Observation of two-dimensional multimode solitons

Tal Carmon, Charalambos Anastassiou,* Song Lan,* Detlef Kip,* Ziad H. Musslimani,† and Mordechai Segev*

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

Demetrios Christodoulides

Department of Electrical Engineering and Computer Science, Lehigh University, Bethlehem, Pennsylvania, 18015

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We present the first experimental observation of (2 + 1)-dimensional multimode (composite) solitons. A single-hump component and a double-hump (dipole-type) component are jointly self-trapped as a composite soliton in a biased photorefractive crystal.

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An optical beam propagating in a self-focusing nonlinear medium is self-trapped and forms a spatial soliton when it is guided in its own self-induced waveguide.[1,2] When the soliton constitutes a single optical field (a scalar soliton), the induced waveguide can guide a single mode only (e.g., in Kerr media) or multiple modes (in a saturable nonlinearity such as a photorefractive[3]). In general, however, a soliton can involve more than one optical field, in which case it is called a vector soliton. This happens when the field components jointly induce a waveguide and trap themselves in it by properly populating the guided (eigen)modes.[2] In the degenerate case, all the field components populate the fundamental mode, and the total intensity structure of the soliton has a single hump.[4,5] Vector solitons, however, can also form when the field components belong to different modes of their jointly induced waveguide, as predicted in the temporal[6] and spatial[7] domains and observed in photorefractives.[8] Such solitons are called composite or multimode solitons, and their intensity can exhibit a single-hump or a multihump structure.[8] Single-hump and double-hump (1 + 1)-dimensional [(1 + 1)D] multimode solitons were found to be stable for a large range of parameters.[8,9] Following the progress in the development of saturable nonlinearities that can support (2 + 1)-dimensional [(2 + 1)D] scalar solitons,[2] it is natural to seek (2 + 1)D composite solitons. Such multimode solitons were first predicted in cylindrically symmetric systems, in which at least one of the components carries a topological charge.[10] Later, a dipole vector soliton was proposed, in which one of the modes resembles a TEM_{01} Gaussian mode.[11] Thus far, however, all experimentally observed multimode solitons have been in a (1 + 1)D geometry.[8,12]

Here we present the first experimental observation of composite (2 + 1)D solitons. We generate single- and double-hump bimodal solitons in which the first component is a TEM_{00}-type mode and the second component is a dipole mode exhibiting a TEM_{01}-like structure.

If vector or multimode solitons are to form, the interference between the field components must not contribute to the nonlinear index change, Δn. Otherwise, the induced waveguide changes during propagation, and thus the field components self-trapped within this waveguide, are not stationary. One method of satisfying this condition is to have the field components polarized orthogonally to each other.[4,6] Another method is to have the components at two widely spaced optical frequencies, so that the interference term is asynchronous with either of the components.[13] A third method relates to nonlinearities that have a noninstantaneous temporal response with a time constant τ. In this technique the components are of the same wavelength and polarization but are mutually incoherent with respect to each other.[14] Thus the phase of the interference term varies (randomly) in time much faster than the nonlinearity can respond, and therefore the contribution of the interference to Δn averages out. Here, by employing the coherence-based method[14] and the photorefractive screening nonlinearity,[15] we generate composite multimode solitons.

We expand and collimate an Ar^+ laser beam and split it into ordinary, o, and extraordinary, e, polarized beams, using a polarizing beam splitter. The o and e beams are polarized perpendicular and parallel, respectively, to the c axis of the crystal. The o beam is used as background illumination covering the crystal uniformly, as is necessary for screening solitons.[16] We then split the e beam in two to create the first (TEM_{00}) and the second (dipole) components. The dipole component is created by inserting a thin piece of glass into half of the beam. The glass is rotated until it induces a $(2m + 1)\pi$ phase shift (m is an integer) between the two halves of the beam, thus forming a dipole (TEM_{01}-like) mode. We make the first component incoherent with the dipole by having the optical length difference between the beams (1 m) exceed the coherence length of the laser (10 cm). Since the phase between these modes varies much faster than the response time of the crystal ($\tau \approx 1$ s), no stationary interference pattern forms on the time scale of the crystal's response.[14,15] The two modes are combined (with a beam splitter) and focused

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to the input face of a 1.1-cm-long $Sr_{0.6}Ba_{0.4}Nb_2O_6$ crystal. The input and output faces of the crystal are imaged on a CCD camera. To view the individual components, we block one component and sample the other in a time interval (~1 ms) much shorter than τ so that Δn does not change within the observation window.

