Observation of staggered surface solitary waves in one-dimensional waveguide arrays

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The observation of nonlinear staggered surface states at the interface between a substrate and a one-dimensional self-defocusing nonlinear waveguide array is reported. Launching of staggered input beams of different power in the first channel of the array results in formation of localized structures in different channels. Our experimental results are confirmed numerically. © 2006 Optical Society of America

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As is well established, surface modes are a special type of wave that may exist at the interface between two different media. Historically, investigation of surface modes was initiated by Tamm, who showed that the inclusion of the neglected surface in the Kronig–Penney model may, under certain conditions, result in electronic states localized at the edge of the solid.[1] These waves are explored in both periodic systems such as superlattices[2] and nonperiodic systems, for example, water–air interfaces.[3] From the practical point of view, Tamm states could be implemented for the fabrication of polariton lasers[4] and optical modulators or filters.[5] In optics, these surface waves have been studied in both linear and nonlinear media. For a linear medium, Kossel has suggested that localized states could exist near the boundary between a homogeneous and a layered medium.[6] Similarly, the propagation of electromagnetic surface waves guided by the boundary of a semi-infinite periodic multilayered medium was investigated in Ref. 7, in which the corresponding propagation eigenvalues of linear surface waves in periodic media were found in the forbidden band. On the other hand, optical surface waves can also exist as an outcome of material nonlinearity, where no counterpart exists in the linear domain. Such nonlinear waves have been investigated at the interface between two dielectrics[8] and at the interface between left- and right-handed materials,[9] to mention a few.

The existence of optical Tamm states near the edge of a nonlinear waveguide array (WA) was predicted in Ref. 10. Such nonlinear surface states have been observed recently in an AlGaAs WA exhibiting a self-focusing cubic nonlinearity.[11] A crossover from nonlinear surface states to discrete solitons[12–17] in both self-focusing and self-defocusing WAs with cubic nonlinearity was studied numerically by Molina *et al.*[18] For a defocusing nonlinearity, light localization at the surface occurs within the bandgap of the periodic material, where the nonlinear modes have a staggered form. The existence of these staggered nonlinear surface modes, already mentioned in Ref. 10, has recently been studied theoretically in more detail by Kartashov *et al.*[19] In this Letter, we investigate both experimentally and numerically the dynamics of nonlinear surface states at the interface between a substrate and a WA in copper-doped photovoltaic lithium niobate (LN) crystals exhibiting both saturation of refractive index change and self-defocusing nonlinearity.[13,17,20,21]

Our sample is an 11 mm long copper-doped LN crystal with approximately 250 parallel waveguides. The channel waveguides are fabricated by indiffusion of titanium, which increases the refractive index with respect to the substrate index. Detailed information on the fabrication conditions can be found in Ref. 17. The width and height of the single-mode channel waveguides are 4 μm and 2.5 μm, respectively, while the distance between two adjacent channels is 4.4 μm. The Cu^{+} concentration equals $0.66 \times 10^{24}\,\mathrm{m}^{-3}$, while the coupling length is $L_c = 1.1$ mm. The experimental setup is sketched in Fig. 1. The green light of a $Nd:YVO_4$ laser at wavelength $\lambda = 532$ nm is split into two beams by means of a Mach–Zehnder interferometer. The two beams of equal power overlap under a small angle and are coupled into the WA by use of a 40× microscope lens. The grating period of the interference pattern is adjusted to match the grating period of the array ($\Lambda = 8.4\ \mu$m). This input pattern has an elliptical shape whose

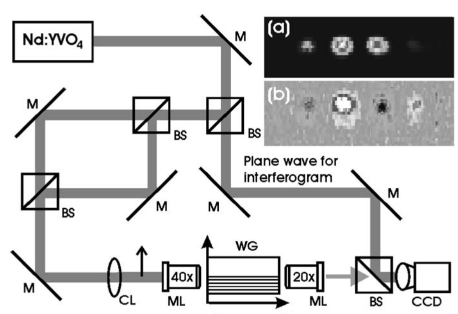

Fig. 1. Experimental setup: M, mirror; BS, beam splitter; CL, cylindrical lens; ML, microscope lens; WA, waveguide array; CCD, CCD camera. Inset: (a) observed (nonlinear) output from the array, and (b) corresponding interference picture.

