Observation of Multihump Multimode Solitons

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We present the first experimental observation of multihump multimode solitons in nature. In a broader perspective, this is the first observation of a multihumped multimode self-trapped wave packet propagating in a dispersive nonlinear medium. Double- and triple-humped spatial profiles are found by incoherent population of two modes of the beams' self-induced waveguide (self-induced potential well). [S0031-9007(98)06174-2]

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Since the recent demonstration of self-trapping of a quasimonochromatic partially spatially incoherent light beam [1] and of a "white" light wave packet which is temporally and spatially incoherent [2] there has been an increased interest in so called multimode solitons. These are self-trapped beams which consist of more than one transverse mode. More specifically, a soliton forms when the optical beam induces (via the nonlinearity) a waveguide and in turn is guided in its own induced waveguide [3]. Prior to [1,2], all observed bright solitons were such that only the lowest mode in the induced waveguide was populated. Therefore, all observed bright solitons were single mode and "single humped" (had a single intensity peak). However, in saturable nonlinear media the induced waveguide can be multimode [3]. When more than one mode of the induced waveguide is populated, the soliton is multimode and can have more than one intensity peak (multihump). Here we present the first observation of a multihumped multimode bright soliton.

The self-trapping of a beam consisting of one populated mode is governed by a single equation. If more than one mode is populated, then one must consider the evolution of multiple beams which are governed by an equal number of equations coupled via the nonlinearity. For such a multimode soliton to exhibit a stationary profile throughout propagation, the modes must *not* interfere with each other, since such interference would cause a periodic oscillation in the optical intensity and thus give rise to a periodic induced waveguide [4]. Elimination of interference between modes can be achieved in two ways: (1) the modes being polarized orthogonal to one another, or (2) the modes being incoherent with respect to each other, that is, the relative phase between the mode varies in time much faster than the response time of the nonlinear medium, which must be noninstantaneous. The first approach gives rise to vector (bipolarization) solitons as first addressed by Manakov [5] in Kerr media. He has shown that under certain conditions two orthogonally polarized beams, which are each the first guided mode of their mutually induced waveguide, will self-trap. Manakov solitons were recently demonstrated [6] in AlGaAs waveguides with optical spatial solitons. The next idea proposed was a bicomponent beam in which one component was "bright" and the other "dark," together forming a bright-dark coupled pair [7]. Bright-dark coupled soliton pairs were first demonstrated [8] using two different wavelengths instead of two orthogonal polarizations for the different components. With the new understanding that a dark soliton is actually the second guided mode of its self-induced waveguide at the cutoff frequency [9], these bright-dark soliton coupled pairs are in fact an intermediate stage for obtaining truly multimode solitons. Degenerate temporal vector solitons, which are bimodal with respect to their common induced potential, were then identified in birefringent optical fibers [10]. Finally, multimode solitons were predicted [11] in a medium with a saturable self-focusing nonlinearity, for which the total intensity of the beam induces a multimode waveguide. Similar multimode temporal solitons were found in isotropic Kerr media [12]. Such multimode solitons had not been demonstrated prior to our present work. In general, multimode solitons making use of orthogonal polarizations have a limiting feature: Because only two polarization states are possible, the maximum number of components (modes) involved is *two*. Using the second approach (mutual incoherence) to create multimode solitons allows having *more than two modes* in the soliton. In some cases *all* of the guided modes of a jointly induced waveguide can be populated. It is this type of multimode beam self-trapping that allows for self-trapping of an incoherent light beam [1,2].

Incoherently coupled two-component spatial solitons using the second methodology (mutual incoherence) were first proposed for photorefractive screening solitons [13] and soon thereafter demonstrated experimentally [14]. There, the bright beam was always the fundamental guided mode and the dark the second guided mode at cutoff of the jointly induced waveguide.

