

# Multiple breakup of high-order spatial solitons

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The breakup of high-order spatial solitons propagating in an AlGaAs slab waveguide is studied. We experimentally observe the breakup of such beams into multiple fragments and identify the mechanism of this breakup as the combined effect of two- and three-photon absorption. We show that the multiple breakup persists even when the value of two-photon absorption is reduced by an order of magnitude owing to the high value of three-photon absorption of AlGaAs at the half-bandgap. The experimental results extend known mechanisms of soliton breakup induced by two-photon absorption and agree well with numerical beam-propagation simulations. © 2008 Optical Society of America  
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Spatial solitons are self-trapped non-diffracting light beams in which the nonlinear index profile balances diffraction. The first-order ( $N=1$ ) soliton has a hyperbolic-secant beam profile, which remains constant during propagation, and is referred to as the fundamental soliton [1,2]. Higher-order ( $N>1$ ) solitons are bound solutions of the nonlinear Schrödinger equation (NLSE) that have energies that are  $N^2$  times higher than that of the fundamental soliton. These bound higher-order solutions exhibit periodic evolution of the beam profile during propagation and are sometimes referred to as “breathing solitons” [2,3]. Whereas fundamental solitons are extremely stable to perturbations, it is well known that higher-order spatial solitons are not as robust and generally break up into diverging fundamental solitons under the influence of perturbations such as linear or two-photon absorption (2PA) [3–6]. In a complete analogy, higher-order *temporal* solitons, which are short pulses having high peak powers, can break up in the presence of absorption or due to numerous additional nondissipative mechanisms such as high-order dispersion, Raman scattering, and self-steepening [2,7]. Such breakups can play an essential role in the process of supercontinuum generation in photonic crystal fibers and in soliton fiber lasers [7–9].

In this Letter we report on experimental investigation of the breakup of high-order ( $N>3$ ) spatial optical solitons in a planar AlGaAs waveguide (Fig. 1). The planar waveguide limits the diffraction to one transverse dimension, which allows effectively two-dimensional propagation and (1+1)-dimension soliton generation [6,10,11]. Our experimental setup is presented schematically in Fig. 1: A Gaussian light beam is injected into an 8 mm-long AlGaAs slab waveguide, using a 40× microscope objective. The AlGaAs slab waveguide has a core height of  $d = 1.5 \mu\text{m}$ , with a core/clad refractive index of  $n_0 = 3.3426$  and  $n_{\text{clad}} = 3.3123$ , respectively. A TE or TM mode excitation is chosen by means of a rotating half-wave plate, and the beam diameter in the  $x$  axis is set using a cylindrical lens. The light source is an optical parametric oscillator (Spectra-Physics OPAL) pumped by a mode-locked Ti:sapphire laser, produc-

ing 150 fs pulses with 80 MHz repetition rate at a wavelength of 1530 nm. The output beam profile and average power are measured at the output facet of the slab by an IR camera (Hamamatsu C5840) and a digital power meter. An additional CCD camera images the top facet of the AlGaAs slab, where multiphoton fluorescence enables direct monitoring of the propagation of high-intensity beams [12].

In previous studies of soliton propagation in planar waveguides, a splitting into two diverging beams was observed as the beam power was increased above the fundamental soliton power [5,6]. This was intuitively explained by the action of 2PA at the point where the breathing  $N=2$  soliton compresses: the nonlinear absorption reduces the power at the beam crest and causes its low intensity wings to split off and form two diverging fundamental solitons [6]. In our experimental setup, selecting a wide 52  $\mu\text{m}$  FWHM input beam enables higher soliton order ( $N>4$ ) to be obtained with the experimentally available power, and for more complex dynamics to be observed. The input beam soliton order is given by  $N = \sqrt{P_{\text{peak}} n_2 a_0 k^2 / 2n_0 d}$ , where  $P_{\text{peak}}$  is the input beam peak power,  $a_0$  is a measure of the beam width (=FWHM/1.76 for a sech profile),  $k$  is the wave vector in the medium, and  $n_2 = 1.6 \times 10^{-13} \text{ cm}^2/\text{W}$  is the nonlinear refractive index [5,11].

