (potential) is periodic in the propagation direction. We generalize the Kerr-media theory of Ref. 10 to describe such vector solitons to general local nonlinearities, and we specifically solve for the case of photorefractive screening nonlinearity.

We begin by deriving the equations that govern the evolution of the envelopes of two counterpropagating $(1 + 1)D$ mutually coherent beams in a general local nonlinear medium whose refractive index is $n(x,z) = n_0 + \Delta n[I(x,z)]$, where n_0 is the linear refractive index, Δn is the index change, I is the intensity, and z and x are the propagation and the transverse directions, respectively. Consider the scheme shown in Fig. 1(a). Two mutually coherent

0146-9592/02/222013-03$15.00/0

beams enter a self-focusing medium from the opposite faces. The scalar optical field, E, can be written as a sum of forward (F) and backward (B) waves: $E = F(x,z)\exp[i(kz - \omega t)] + B(x,z)\exp[-i(kz + \omega t)] + \text{c.c.}$ The wave vector is $k = \omega n_0/c$, ω is the temporal frequency, and c is the speed of light in vacuum. To within a proportionality factor, the time-averaged intensity is $I \propto |E|^2 = |F|^2 + |B|^2 + F^*B\exp(-2ikz) + B^*F\exp(2ikz)$. Within the slowly varying amplitude approximation the intensity is periodic in z, with period $\Lambda = \pi/k$. Because Δn depends solely on the intensity, it is also periodic in z and can be Fourier expanded:

$$\Delta n(x,z) = \Delta n_0 \sum_{m=-\infty}^{m=\infty} C_m(F,B)\exp(2imkz). \qquad (1)$$

In a local focusing medium Δn_0 is a real constant and $C_m = (C_{-m})^*$. To study the time-harmonic propagation we substitute E into the Helmholtz equation. Assuming that $|\Delta n| \ll n_0$, applying the paraxial approximation, and selecting synchronous terms lead to

$$\frac{\partial^2 F}{\partial x^2} + 2ik\frac{\partial F}{\partial z} = -\frac{2k^2\Delta n_0}{n_0}(C_0F + C_1B),$$

$$\frac{\partial^2 B}{\partial x^2} - 2ik\frac{\partial B}{\partial z} = -\frac{2k^2\Delta n_0}{n_0}(C_0B + C_{-1}F). \qquad (2)$$

In Eqs. (2), there are two nonlinear terms for each beam. The first terms, C_0, reflect an average value of Δn (averaged along z). These C_0 terms represent the waveguide induced by both beams that can guide other beams at a frequency that may be different from that of F and B, just like any soliton-induced waveguide. The second terms on the right-hand sides of Eqs. (2) result from the periodic modulation in Δn along z, which couples the two beams through Bragg reflections. A portion of the forward-propagating F beam is Bragg reflected backward and is added coherently to the B beam propagating in the $-z$ direction. At the same time, a portion of B is Bragg reflected to propagate in the $+z$ direction and is added coherently to F. These Bragg-reflected beams are $\pi/2$ phase retarded relative to the primary beams into which they are reflected.[11] As the Bragg-reflected beams are added to the primary beams, they effectively slow down the phase velocities of the total beams, which is equivalent to increasing the refractive index. Because the effect is more intense at the center of the beams than at the beams' margins, it reduces the natural beam divergence. We termed this focusing mechanism holographic focusing.[12] In contrast to conventional focusing, holographic focusing occurs only for those beams that induce the hologram.

For photorefractive screening nonlinearity,[13,14] $\Delta n = -\Delta n_0/(1 + I/I_B)$, where I_B is the background intensity (or the dark irradiance); hence the coefficients are

$$C_0 = -\{[1 + (|f| + |b|)^2][1 + (|f| - |b|)^2]\}^{-1/2},$$

$$C_1 = \frac{-fb^*}{2|f|^2|b|^2}[1 + C_0(1 + |f|^2 + |b|^2)],$$

and $C_{-1} = C_1{}^*$, where f and b are the forward- and backward-normalized complex envelopes, $f = F/\sqrt{I_B}$ and $b = B/\sqrt{I_B}$, respectively. We seek solutions that possess the same transverse wave function, of the form $f = u(x)\exp(-i\beta z)$ and $b = u(x)\exp(i\beta z)$. Transforming Eqs. (2) into normalized units, $\zeta = (k\Delta n_0/n_0)z$ and $\xi = \sqrt{2k^2\Delta n_0/n_0}x$, and substituting the above ansatz and coefficients yield

$$u'' + \beta u - \frac{1}{2u} + \frac{1}{2u\sqrt{1 + 4u^2}} = 0. \qquad (3)$$

Employing the quadrature method[13] for Eq. (3), we obtain the soliton wave functions shown in Fig. 1(b) for several values of u_0, where $u_0 = u(0)$ and the existence curve is shown in Fig. 1(c).

