Dipole solitons in optically induced two-dimensional photonic lattices

Jianke Yang

Department of Mathematics and Statistics, University of Vermont, Burlington, Vermont 05401

Igor Makasyuk, Anna Bezryadina, and Zhigang Chen*

Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132

Received February 12, 2004

Dipole solitons in a two-dimensional optically induced photonic lattice are theoretically predicted and experimentally demonstrated for the first time to our knowledge. It is shown that such dipole solitons are stable and robust under appropriate conditions. Our experimental results are in good agreement with theoretical predictions.

OCIS codes: 190.5330, 190.0190.

Recently, self-trapping of light in periodic photonic lattices has aroused much interest because of its novel physics, light-routing applications, and connections to photonic crystals.[1,2] So far, scalar or vector lattice solitons as well as vortex lattice solitons have been studied both theoretically and experimentally.[3–12]

In this Letter we predict theoretically and demonstrate experimentally, for the first time to our knowledge, the existence of dipole solitons in a two-dimensional (2D) optically induced photonic lattice. These solitons are out of phase (OOP) between their two humps. In the absence of a photonic lattice these solitons cannot exist because of the repulsive force between the humps. However, in the presence of a lattice, the lattice could trap the two humps against repulsion, leading to the formation of dipole solitons. Our stability analysis shows that these solitons are stable in the intermediate-intensity regime. In addition, increasing the applied dc voltage further stabilizes these solitons. Experimentally, we observed these solitons in the regime of a high bias field and found that they are stable and robust under appropriate conditions. These novel types of lattice dipole soliton are expected to arise in other periodic nonlinear systems.

A nondimensional theoretical model for light propagation in a linear photorefractive lattice is[5]

$$iU_z + U_{xx} + U_{yy} - \frac{E_0}{1 + I_t + |U|^2}\,U = 0\,, \qquad (1)$$

where U is the slowly varying amplitude of the probe beam normalized by the dark irradiance of crystal I_d, and $I_l = I_0 \sin^2[(x+y)/\sqrt{2}]\sin^2[(x-y)/\sqrt{2}]$ is a square-lattice intensity function (in units of I_d) that closely resembles the lattice in our experiments. Here I_0 is the lattice peak intensity, z is the propagation distance (in units of $2k_1D^2/\pi^2$), (x, y) are transverse distances (in units of D/π), E_0 is the applied dc field [in units of $\pi^2/(k_0^2 n_e^4 D^2 r_{33})$], D is the lattice spacing, $k_0 = 2\pi/\lambda_0$ is the wave number (λ_0 is the wavelength), $k_1 = k_0 n_e$, n_e is the unperturbed refractive index, and r_{33} is the electro-optic coefficient of the crystal for an extraordinarily polarized light beam. Consistent with our experiment, we chose lattice intensity $I_0 = 3I_d$, lattice spacing $D = 20\ \mu$m, $\lambda_0 = 0.5\ \mu$m, $n_e = 2.3$, and $r_{33} = 280$ pm/V. Thus in this Letter one x or y unit corresponds to 6.4 μm, one z unit corresponds to 2.3 mm, and one E_0 unit corresponds to 20 V/mm in physical units.

Dipole solitons in Eq. (1) are sought in the form of $U = u(x, y)\exp(-i\mu z)$, where u is a real-valued function and μ is the propagation constant. Solution u is determined by an iteration method. These solitons have two peaks located in the two adjacent diagonal lattice sites, and these peaks are OOP. We found such dipole solitons in a large region of the parameter (E_0, μ) space. For instance, at $E_0 = 6$ these solitons exist when $1.455 < \mu < 3.51$ or equivalently when their peak intensities I_p are in the range of $0.94I_d < I_p < 15.7I_d$. Such solitons with peak intensities $12I_d$, $3I_d$, and I_d are displayed in Fig. 1 (the corresponding propagation constants μ are 1.80, 3.11, and 3.50, respectively). As seen from this figure, the location and localization of dipole solitons change with their peak intensities. However, in all these cases the intensity between the two main humps is very low (close to zero) because of the destructive interference, indicating the OOP feature of the dipole. At high intensities the two humps of the dipoles do not reside at the centers of two diagonal lattice sites [see Fig. 1(a)]. Instead, they reside at the outskirts of diagonal lattice sites, so that the separation between them is considerably larger than the diagonal lattice spacing. When the intensity of the dipole soliton