In the first experiment we launch a 19-μm FWHM fundamental component, u, and a 20-μm (peak-to-peak separation) dipole, d. The peak fundamental intensity (normalized to the background intensity) is $|u_o|^2 = 14$ and is equal to the peak dipole intensity, $|d_{\text{peak}}|^2$. The intensities of $|u|^2$ (fundamental), $|d|^2$ (dipole), and $|u|^2 + |d|^2$ (total intensity) at the input face of the crystal are shown in Figs. 1(a), 1(b), and 1(c), respectively. The normally diffracting outputs after 1.1-cm propagation (~3 diffraction lengths) of $|u|^2$, $|d|^2$, and $|u|^2 + |d|^2$ are shown in Figs. 1(d), 1(e), and 1(f), respectively. When 5500 V is applied (in the crystalline c-axis direction) between the electrodes separated by 1.5 cm, a composite soliton forms. The intensities at the output face of the crystal, $|u|^2$, $|d|^2$, and $|u|^2 + |d|^2$, are shown in Figs. 1(g), 1(h), and 1(i), respectively. This composite soliton is double humped and looks exactly like the input, apart from a slight rotation around its center of mass.

The two modes self-trap when they are launched together, forming a composite soliton. However, the stand-alone components do not trap on their own at the value of the nonlinearity that supports the composite soliton. The reason for this has to do with the parameter range that supports a composite soliton: the existence range. Scalar solitons are governed by the soliton existence curve: A soliton of a given peak intensity and width-to-wavelength ratio forms at a particular value of the maximum index change.[17] A two-mode soliton, however, has an existence range that, in addition, depends on the relative strength of the first to the second mode.[8] From the theory of (1 + 1)D multimode solitons,[8] we know that for a given intensity of the first mode there is a range of intensities of the second mode for which self-trapping occurs. Intuitively, if the second-mode constituent is too large, then the composite soliton turns into two separate solitons that, having a relative phase of π, repel each other. To show this experimentally, we launch the first and the second modes separately and apply the same nonlinearity that gave rise to the composite soliton. For the stand-alone first mode the nonlinearity is too high (because a composite soliton requires a higher nonlinearity than a scalar soliton of the same width[10]) and the output is distorted, as shown in Fig. 1(j). On the other hand, the stand-alone dipole forms two separate solitons that repel each other to an output separation of 75 μm (~4 times larger than the input), as shown in Fig. 1(k).

In the next set of experiments (Fig. 2) we reduce the intensity of the dipole component to $|d_{\text{peak}}|^2 = 10$ so that the composite soliton will be single humped, and we go deeper into saturation by increasing $|u_o|^2$ to 30. The input intensities of the fundamental mode, the dipole mode, and total input intensity are shown in Figs. 2(a), 2(b), and 2(c), respectively. The corresponding normally diffracting output beams are shown in Figs. 2(d), 2(e), and 2(f), respectively. A composite soliton forms when 5300 V is applied. The corresponding self-trapped fundamental, dipole, and total intensity are shown in Figs. 2(g), 2(h), and 2(i). From Fig. 2(i) we can see that this composite soliton is single humped. Again the stand-alone components do not self-trap if they are not simultaneously launched: The first mode becomes elliptical [Fig. 2(j)], whereas the separation between the peaks of the dipole increases to 55 μm [Fig. 2(k)] from the input 17-μm separation of Fig. 2(h).

In conclusion, we have experimentally demonstrated the first composite (2 + 1)D soliton. Self-trapping of multimode [(2 + 1)D] solitons opens up the possibility of distortionless image transmission through highly

