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Multisoliton emission from a nonlinear waveguide

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We demonstrate numerically that external excitation of a nonlinear waveguide can produce sequential threshold behavior via multisoliton emission from the waveguide. This behavior is similar to that predicted to occur at a nonlinear interface.

Following the pioneering work of Kaplan[1] on the reflection of a plane wave from a linear-nonlinear interface, several papers appeared on this subject.[2-9] This interest stemmed from the possibility of bistable reflection from such an interface.[1] Although it is now generally accepted that bistable reflection is not possible (as opposed to a hysteretic response) several of the results from the theoretical studies, such as the nonlinear Goos-Hänchen[7,9] effect and the transmission of self-focused channels (or solitons) through the interface,[2,7] are of interest in their own right. To the best of our knowledge only the former effect has received further attention.

In this Brief Report we consider the external excitation of a nonlinear waveguide (NLWG) where the film and substrate are linear but the cladding displays a nonlinear refractive index (optical Kerr effect). Intuitively one may expect that effects reminiscent of the nonlinear interface problem can arise since the NLWG comprises at least one such interface. Here we report results showing the transmission of solitons through the film-cladding interface, the number and angle of emission of which depends on the input flux. [The input beam profile is held fixed as the zeroth-order transverse-electric (TE) mode of the linear guide.] The flux trapped in the waveguide then shows sequential threshold behavior as a function of the input flux as a result of this multisoliton emission. An intuitive explanation for the thresholds utilizing the NLWG dispersion curve for the system is given. We remark that the emission of a soliton from a NLWG has previously been reported as a route by which unstable nonlinear guided waves (NLGW's) decay.[10] However, in that case the input flux fixes the input beam profile whereas here we hold the input profile fixed which is more in line with experimental procedures. Potential applications of this effect include optical limiting, coupling of adjacent waveguides in the absence of evanescent field overlap, and a light-driven angular scanning element.

We consider TE waves of frequency ω in a slab waveguide, then assuming that the electric field is homogeneous in the y direction (z and x being the propagation and transverse coordinates in units of c/ω) and writing the field as

$$\mathbf{E}(\mathbf{r},t)=\tfrac{1}{2}\mathbf{y}[W(x,z)e^{i(\beta z-\omega t)}+\text{c.c.}] \tag{1}$$

yields the usual slowly varying envelope equation for $W(x,z)$:[11]

$$2i\beta\frac{\partial W}{\partial z}+\frac{\partial^2 W}{\partial x^2}-[\beta^2-n^2(x,|W|^2)]W=0\ . \tag{2}$$

Here the refractive index in the various media is given by

$$n^2(x,|W|^2)=n_\gamma^2+\alpha_\gamma|W(x,z)|^2,\quad \gamma=c,f,s \tag{3}$$

the subscripts c,f,s referring to the cladding ($x\le -d$), film ($-d\le x\le d$), and substrate ($x\ge d$), respectively. For the results presented here we specifically set $n_c=n_s=1.55$, $n_f=1.57$, $\alpha_c=10^{-2}$, and $\alpha_f=\alpha_s=0$, which corresponds to a self-focusing Kerr-type nonlinear cladding.

The NLGW's are found as the solutions of Eq. (2) such that $W(x,z)=W_0(x)$:[12] Equation (2) along with the continuity conditions on the tangential components of the electric and magnetic fields can then be used to generate the dispersion curves (guided wave flux S versus effective index β) for the system. In Fig. 1(a) we show the dispersion curve for the TE_0 NLGW's of a NLWG described by the parameters given above (note that since there is only one nonlinear medium the NLGW is uniquely specified by β). For this particular configuration the negative-slope region of the dispersion curve is unstable under propagation and is indicated by a dashed line, the regions marked I and II are stable.[11] The inset beside each branch shows the general nature of the solution on that branch (e.g., on branch II the solution is concentrated around the film-cladding interface[12]), and the critical flux S_c is that flux above which the NLGW's on branch I cease to exist (for the example here $S_c\cong 0.195$).

Our numerical experiment consisted of launching an input beam of fixed profile but variable flux onto the

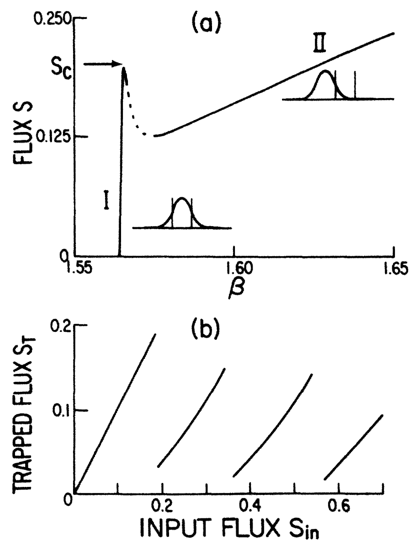

FIG. 1. (a) Nonlinear guided wave flux S vs effective index β for parameter values $n_c = n_s = 1.55$, $n_f = 1.57$, $\alpha_c = 10^{-2}$, $\alpha_s = \alpha_f = 0$, and $d = 8$. The dashed region is unstable and the insets indicate the general nature of the NLGW's on branches I and II. (b) Flux trapped in the guide S_T vs the input flux S_{in}. The input beam profile is held fixed as the linear TE_0 guide mode.