A summary of the experimentally measured beam profiles at the slab output for a TE-polarized input beam at different average powers is presented in

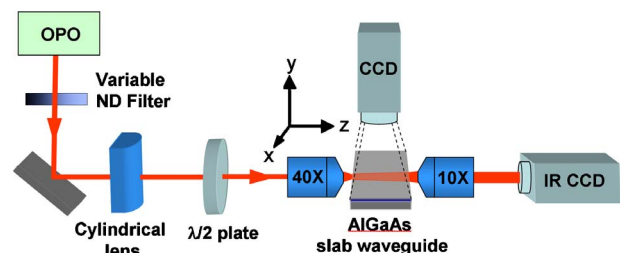


Fig. 1. (Color online) Schematic layout of the experimental setup. The InGaAs slab waveguide limits the diffraction to one transverse direction ( $x$  axis). The output beam profile and average power are measured at the output facet by an IR camera. An additional CCD camera images the beam propagation from the top facet.

Fig. 2(a). At low powers, when nonlinear self-focusing effects are negligible, the Gaussian beam diffracts in a linear fashion. As the input power is increased, self-focusing sets in, and the spatial width of the output beam decreases until the output mode has collapsed to dimensions smaller than those of the input beam. As the beam power is further increased, the beam profile breaks into a two-peaked distribution, in agreement with previous observations for the  $N=2$  soliton [5,6]. However, when the beam power is even further increased, a distinct three-peaked beam profile emerges, which sustains its shape throughout the maximum experimentally available power. At the highest input power, we have managed to map the propagation of the beam inside the 8-mm-long slab by directly observing the fluorescence pattern at the top of the slab waveguide. An image of the full 8-mm-long propagation is reconstructed from several concatenated CCD images and is presented in Fig. 3(a), showing initial self-focusing dynamics of the beam, which results in high-power densities, followed by a symmetric breakup into three fragments.

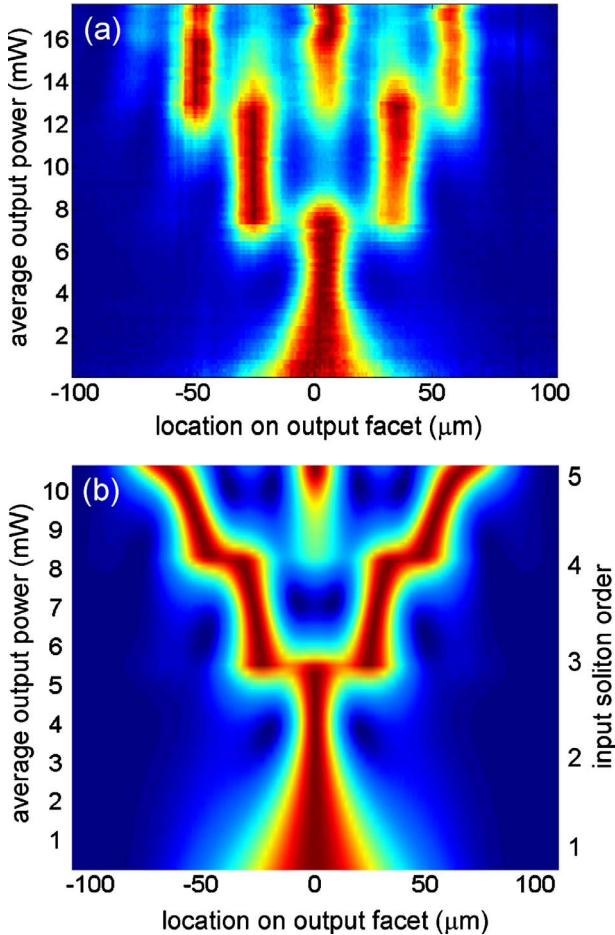


Fig. 2. (Color online) Summary of the beam profiles at the slab output for a TE-polarized input beam of  $52 \mu\text{m}$  diameter at different input powers. (a) Experimentally measured profiles. The  $y$  axis depicts measured power at the slab output. (b) Numerically simulated profiles for the same input beam with the material parameters taken from [11]. The  $y$  axis depicts the input beam soliton order and the resulting simulated average power at the slab output.