Here we report on the first observation of two-component bright multimode solitons. The multimode solitons are made by two different populated modes of their jointly self-induced waveguide with the same polarization. Double- and triple-humped beam profiles are observed corresponding to combinations of the first + second modes, and second + third modes, respectively. Multihumped solitons occur because the higher modes are sufficiently populated to see the structural features of the higher modes. We observed 1D self-trapped multimode beams in biased photorefractive media, for which the explicit form of nonlinearity is well established [15] and confirmed in many experiments [16].

In a recent Letter, we have solved for the necessary conditions or "existence range" for self-trapping such a multimode beam [17]. We have shown that a beam consisting of *multiple* modes with the *same* polarization can be self-trapped if the modes are made to be incoherent with each other and if self-consistency is satisfied between the self-trapped beam and its induced waveguide. We have found that for such a self-trapped multimode beam, there is a parameter range within which nondiffracting solutions exist. In particular, we have solved for the existence range of two-component and three-component soliton beams in photorefractive media for which each component is associated with a *different* guided mode (bound state) of the jointly induced waveguide. Figure 1 here shows the existence range when combinations of the first and second guided modes are populated. A self-consistent solution has a given modal amplitude distribution $(d_1, d_2, \ldots)$ as an initial condition, and one needs to determine which distributions allow for self-trapping of a beam. Whether or not the equations can be solved self-consistently depends upon the modal amplitude. In Fig. 1 the horizontal axis indicates the modal amplitude of the first guided mode d_1 and the vertical axis is the normalized full width half maximum (FWHM) of the total intensity made up from the two modes ($\Delta\xi = \Delta x k n_b^2 \sqrt{r_{\mathrm{eff}} V/\ell}$, as in Ref. [15]). The bottom edge of the curve corresponds to the case where only the first mode is populated (fundamental soliton solutions). Other points correspond to adding a contribution from the second mode. The upper edge of the curve is where the second mode attains its maximum allowed value, which also gives the widest possible bimodal self-trapped solution. Points A, B, and C represent modal compositions that allow self-trapping, whereas point D is outside of the existence range. We have shown that the beam created at point D will form two diverging solitons [17]. We have performed a preliminary stability analysis using beam propagation methods and found that the solitons remain intact within at least ten diffraction lengths for perturbations of a few percent in their initial amplitudes, widths, or transverse displacement. Whether or not these composite solitons are stable in the absolute sense is currently under study.

In Figs. 2–6 we show typical experimental results of two component multimode solitons, in combinations (1) first mode only (Fig. 2), (2) first + second modes (Figs. 3–5), and (3) second + third modes (Fig. 6). Figure 5 shows the combination of first and second modes that does *not* satisfy self-consistency. Each figure shows photographs and beam profiles at the input and output crystal faces, imaged onto a camera with a lens. Our experimental setup is almost identical to the one used in Ref. [14]. We used two mutually incoherent extraordinarily polarized beams from a 488 nm argon-ion laser of a coherence length of ~10 cm. To make the input beams incoherent with each other, we have one beam travel 1 m farther than the other before recombining them. Thus, the interference between the beams varies every ~0.3 nsec, much faster than the response time of our nonlinear medium (~0.1 sec) at these intensities. Our beams are one-dimensional stripes generated by use of cylindrical lenses, which image the various beam components onto the input face of the crystal. Higher order modes are generated by inserting thin pieces of glass in certain parts of the optical beam to induce $(2m+1)\pi$ phase shifts (m = integer) across portions of the beam. Recalling that the photorefractive effect has a long response time, after the composite multimode soliton is formed we can block one beam component and quickly sample the other component. The induced waveguide does not change in this short time interval, and thus we can monitor separately each of the two modal components of the bimodal soliton. Following this stage, if we wait a long enough time (seconds) with one component blocked, the nonlinear medium reacts and goes into a new steady state in response to the single beam input. Typically, one beam alone does not form a soliton at the specific values of nonlinearity and modal ratio ($d_2/d_1, d_3/d_2$, etc.) used for the composite soliton, so that at these conditions each beam component alone deviates considerably from a soliton (stationary) behavior.