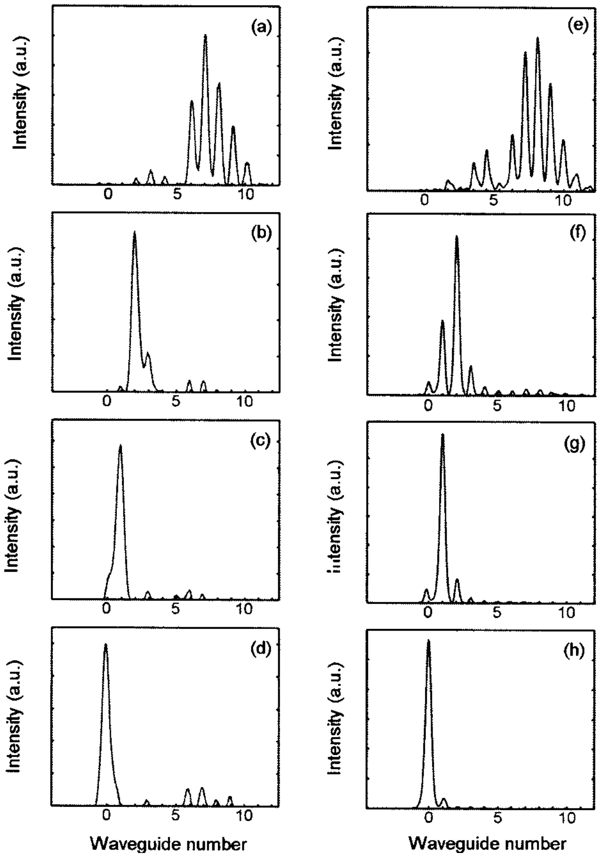

Fig. 2. Output patterns for staggered input excitation of three channels (intensity ratio 1:0.5:0.1) at four different input powers. Left column: experimental results for (a) discrete diffraction (low-power regime), (b) $P=9\ \mu\mathrm{W}$, (c) $P=22.5\ \mu\mathrm{W}$, and (d) $P=225\ \mu\mathrm{W}$. Right column: simulation results for (e) linear discrete diffraction, (f) $P=10\ \mu\mathrm{W}$, (g) $P=22\ \mu\mathrm{W}$, and (h) $P=230\ \mu\mathrm{W}$.

height matches the depth of each waveguide (approximately 2.5 μm). In this way a staggered input pattern is obtained that consists of a central maximum and a small number of next neighbors that are phase shifted by π relative to the center. We adjust the sample to match the maximum of the staggered input and the first channel of the array. The intensity ratio of next neighbors (with respect to the central maximum) can be adjusted by changing the ellipticity of the input beam by use of cylindrical lens CL. On the other hand, single-channel excitation can be obtained by blocking one beam of the interferometer.

The output light is imaged onto a CCD camera by a 20× microscope lens. In the inset in Fig. 1 the interferogram shows that the localized structures at the output are indeed of staggered form. To obtain the interferogram we interfere a plane wave with the output image, which in the case shown has a maximum at the second channel.

In the left column of Fig. 2 we present typical experimental results for staggered input profiles covering three channels with intensity ratios 1:0.5:0.1. One can recognize the linear regime of discrete diffraction [Fig. 2(a)],[15] intermediate states close to the edge of the array [Figs. 2(b) and 2(c)], and highly nonlinear surface states residing in the first channel of the array [Fig. 2(d)].[10,11,18] The amplitudes are normalized with respect to the highest power that was necessary to form a discrete surface solitary wave in Fig. 2(d). In full analogy with Ref. 18, we have observed the same behavior as the maximum of the input beam moves away from the edge of the array but for lower input light power, $P=195\ \mu\mathrm{W}$.

