Two-dimensional multipole solitons in nonlocal nonlinear media

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We present the experimental observation of scalar multipole solitons in highly nonlocal nonlinear media, including dipole, tripole, quadrupole, and necklace-type solitons, organized as arrays of out-of-phase bright spots. These complex solitons are metastable, but with a large parameters range where the instability is weak, permitting their experimental observation. © 2006 Optical Society of America

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The formation of solitons in a nonlinear medium is one of the most interesting phenomena encountered in nonlinear optics. Solitons can take on complex forms, such as dipole solitons,[1,2] multihump solitons,[3] solitons organized as necklaces,[4–8] and even complex beams carrying angular momentum, like rotating propellers.[9] Typically, bright solitons possessing complicated forms in conservative systems necessitate the presence of multiple fields; i.e., they are vector (composite) solitons[1–4,6–8] (in contrast to nonconservative systems, where stable soliton complexes are possible[10,11]). In fact, in local nondissipative nonlinear media the only examples of multihump scalar solitons are necklace solitons,[4,5] rings of out-of-phase bright spots holding each other together and arresting the instabilities. The diffraction broadening of such a beam is indeed eliminated by the nonlinearity; yet these scalar self-trapped necklace beams still inevitably (slowly) expand, because there is a net outward force exerted on each spot by all other spots composing the ring.[4,5] Adding angular momentum to the necklace introduces rotation that slows down the expansion but never stops it completely.[5] Thus the general conclusion is that scalar solitons in homogeneous, local, nonlinear media with no gain (or loss) cannot form complex states. The picture changes drastically when the nonlinear material response is nonlocal. Nonlocality has profound effects on the complexity of solitons, since it makes it possible to overcome repulsion between out-of-phase bright[12–19] or in-phase dark solitons[20] that can form bound states observed in 1D settings.[21,22] In two transverse dimensions, however, the only complex structures thus far observed with scalar solitons have been bright vortex rings.[23] Even though the simplest bound states of 2D solitons in nonlocal media were predicted in the 1980s,[13] they still were not observed experimentally.

Here we present the experimental observation of various types of multipole scalar solitons in a thermal nonlocal nonlinear medium. We find that multipole solitons in such a medium are oscillatory unstable, yet their instability decay rates can be very small under appropriate conditions, giving rise to experimentally accessible metastable complex soliton states.

Our system is described by the evolution equation for the slowly varying light field amplitude A coupled to the steady-state heat transfer equation describing the temperature distribution in the lead glass sample.[23] The light beam is slightly absorbed and acts as a heat source. Heat diffuses, creating a nonuniform temperature distribution, which gives rise to a refractive index change proportional to the temperature change. The resulting system of equations in dimensionless form reads as[23]

$$i\frac{\partial q}{\partial \xi} = -\frac{1}{2}\left(\frac{\partial^2 q}{\partial \eta^2} + \frac{\partial^2 q}{\partial \zeta^2}\right) - nq,$$

$$\frac{\partial^2 n}{\partial \eta^2} + \frac{\partial^2 n}{\partial \zeta^2} = -|q|^2. \qquad (1)$$

Here $q=(k_0 w_0^2 \alpha\beta/\kappa n_0)^{1/2}A$ is the dimensionless light field amplitude; $n=k_0^2 w_0^2 \delta n/n_0$ is proportional to nonlinear change δn in the refractive index n_0, k_0 being the optical wavenumber; α, β, and κ are the optical absorption coefficient, the thermal dependence of the refractive index ($\beta = \mathrm{d}n/\mathrm{d}T$), and the thermal conductivity coefficient, respectively; the transverse coordinates η, ζ are scaled to the beam width w_0, while the longitudinal coordinate ξ is scaled to diffraction length $k_0 w_0^2$. In our lead glass sample, $n_0 = 1.8$, the thermal coefficient is $\beta = 14\times 10^{-6}\ \mathrm{K}^{-1}$, the absorption coefficient is $\alpha \approx 0.01\ \mathrm{cm}^{-1}$, and the thermal conductivity is $\kappa = 0.7\ \mathrm{W/(mK)}$. Such glass parameters are sufficient to support solitons with widths of $\sim 50\ \mu\mathrm{m}$, which give rise to an index change $\delta n \sim 5\times 10^{-5}$ for a total optical power of 1 W. Notice that system (1) conserves the energy flow $U=\int\int_{-\infty}^{\infty}|q|^2 d\eta d\zeta$.