The experimental setup is shown in Fig. 2. An Ar^+ laser beam at 488 nm is split equally into two beams, 1 and 2, that are focused to narrow stripes (15-μm FWHM) on the opposite faces, A and B, of an SBN:60 crystal [4.5 mm × 10 mm × 5 mm ($a \times b \times c$)] in the configuration appropriate for photorefractive screening solitons.[15] Two cameras image the two faces of the crystal. Note that the light gathered by each camera consists of both a transmitted beam and a back-reflected beam. The ratio of the peak intensity of each beam to the background intensity is 20.

Figures 3a and 3b show the image and the intensity profiles taken by camera A at input face B and at output face A, respectively, when beam 1 is blocked and the nonlinearity is off. When we let the two beams propagate and turn on the nonlinearity (by applying an external voltage of 900 V), the beams mutually self-trap (Fig. 3c). The width (FWHM) of this combined beam is 15 μm, equal to the FWHM of each of the input beams at both surfaces. Thus the combined wave, consisting of both counterpropagating beams, forms a vector soliton at the specific value of nonlinearity determined by the applied field, the

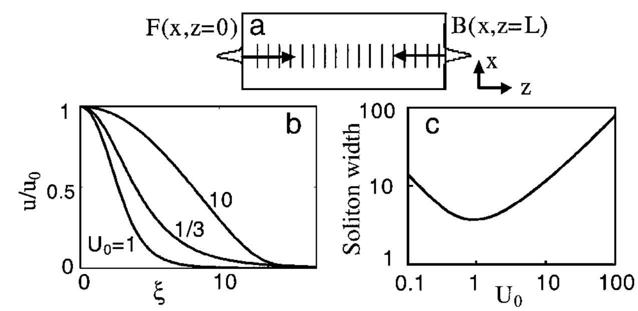

Fig. 1. a, Schematic of a spatial vector soliton formed by counterpropagating fields. b, Normalized vector soliton wave function versus dimensionless length ξ for several values of peak amplitude (u_0). c, FWHM of the intensity of the vector soliton versus u_0.

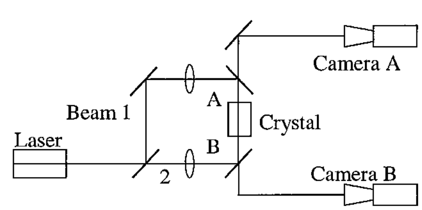

Fig. 2. The experimental setup.

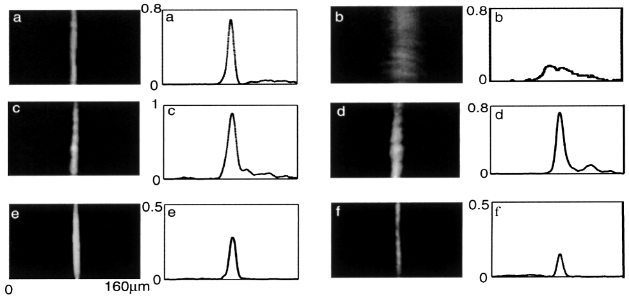

Fig. 3. Experimental results: Images and intensity profiles taken by camera A (of Fig. 2). Intensities of beam 2 at a, the input (left) and b, the output (right) surfaces of the crystal when beam 1 is blocked and the nonlinearity is off. c, Total intensity of the vector solitons at the left face of the crystal. d, Intensity at the left surface when beam 1 is blocked and the nonlinearity is on, showing that, at this value of nonlinearity, beam 2 alone does not form a soliton. e, Reflections of beam 1 by both the surfaces and the grating. f, Reflection of beam 1 by the surfaces alone.

intensity ratio, and the crystal parameters (refractive index and electro-optic coefficient). To exemplify the fact that the vector soliton is formed by both counterpropagating components, we block beam 1 and observe the output of beam 2 without changing the voltage (i.e., for the same value of nonlinearity used to generate the vector soliton). The result is shown in Fig. 3d, where the output is now 18 μm FWHM (compared to the 15-μm input), with some irregularities on its beam profile.