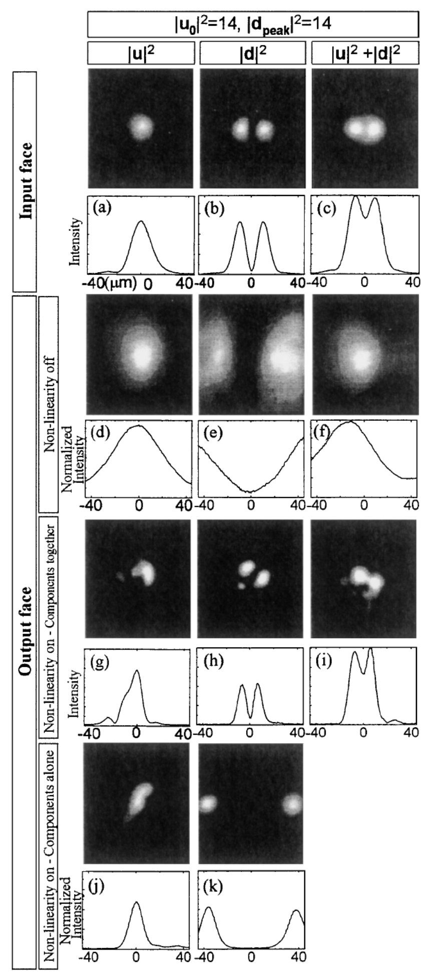

Fig. 1. Double-hump multimode [(2 + 1)D] soliton with $|u_o|^2 = |d_{\text{peak}}|^2 = 14$. (a)–(c) Input intensities: (a) $|u|^2$, (b) $|d|^2$, (c) $|u|^2 + |d|^2$. (d)–(f) Diffracted output intensities with nonlinearity off: (d) $|u|^2$, (e) $|d|^2$, (f) $|u|^2 + |d|^2$. (g)–(i) Composite soliton output intensities at 4230 V/cm: (g) $|u|^2$, (h) $|d|^2$, (i) total intensity of the double-hump soliton, $|u|^2 + |d|^2$. The individual stand-alone components at 4230 V/cm do not self-trap by themselves: (j) $|u|^2$ by itself is distorted because the nonlinearity its too high for a scalar soliton, and (k) the stand-alone dipole forms two separate solitons that repel each other. The intensity in each part of the figure is normalized to the peak intensity.

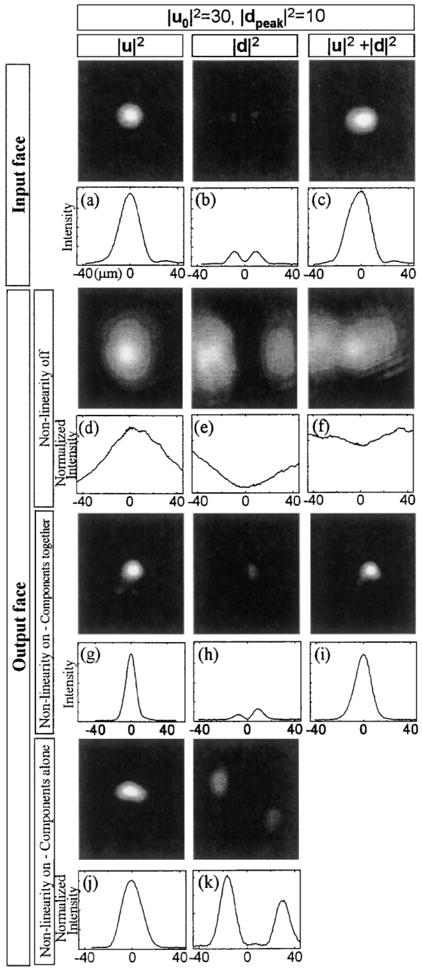

Fig. 2. Same as in Fig. 1 but with $|u_o|^2 = 30$ and $|d_{\text{peak}}|^2 = 10$. This single-hump soliton forms for an applied field of 4060 V/cm.

nonlinear self-focusing media.[18] If the envelope of a highly multimode soliton is modulated to contain an image (superimposed on the intensity profile of the soliton), then this image can be transmitted through the self-focusing medium and remain unchanged through propagation. This method is in contradistinction to image transmission through a multimode fiber, for which the fiber modes are coherent with each other, yet they propagate at different velocities (intermodal dispersion) and thus destroy the image.

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*C. Anastassiou, S. Lan, D. Kip, and M. Segev are also with the Department of Electrical Engineering, Princeton University, Princeton, New Jersey 08544. D. Kip is also with the Department of Physics, Osnabrück University, 49069 Osnabrück, Germany.

†Z. H. Musslimani is also with the Department of Mathematics, Technion–Israel Institute of Technology, Haifa 32000, Israel.

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