We search for soliton solutions of Eqs. (1) of the form $q(\eta,\zeta,\xi)=w(\eta,\zeta)\exp(ib\xi)$, where $w(\eta,\zeta)$ is a real function and b is the propagation constant. The soliton intensity vanishes at the boundaries of the integration window, while the refractive index $n\rightarrow n_b$, where the limiting value n_b is related to the temperature of the sample boundaries, which are kept at fixed and equal temperature. Mathematically, adding the constant background n_b in the refractive index is equivalent to a shift of propagation constant b by the same amount; henceforth we set $n_b=0$. In this case, the soliton properties are determined solely by b and the width of integration window. We then set the window size $\eta,\zeta\in[-20,20]$, closely resembling the actual transverse size of our sample. Using the numerical methods described in Refs. 17 and 23, we find a variety of well-localized multipole solitons and test their stability by propagating them numerically in the presence of complex (amplitude and phase) noise. Figure 1 shows illustrative examples of multipole solitons, including dipole (Fig. 1b), tripole (Fig. 1d), and quadrupole (Fig. 1f) solitons, as well as necklace solitons (Fig. 1h) comprising several bright spots with phase changing by π between adjacent spots. In a highly nonlocal nonlinear medium, the refractive index is determined by the intensity distribution over the entire transverse plane, and under proper conditions the nonlocality can lead to an increase of refractive index in the overlap region between out-of-phase solitons even when intensity there is zero, thus giving rise to formation of multipole solitons. Note that the width of the refractive index distribution (the light-induced potential) greatly exceeds the width of an individual light spot. This is a direct indication of the very large range of nonlocality in thermal media. We find that for all types of soliton the energy flow monotonically increases with b, which is accompanied by a decrease in the integral soliton width. Similarly, the separation δW between the intensity maxima of the multipole solitons is also found to decrease with b.

Our experiments are carried out in lead glass samples with a square 2 mm×2 mm cross section, which are 84 mm long in the propagation direction. All four transverse boundaries of the sample are thermally connected to a heat sink and maintained at room temperature. In these experiments we use an 1.8 W laser beam at a 488 nm wavelength. We launch the dipole soliton by introducing a π phase jump across the Gaussian laser beam by inserting a piece of flat glass (of a proper thickness) through one half of the beam cross section and imaging it (demagnified) onto the input face of the sample at normal incidence. We launch the tripole soliton in a similar fashion, with two parallel pieces of glass, each introducing a π phase delay, passing through either one third or two thirds of the beam cross section. For the quadrupole soliton, we use two π phase-delays, organized perpendicular to one another in the transverse plane, and each passing through one half of the laser beam. Finally, to create the 16-lobe necklace soliton, we reflect the laser beam off a properly designed phase mask and subsequently image the beam onto the input face of the sample. We monitor the intensity distribution at the input and output faces by imaging the input and output beams onto a CCD camera. Typical experimental results, with comparisons with the theoretical simulations, are summarized in Fig. 1. The left-hand column of each row shows the input beam in each case. At low power (10 mW) the beams linearly diffract for 84 mm, after which they broaden significantly (middle columns). At high power (1.8 W) each beam forms a soliton, which maintains its intensity profile while propagating for 84 mm (right-hand columns).

Extensive simulations of the propagation dynamics of perturbed solitons reveal that, in fact, all multipole solitons in thermal media are oscillatory unstable. Small perturbations in the input field distribution cause progressively increasing oscillations in the in-