To prove the existence of periodic modulation along the propagation axis of the solitons, that is, a grating within the soliton-induced waveguide, we examine the reflection of beam 1 when beam 2 is blocked. First we form the vector solitons and let the photorefractive nonlinearity reach its steady state, at which both the induced waveguide and the grating within it are set. Next, we block beam 2 and, within a time window much shorter than the response time of the nonlinearity ($\sim$1 s at our intensities of 1 W/cm^2) but longer than the CCD response time ($\sim$1 ms), we monitor the reflection of beam 1. The reflection (Fig. 3e) contains reflections from the input and output surfaces as well as the Bragg reflection off the grating. Roughly 33% of the power of beam 1 is reflected. Finally, to distinguish between the surface reflections and the Bragg reflection we let the grating completely decay (by waiting a few minutes after beam 2 is blocked) and then monitor the surface reflections alone (Fig. 3f). The difference between Figs. 3e and 3f gives the grating reflection, which turns out to be $\sim$19% reflection efficiency. This established that the index grating within the soliton-induced waveguide is rather efficient.

Before closing, we note that the optically induced grating inside the soliton-induced waveguide can act as an optical waveguide filter. Such a dynamic waveguide filter can be used as a highly selective and narrow-bandwidth optical fiber, which we can tune in real time by varying the soliton parameters. Waveguide filters are important components of planar light-wave circuits. Narrow-band waveguide filters are generally nontunable and are sensitive to fabrication errors. Soliton-induced waveguide filters can offer much flexibility by being adjustable and tunable in real time and at the same time robust against fabrication errors, index inhomogeneities, etc.

In conclusion, we have demonstrated a vector soliton formed by counterpropagating of coherent beams that induce a periodic index grating along the propagation axis.

This work was supported by the Israeli Science Foundation, by the U.S. Army Research Office, and by the MURI program on optical spatial solitons. O. Cohen and T. Carmon gratefully acknowledge the support of the Eshkol Fellowship.

References

1. See the review in G. I. Stegeman and M. Segev, Science **286,** 1518 (1999).
2. A. W. Snyder, S. J. Hewlett, and D. J. Mitchell, Phys. Rev. Lett. **72,** 1012 (1994).
3. S. V. Manakov, Sov. Phys. JETP **38,** 248 (1974).
4. J. U. Kang, G. I. Stegeman, J. S. Aitchison, and N. Akhmediev, Phys. Rev. Lett. **76,** 3699 (1996).
5. M. Segev, G. C. Valley, S. R. Singh, M. I. Carvalho, and D. N. Christodoulides, Opt. Lett. **20,** 1766 (1995).
6. S. Trillo, S. Wabnitz, E. M. Wright, and G. I. Stegeman, Opt. Lett. **13,** 871 (1988).
7. M. Shalaby and A. J. Barthelemy, IEEE J. Quantum Electron. **28,** 2736 (1992).
8. D. N. Christodoulides, S. R. Singh, M. I. Carvalo, and M. Segev, Appl. Phys. Lett. **68,** 1763 (1996).
9. Z. Chen, M. Segev, T. Coskun, and D. N. Christodoulides, Opt. Lett. **21,** 1436 (1996).
10. M. Haelterman, A. P. Sheppard, and A. W. Snyder, Opt. Commun. **103,** 145 (1993).
11. For plane waves and a fixed grating this $\pi/2$ retardation was obtained analytically; see H. Kogelnik, Bell Syst. Tech. J. **48,** 2909 (1969).
12. O. Cohen, R. Uzdin, T. Carmon, J. W. Fleischer, M. Segev, and S. Odoulov, Phys. Rev. Lett. **89**, 133901 (2002).
13. M. Segev, G. C. Valley, B. Crosignani, P. DiPorto, and A. Yariv, Phys. Rev. Lett. **73,** 3211 (1994).
14. D. N. Christodoulides and M. I. Carvalho, J. Opt. Soc. Am. B **12,** 1628 (1995).
15. M. Shih, M. Segev, G. C. Valley, G. Salamo, B. Crosignani, and P. DiPorto, Electron. Lett. **31,** 826 (1995).