Scalar wave propagation in a nonlinear one-dimensional waveguide array can be modeled within the paraxial approximation by

$$i\frac{\partial E}{\partial y}+\frac{1}{2k}\frac{\partial^2 E}{\partial z^2}+k\frac{n(z)+\Delta n_{\mathrm{nl}}}{n_s}E=0. \tag{1}$$

The amplitude of the optical field is denoted by E, while $k=2\pi n_s/\lambda$ represents the wavenumber. Here, $n_s=2.2341$ is the substrate refractive index and λ is the wavelength of light in vacuum. The periodically modulated refractive index is denoted by $n(z)$, while Δn_{nl} is the nonlinear index change ($\Delta n_{\mathrm{nl}} \ll n_s$). This effective waveguide array can be approximated by $n(z)=2.2341+0.0037\cos^2(\pi z/\Lambda)$. The ferroelectric c-axis points along the transverse z-axis, and, as our sample is x-cut, the propagation direction is along the y-axis.

To check our experimental results we performed numerical simulations based on a nonlinear beam propagation method. We used the parameters of our

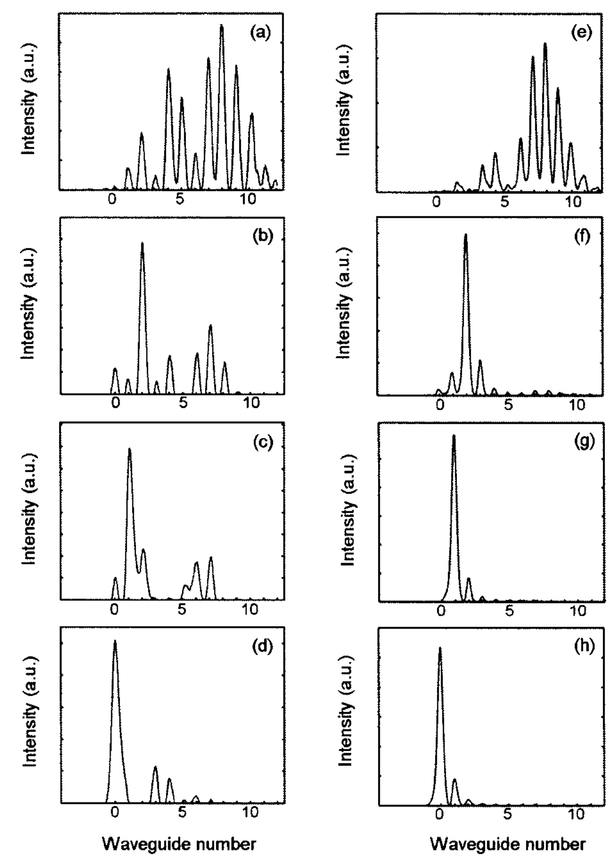

Fig. 3. Output patterns for single-channel excitation and four different input powers. Left column: experimental results for (a) discrete diffraction, (b) $P=32.5\ \mu\mathrm{W}$, (c) $P=270\ \mu\mathrm{W}$, and (d) $P=450\ \mu\mathrm{W}$. Right column: simulation results for (e) discrete diffraction, (f) $P=32\ \mu\mathrm{W}$, (g) $P=275\ \mu\mathrm{W}$, and (h) $P=450\ \mu\mathrm{W}$.

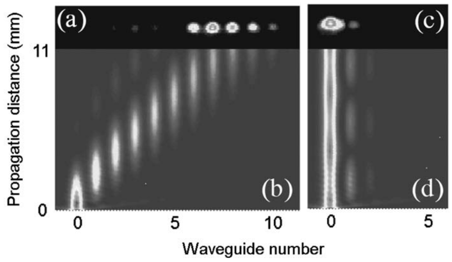

Fig. 4. Comparison of (a), (c) experimental and (b), (d) numerical results for single-channel excitation: (a), (b) Discrete diffraction and (c), (d) localization at $P=490\ \mu$W.

WA and a saturable defocusing nonlinearity of the form $\Delta n_{\mathrm{nl}}=\Delta n_0 I/(I+I_d)$, with $|\Delta n_0|\leq 0.002$ and $I/I_d=4$, where I_d is the dark irradiance and I is the light intensity. Results that fit nicely to our experimental results are also given in Fig. 2 (right column). Here we used a Gaussian beam width (FWHM) of 3.6 μm for the input into each channel and the same intensity ratios 1:0.5:0.1 as in the experiment.