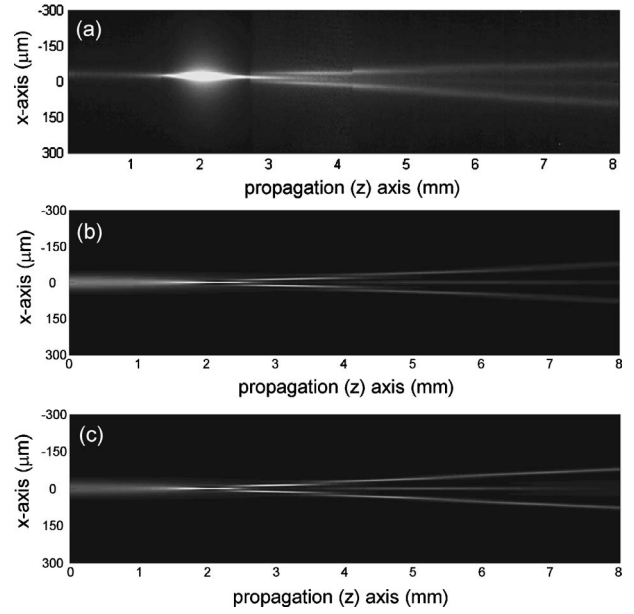


Fig. 3. Beam propagation images. (a) Experimentally obtained image of the fluorescence pattern at the top facet of the 8-mm-long AlGaAs slab, showing the propagation of a TE input beam at the highest experimentally available power (average power at the slab output of  $\sim 17$  mW). This case corresponds to an  $N \sim 5$  soliton (see Fig. 2). (b) Simulated propagation of a beam with power corresponding to an  $N=5$  soliton, in an 8 mm-long AlGaAs slab with the parameters taken from [11]. (c) Same as (b) but with 3PA as the only dissipation mechanism ( $\alpha_1 = \alpha_2 = \beta_2 = 0$ ).

To further investigate the dynamics of the beam propagation leading to the observed threefold splitting in the output beam profile, we have numerically simulated the beam propagation, taking into account diffraction, nonlinear self-focusing, and absorption mechanisms. Under these conditions the propagating electric-field spatial envelope can be described by the NLSE [6,10]:

$$\frac{\partial A}{\partial z} = i \left( \frac{1}{2k_0 n_0} \frac{\partial^2}{\partial x^2} + n_2 k_0 |A|^2 \right) A - \frac{1}{2} (\alpha_1 + \alpha_2 |A|^2 + \alpha_3 |A|^4) A, \quad (1)$$

where  $A(x, z)$  is the propagating electric-field envelope, normalized such that  $I(x, z) = |A(x, z)|^2$  is the peak intensity of the beam, and  $k_0$  is the wave vector in vacuum. The intensity-dependent absorption is given by the sum of linear and nonlinear 2PA and three-photon absorption (3PA) [10]:  $\alpha(I) = \alpha_1 + \alpha_2 I + \alpha_3 I^2$ . The values of the absorption coefficient in AlGaAs are  $\alpha_1 = 0.1 \text{ cm}^{-1}$ ,  $\alpha_3 = 0.04 \text{ cm}^3/\text{GW}^2$ , and  $\alpha_2 = 0.03 \text{ cm}/\text{GW}$  for the TM mode and  $\alpha_2 = 0.3 \text{ cm}/\text{GW}$  for the TE mode [11]. The effect of pulse temporal broadening due to group-velocity dispersion (GVD) was considered numerically by an additional reduction of the pulse peak power according to  $P_{\text{peak}}(z) = P_{\text{peak}}/[1 + z/(\tau_0^2/2\beta_2)]$ , where  $\tau_0$  is the initial pulse length and  $\beta_2 = 1.35 \text{ ps}^2/\text{m}$  is the GVD coefficient of AlGaAs at 1530 nm wavelength [2,11]. The numeri-

cal simulation results were obtained by solving the NLSE using the split-step Fourier method [2]. Numerical results for the experimental parameters given in [11] are presented in Figs. 2(b) and 3(b). The numerical results are in good agreement with the experimental results except a factor of  $\sim 1.7$  in the average output power, without the use of any fit parameter.

Further investigation into the role of 2PA versus 3PA in the multiple-soliton breakup has been made by rotating the input polarization from TE to TM. This reduces the value of  $\alpha_2$  tenfold, while introducing only negligible changes on the other propagation parameters [10]. Specifically, the nonlinear refractive index is lowered by  $\sim 5\%$ , and the effective index for the guided mode, which is proportional to the mode field diameter, is changed by a negligible amount ( $< 0.0007$ ) [13]. As a result, the TM polarization will require slightly higher powers (about 5% more) to have the same soliton order. Experimentally measured beam profiles for the TM mode show similar patterns to the ones observed for the TE mode in agreement with numerical simulations (not shown). These results suggest that 3PA is a significant mechanism in higher-order soliton breakup in AlGaAs waveguides, in accordance with the high value of 3PA for AlGaAs at the half-bandgap. To verify this conclusion, detailed numerical investigation of the  $N=5$  soliton breakup process with different values of linear and nonlinear absorption coefficients has been done. The  $N=5$  soliton case corresponds to the simulated output power of 10.4 mW and the maximum experimentally available output power of  $\sim 17$  mW (Fig. 2). It was found that the  $N=5$  soliton breaks up into three fragments even when 3PA is the only dissipating mechanism [Fig. 3(c)]. A summary of the simulated evolution of the beam's total average power (averaged over the beam width and temporal duration) during propagation for