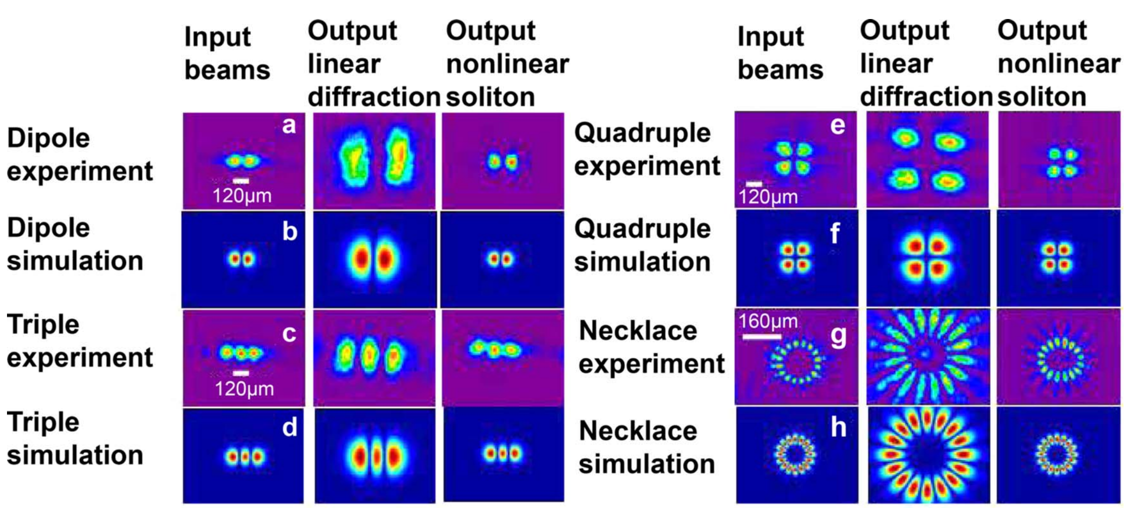

Fig. 1. (Color online) Experimental and theoretical observations of complex scalar solitons in the form of, a, b, dipole solitons; c, d, tri-pole solitons; e, f, quadrupole solitons; g, h, necklace solitons. Left-hand columns, input beams; central columns, output beams after linear diffraction broadening for 84 mm of propagation; right-hand columns, high-power self-trapped output beams after the same distance.

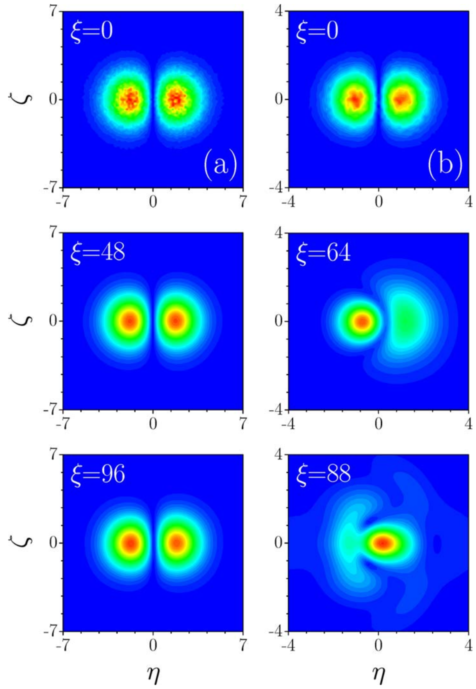

Fig. 2. (Color online) Propagation dynamics of slightly perturbed dipole-mode solitons with (a) $b=3$ and (b) $b=12$.

tensities of bright spots composing the soliton, leading eventually to the destruction of the multipole soliton structure. For example, Fig. 2 shows the long-range dynamics of a perturbed (5% complex amplitude noise) dipole soliton and its transformation into a ground-state soliton for two values of b. The strength of the instability dramatically decreases with decreasing energy flow U, so that already at moderate energy levels the solitons survive over large distances (hundreds of diffraction lengths), greatly exceeding the present experimentally feasible sample lengths. We emphasize that we find the necklace solitons also to be metastable in our nonlocal thermal media. To our knowledge, these necklaces are the only known case where nonlocality acts to **destabilize** a self-trapped structure (that in this case is not stationary, but is otherwise robust in local nonlinear media[4]), in contrast to the natural tendency of nonlocality to stabilize self-trapped states.[24–26]

In conclusion, we have demonstrated experimentally 2D metastable multipole solitons in highly nonlocal nonlinear media. The long range of nonlocality enables the formation of a variety of scalar solitons possessing complex structures, varying from dipole solitons, to tripoles, to quadrupoles, to necklaces. Such high nonlocality should be able to support even complex soliton structures carrying angular momentum.[27] This is indeed our next experimental challenge.

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