waveguide. The input profile was chosen as the linear TE_0 mode of the waveguide: such a situation could be realized experimentally by, say, prism coupling into the TE_0 modes of a linear waveguide section and interfacing this onto the nonlinear system.[13] In Fig. 1(b) we show the flux trapped in the waveguide S_T versus the input flux S_{in}, and a sequence of thresholds is clearly seen. Note in particular that the first threshold occurs for an input flux very close to S_c. This threshold can be explained as follows: for $S_{in} < S_c$ the input beam very closely matches the NLGW's on branch I (the system is essentially linear on this branch) leading to very efficient coupling of the input into these waves.[14] This is illustrated in Fig. 2(a) where $S_{in} = 0.15$. In contrast, for $S_{in} > S_c$ only branch-II solutions are available to the system and the input beam matches these solutions very poorly [see Fig. 1(a)], leading to an abrupt reduction in coupling efficiency and therefore trapped flux.[14] The point of interest here is the way in which this nonlinear system sheds the excess energy: a single self-channeled wave, or soliton, is emitted through the film-cladding interface into the nonlinear medium and propagates away from it leaving a branch-I NLGW of reduced flux; this is shown in Fig. 2(b) for $S_{in} = 0.2$, just past the critical flux. (The soliton nature of the emitted wave was verified by separating out this component and colliding it with a copy of itself in the nonlinear medium, the two waves simply passed through each other as solitons should.) As the input flux is further increased single-soliton emission continues with the flux of the soliton staying essentially constant (this is evidenced by the almost linear slope of this portion of the S_T versus S_{in} curve), and the flux trapped in the branch-I NLGW increasing accordingly. On the basis of the above argument we should therefore expect a second threshold since the trapped flux will eventually exceed S_c leading to emission of a second soliton, and indeed the argument can be extended *ad infinitum* since there is no saturation in the present model.[7] This point of view is verified in Fig. 1(b) where we have followed up to the third threshold: the corresponding two- and three-soliton emissions are shown in Figs. 2(c) and 2(d), respectively. (The transmission of two solitons through a nonlinear interface was first observed numerically by Rosanov.[2]) Note, however, that the higher thresholds do not simply occur at multiples of the critical flux S_c as one might expect from the above argument, since, e.g., in Fig. 2(c) the second soliton is emitted when the first is still in the near vicinity of the waveguide and this effects the second threshold and so on for higher thresholds. We also remark that these calculations were essentially free of radiation; that is, the input flux could be almost completely accounted for by adding the fluxes in the trapped and soliton components. Furthermore, we have performed the same calculations using a Gaussian input beam which resembles the linear TE_0 waveguide mode and obtained essentially identical results to those discussed here. Therefore, the recipe given here for exciting a NLWG to produce soliton emission is a very efficient method which is relatively insensitive to fluctuations in the input beam profile.

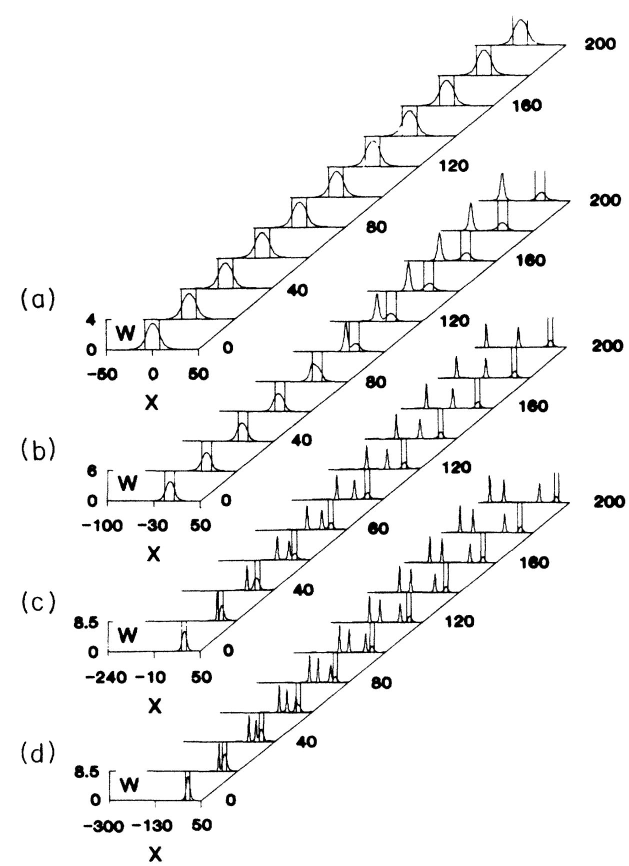

FIG. 2. Evolution of the input fields for flux levels (a) 0.15, (b) 0.2, (c) 0.4, (d) 0.6. The vertical lines indicate the waveguide boundaries and the propagation coordinate is in units of free-space wavelengths.