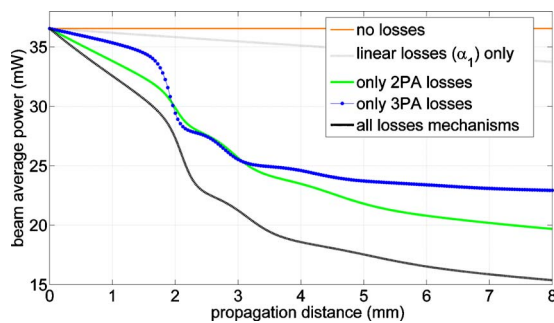


Fig. 4. (Color online) Numerically simulated evolution of the total average power (averaged over the beam width and temporal duration) for an input beam corresponding to an  $N=5$  soliton under different dissipating mechanism. This  $N=5$  soliton corresponds to the maximum experimentally available output power (Fig. 2), which is the same as in Fig. 3. The values of the different absorption coefficients are taken from [11] or taken to be zero, accordingly.

the  $N=5$  soliton is presented in Fig. 4. These results illustrate the effect of the different dissipating mechanisms during the propagation and breakup processes, owing to the sharp drop in power at the locations of highest beam intensities that occurs after propagation of  $\sim 2$  mm and  $\sim 3$  mm (Fig. 3). A breakup of the breathing solution is obtained when either of the nonlinear 2PA or 3PA effects is present.

Although multiple breakup is a complex process resulting from the interplay of nonlinear effects, diffraction, and dispersion, one can still have a qualitative understanding for the breakup mechanism. As the breathing soliton focuses, the energy loss due to the nonlinear absorption increases. As a result, the remaining power is too low to support the bound multisoliton state, which breaks up. The final outcome of this complex process depends on the exact propagation parameters and measuring point, as can be observed in the measured and simulated beam propagations (Figs. 2 and 3).

In summary, we have presented an experimental study of the breakup of high-order spatial soliton beams into multiple fragments in an AlGaAs slab waveguide. The results extend known mechanisms of soliton breakup by 2PA and agree well with numerical beam-propagation simulations.

O. Katz and Y. Lahini contributed equally to this work. Y. Lahini is supported by the Adams Fellowship of the Israel Academy of Sciences and Humanities.

## References

1. G. I. A. Stegeman, D. N. Christodoulides, and M. Segev, *IEEE J. Sel. Top. Quantum Electron.* **6**, 1419 (2000).
2. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic Press, 2001).
3. V. V. Afanasjev, J. S. Aitchison, and Y. S. Kivshar, *Opt. Commun.* **116**, 331 (1995).
4. J. E. Prilepsky and B. I. Verkin, *Phys. Rev. E* **75**, 036616 (2007).
5. Y. Silberberg, *Opt. Lett.* **15**, 1005 (1990).
6. J. S. Aitchison, Y. Silberberg, A. M. Weiner, D. E. Leaird, M. K. Oliver, J. L. Jackel, E. M. Vogel, and P. W. E. Smith, *J. Opt. Soc. Am. B* **8**, 1290 (1991).
7. M. G. Banaee and Jeff F. Young, *J. Opt. Soc. Am. B*, Vol. **23**, No. 7, 1484 (2006).
8. D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, *Phys. Rev. A* **72**, 043816 (2005).
9. O. Katz, Y. Sintov, Y. Nafcha, and Y. Glick, *Opt. Commun.* **269**, 156 (2007).
10. J. S. Aitchison, D. C. Hutchings, J. U. Kang, G. I. Stegeman, and A. Villeneuve, *IEEE J. Quantum Electron.* **33**, 341 (1997).
11. J. U. Kang, G. I. Stegeman, A. Villeneuve, and J. S. Aitchison, *Pure Appl. Opt.* **5**, 583 (1996).
12. D. Mandelik, H. Eisenberg, Y. Silberberg, R. Morandotti, and J. S. Aitchison, *Phys. Rev. Lett.* **90**, 253902 (2003).
13. J. U. Kang, G. I. Stegeman, J. S. Aitchison, and N. Akhmediev, *Phys. Rev. Lett.* **76**, 3699 (1996).