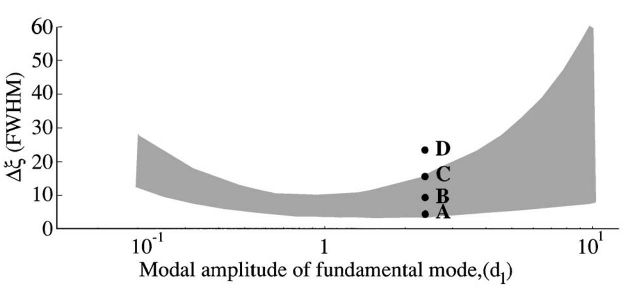

FIG. 1. Existence range for bimodal solitons consisting of populated first and second modes. Points A, B, and C represent trappable nonevolving beams, whereas point D is untrappable since it lies outside the existence range.

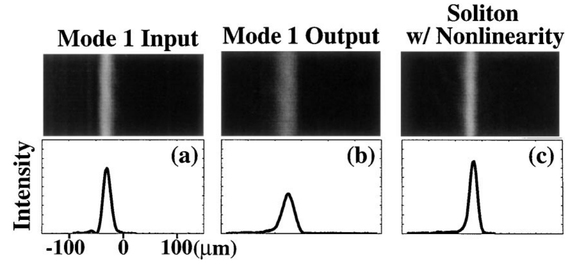

FIG. 2. Single mode soliton with intensity ratio = 5 (a), (b) input (18 μm FWHM) and linear diffraction (27 μm); (c) soliton formed (18 mm) with application of 240 V/4 mm.

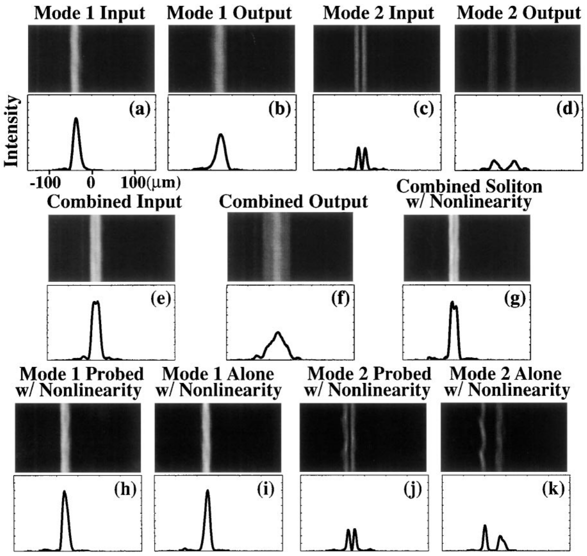

FIG. 3. Multimode soliton with mode 2/mode 1 = 0.25 (a), (b) input (18 μm FWHM) and linear diffraction (27 μm) of mode 1; (c),(d) input (28 μm) and linear diffraction (62 μm) of mode 2; (e),(f) combined input (26 μm) and combined linear diffraction (58 μm); (g) composite soliton formed (26 μm) with application of 500 V/4 mm; (h) first mode obtained after quickly blocking second mode; (i) steady state of first mode *alone* with nonlinearity "on"; (j) second mode obtained after quickly blocking first mode; and (k) steady state of second mode *alone* with nonlinearity on.