Some features of this soliton emission draw attention. Firstly and perhaps most importantly, the first threshold provides a highly desirable optical limiter characteristic: the input-output transfer is essentially 100% right up to this point at which the output drops drastically. Presumably the switch contrast shown in Fig. 1(b) could be further increased by varying the guide parameters. Furthermore, the output, which is always a branch-I NLGW and closely resembles the linear TE_0 mode of the waveguide, is collimated. Thus, in contrast to previous proposals for optical limiters based on nonlinear refractive effects,[15–17] the present system does not impose any undesirable phase-curvature on the output beam. Secondly, the angle of emission of the solitons is a function of the input flux. This effect was also observed by Tomlinson *et al.*[7] in their study of nonlinear interfaces. As pointed out by these authors, this effect has potential use as a light-driven angular scanning element. Finally, we have found that a soliton emitted from one NLWG can be at least partially trapped by a second adjacent guide. This offers the possiblity of directional-coupler action without the need for evanescent field overlap of the guides. Furthermore, since soliton emission occurs only above a given threshold flux, coupling between the guides will experience the same threshold behavior which could be used to construct logic elements.

In conclusion, we have shown that external excitation of a NLWG can produce sequential threshold behavior through multisoliton emission, and a simple explanation for the threshold behavior has been advanced based on the NLGW dispersion curves.

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[1]A. E. Kaplan, Pis'ma Zh. Eksp. Teor. Fiz. **24**, 132 (1976) [JETP Lett. **24**, 114 (1976)]; Zh. Eksp. Teor. Fiz. **72**, 1710 (1977) [Sov. Phys—JETP **45**, 896 (1977)].

[2]N. N. Rosanov, Opt. Spektrosk. **47**, 606 (1979) [Opt. Spectrosc. (USSR) **47**, 335 (1979)].

[3]P. W. Smith, J. P. Hermann, W. J. Tomlinson, and P. J. Maloney, Appl. Phys. Lett. **35**, 846 (1979).

[4]D. Marcuse, Appl. Opt. **19**, 3130 (1980).

[5]W. J. Tomlinson, Opt. Lett. **5**, 323 (1980).

[6]P. W. Smith, W. J. Tomlinson, P. J. Maloney, and J. P. Hermann, IEEE J. Quantum Electron. **QE-17**, 340 (1981).

[7]W. J. Tomlinson, J. P. Gordon, P. W. Smith, and A. E. Kaplan, App. Opt. **21**, 2041 (1982).

[8]P. W. Smith and W. J. Tomlinson, IEEE J. Quantum Electron. **QE-20**, 30 (1984).

[9]N. N. Akhemdiev, V. I. Korneev, and Yu. V. Kuz'menko, Zh. Eksp. Teor. Fiz. **88**, 107 (1985) [Sov. Phys—JETP **61**, 62 (1985).

[10]J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Opt. Lett. **11**, 315 (1986).

[11]J. V. Moloney, J. Ariyasu, C. T. Seaton, and G. I. Stegeman, Appl. Phys. Lett. **48**, 826 (1986).

[12]C. T. Seaton, J. D. Valera, R. L. Shoemaker, G. I. Stegeman, J. Chilwell, and S. D. Smith, J. Quantum Electron. **QE-21**, 774 (1985).

[13]H. Vach, C. T. Seaton, G. I. Stegeman, and I. C. Khoo, Opt. Lett. **9**, 238 (1984).

[14]We have shown that in order to selectively excite the NLGW's one must tailor the input beam to match that solution; failure to do so leads to decay of the input field: E. M. Wright, G. I. Stegeman, C. T. Seaton, and J. V. Moloney, Appl. Phys. Lett. **49**, 435 (1986).

[15]J. A. Hermann and M. E. Grigg, Opt. Commun. **49**, 367 (1984).

[16]J. A. Hermann, J. Opt. Soc. Am. B **1**, 729 (1984).

[17]E. W. Van Stryland, H. Vanherzeele, M. A. Woodall, M. J. Soileau, A. L. Smirl, S. Guha, and T. F. Boggess, Opt. Eng. **24**, 613 (1985).