A second set of experiments was performed using single-channel excitation.[11] The results are presented in Figs. 3(a)–3(d). The corresponding numerical results are shown in Figs. 3(e)–3(h). Once again, we observe discrete diffraction [Figs. 3(a) and 3(e)], multiple localized states near the edge of the nonlinear WA [Figs. 3(b), 3(c), 3(f), and 3(g)], as well as strongly localized surface modes [Figs. 3(d) and 3(h)]. Here the corresponding power necessary to obtain a discrete soliton in the center of the array is only $P\approx 390\ \mu$W. In Fig. 4 we present a comparison between experiment (top) and numerics (bottom) for single-channel excitation. The agreement between our experimental and numerical results is fairly good in both the linear (discrete diffraction) regime [Figs. 4(a) and 4(b)] and the strongly nonlinear (surface soliton) regime [Figs. 4(c) and 4(d)].

To summarize, we have experimentally observed staggered surface states (nonlinear Tamm states) in the vicinity of the interface between a homogeneous medium (substrate) and a semi-infinite periodic medium with defocusing nonlinearity. Moreover, we also confirmed the existence of localized structures at different positions of the array by changing only the power of the input beam.

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References

1. I. Tamm, Phys. Z. Sowjetunion **1**, 733 (1932).
2. H. Ohno, E. E. Mendez, J. A. Brum, J. M. Hong, F. Agulló-Rueda, L. L. Chang, and L. Esaki, Phys. Rev. Lett. **64**, 2555 (1990).
3. D. Middleton and R. H. Mellen, J. Acoust. Soc. Am. **90**, 741 (1991).
4. A. Kavokin, I. Shelykh, and G. Malpuech, Appl. Phys. Lett. **87**, 261105 (2005).
5. K. Mehrany, S. Khorasani, and B. Rashidian, Semicond. Sci. Technol. **18**, 582 (2003).
6. D. Kossel, J. Opt. Soc. Am. **56**, 1434 (1966).
7. P. Yeh, A. Yariv, and C.-S. Hong, J. Opt. Soc. Am. **67**, 423 (1977).
8. W. J. Tomlinson, Opt. Lett. **5**, 323 (1980).
9. I. V. Shadrivov, A. A. Sukhorukov, Yu. S. Kivshar, A. A. Zharov, A. D. Boardmann, and P. Egan, Phys. Rev. E **69**, 016617 (2004).
10. K. G. Makris, S. Suntsov, D. N. Christodoulides, G. I. Stegeman, and A. Haché, Opt. Lett. **30**, 2466 (2005).
11. S. Suntsov, K. G. Makris, D. N. Christodoulides, G. I. Stegeman, A. Haché, R. Morandotti, H. Yang, G. Salamo, and M. Sorel, Phys. Rev. Lett. **96**, 063901 (2006).
12. D. N. Christodoulides and R. I. Joseph, Opt. Lett. **13**, 794 (1988).
13. Yu. S. Kivshar, Opt. Lett. **18**, 1147 (1993).
14. H. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81**, 3383 (1998).
15. N. K. Efremidis, S. Sears, D. N. Christodoulides, J. W. Fleischer, and M. Segev, Phys. Rev. E **66**, 046602 (2002).
16. M. Stepić, D. Kip, Lj. Hadžievski, and A. Maluckov, Phys. Rev. E **69**, 066618 (2004).
17. F. Chen, M. Stepić, C. E. Rüter, D. Runde, D. Kip, V. Shandarov, O. Manela, and M. Segev, Opt. Express **13**, 4314 (2005).
18. M. I. Molina, R. A. Vicencio, and Yu. S. Kivshar, Opt. Lett. **31**, 1693 (2006).
19. Y. V. Kartashov, V. A. Vysloukh, and L. Torner, Phys. Rev. Lett. **96**, 073901 (2006).
20. K. Peithmann, J. Hukriede, K. Buse, and E. Krätzig, Phys. Rev. B **61**, 4615 (2000).
21. Shortly after submission of this Letter we became aware of the following preprint describing similar experimental results: C. R. Rosberg, D. N. Neshev, W. Krolikowski, A. Mitchell, R. A. Vicencio, M. I. Molina, and Yu. S. Kivshar, “Observation of surface gap solitons in semi-infinite waveguide arrays,” arXiv: physics/0603202.