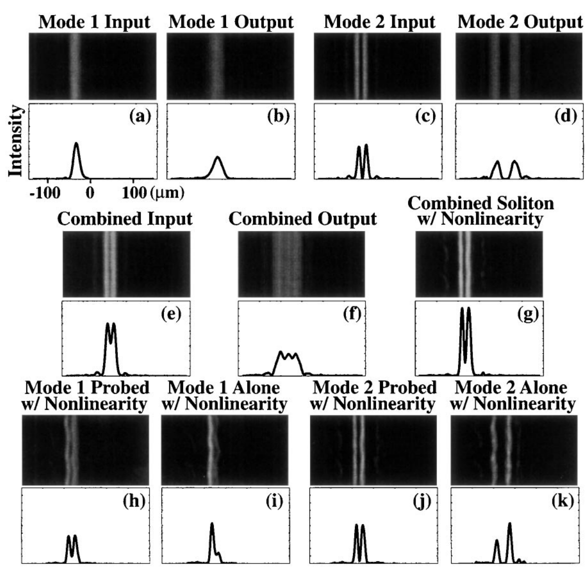

FIG. 4. Multimode soliton with mode 2/mode 1 = 1.0 (a),(b) input (18 μm FWHM) and linear diffraction (27 μm) of mode 1; (c),(d) input (28 μm) and linear diffraction (62 μm) of mode 2; (e),(f) combined input (26 μm) and combined linear diffraction (58 μm); (g) composite soliton formed (26 μm) with application of 800 V/4 mm; (h) first mode obtained after quickly blocking second mode; (i) steady state of first mode alone with nonlinearity on; (j) second mode obtained after quickly blocking first mode; and (k) steady state of second mode alone with nonlinearity on.

Figure 2 shows self-trapping of the input corresponding to point A of Fig. 1, which is the typical single mode screening soliton. The fundamental mode has a width of 17 μm and diffracts to 27.6 μm. With the application of 240 V/4 mm the beam self-traps to 17 μm.

Figure 3 shows the experimental results of a composite soliton in which both the first and second modes are populated with the ratio of mode 2/mode 1 = 0.25. As shown in Fig. 3(g), self-trapping occurs when both modes are present. This example exhibits a *doubly humped multimode soliton intensity profile* that induces a double-humped index profile. Figures 3(h) and 3(j) show the (separate) modal constituents of the bimodal soliton. As shown in Figs. 3(i) and 3(k), each component alone does not form a soliton on its own, even in the presence of nonlinearities. For example, the distance between the two peaks of the second mode has increased with the nonlinearity on from 15 μm at the input to 37 μm at the output [Figs. 3(c) and 3(k)]. On the other hand, mode 1 alone undergoes compression from 16 to 14 μm.

Figure 4 shows the combination of a first and second mode with the ratio of mode 2/mode 1 = 1.0. As shown in Fig. 4(g), self-trapping occurs when both modes are present exhibiting a profoundly double-humped intensity

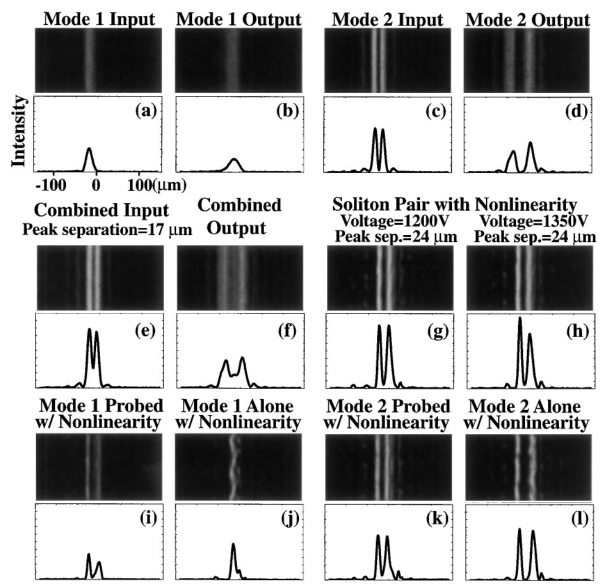

FIG. 5. Diverging soliton pair created with mode components of a stable solution weighted incorrectly with mode 2/mode 1 = 2.0 (a),(b) input (18 μm FWHM) and linear diffraction (27 μm) of mode 1; (c),(d) input (28 μm) and linear diffraction (62 μm) of mode 2; (e) combined input (29 μm) with a 17 μm separation between peaks, (f) combined linear diffraction (60 μm); (g) soliton pair formed with a peak separation of 24 μm with 1200 V/4 mm; (h) soliton pair formed with a peak separation of 24 μm with 1350 V/4 mm; (i) the coupling of the first beam into the soliton pair after quickly blocking second beam; (j) steady state of first beam alone with nonlinearity on; (k) the coupling of the second beam into the soliton pair after quickly blocking first beam; and (l) steady state of second beam alone with nonlinearity on.

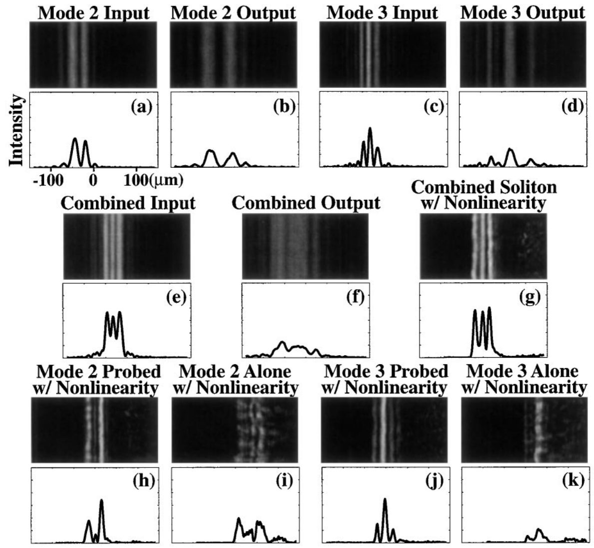

FIG. 6. Multimode soliton with mode 3/mode 2 = 1.0 (a),(b) input (38 μm FWHM) and linear diffraction (74 μm) of mode 2; (c),(d) input (36 μm) and linear diffraction (100 μm) of mode 3; (e),(f) combined input (40 μm) and combined linear diffraction (100 μm); (g) composite soliton formed (42 μm) with application of 2700 V/4 mm; (h) second mode constituent obtained after quickly blocking third mode; (i) steady state of second mode alone with nonlinearity on; (j) third mode after quickly blocking second mode; and (k) steady state of third mode alone with nonlinearity on.

profile. Figures 4(h) and 4(j) show the (separate) modal constituents of the bimodal soliton. In this particular case, even the lowest mode, shown in Fig. 4(h), is double peaked. As shown in Figs. 4(i) and 4(k), each beam component (modal constituent) alone does not form a soliton on its own. Experimentally, the fundamental guided mode is double humped more than expected. This is because the input beam profiles are not exactly the "correct profiles" predicted by theory that support stationary propagation. This causes the beam to slightly oscillate, for which we have found numerically that the first mode looks slightly more double humped than expected for the given crystal length we use.

Figure 5 shows the combination of first and second modes with the ratio of mode 2/mode 1 = 2.0. As shown in Fig. 1 (point D) this combination is *not* a solution and does not form a composite soliton. Figure 5(e) shows the combined input with a width of 29 μm and the separation between the peaks at 17 μm. In this case, the two intensity peaks each form their own soliton and diverge from each other. This can be seen in Fig. 5(g), where two distinct solitons exist and their separation has increased to 24 μm. Higher voltages does not bring the solitons back towards each other but instead leads to beam breakup as seen when the voltage was increased from 1200 [Fig. 5(g)] to 1350 volts [Fig. 5(h)]. Figures 5(i) and 5(k) show the (separate) modal constituents of the two solitons. Experimentally, the fundamental beam becomes double humped as it breaks into two components that diverge as with the total intensity, as expected from theory. This is because the system can now be viewed as a pair of diverging multi-component solitons, each containing components from each input beam.

Figure 6 shows the combination of a second + third mode with the ratio of mode 3/mode 2 = 1. This example dramatically shows the contrast between the outputs when both beams are together and when each beam is individually launched, as shown in Figs. 6(g), 6(i), and 6(k). This composite multimode soliton and its induced waveguide are, in this case, both triple humped.

In conclusion, we have presented the first observation of multihump multimode self-trapped beams in nature.

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