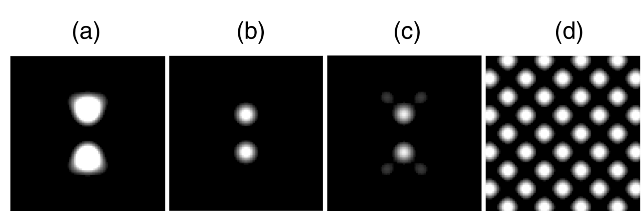

Fig. 1. Dipole solitons at $E_0 = 6$ and peak intensities of (a) $12I_d$, (b) $3I_d$, (c) I_d. (d) Lattice field.

is moderate, the two humps of the dipoles do reside at the centers of diagonal lattice sites as shown in Fig. 1(b), and the soliton is localized. If the intensity is low, however, the soliton becomes less localized, and the intensity field spreads to more lattice sites in the manner shown in Fig. 1(c).

In experimental conditions the input beams are typically a pair of OOP Gaussian beams. Thus it is desirable to simulate theoretical model (1) with a pair of Gaussian beams as initial conditions. For this purpose we take crystal length $L = 10$ mm, lattice spacing $D = 20$ mm, and lattice peak intensity $I_0 = 3I_d$. The peak intensities of both Gaussian beams are 1/6 of the lattice intensity (i.e., $0.5I_d$), and the FWHM of these Gaussian beams is 10 μm. The simulation results are plotted in Fig. 2 (top). We see that at a low field of 40 V/mm the beams experience discrete diffraction, in which light tunnels away from the dipole center along the original orientation [Fig. 2(b)]. The reason is that no light can be in lattice sites between the dipole because of destructive interference. Such a discrete diffraction pattern also confirms the initial phase relation between the two humps of the dipole. At a high dc field of 200 V/mm, dipole solitons are realized, as shown in Fig. 2(c) for which most of the light is trapped in the two lattice sites where the dipole sits initially at the input. Without the lattice the two OOP humps would repel each other[13] [Fig. 2(d)].

The dipole solitons predicted above were also observed in our experiment. Similar to earlier experiments with fundamental and vortex solitons in 2D optically induced lattices,[8,11] a biased photorefractive crystal (SBN:60, 5 mm × 5 mm × 8 mm) is used as a self-focusing nonlinear medium. The crystal is illuminated by a lattice beam created by periodic spatial modulation of a partially coherent beam ($\lambda_0 = 488$ nm) from a diffuse laser source.[14] The lattice beam is ordinarily polarized, with its principal axes oriented in the diagonal directions. The dipole beams, however, are extraordinarily polarized. With such a configuration the lattice remains nearly invariant, but the dipole itself experiences a strong self-focusing nonlinearity.[5] The two beams for the dipole are generated from a Mach–Zehnder interferometer, with a piezoelectric-transducer mirror tuning the relative phase between them to be $\sim\pi$ (i.e., OOP). The separation between the two beams is adjusted to match the diagonal lattice spacing ($\sim$28 μm). After exiting the interferometer, the two beams are launched into two nearby lattice sites in the vertical direction [Fig. 2(a)], propagating collinearly with the lattice beam through the crystal. In addition, a broad incoherent beam is used as background illumination for fine-tuning the nonlinearity.

Typical experimental results of dipole lattice solitons are shown in Fig. 2 (bottom panel). Intensity ratio I_0/I_d is $\sim$3, and the intensity of the dipole beam is $\sim$6 times weaker than that of the lattice. At a low bias field the dipole undergoes discrete diffraction in the lattice [Fig. 2(b)], exhibiting interesting patterns similar to those found in our simulation. At a high bias field the dipole beam is trapped by the lattice potential and forms a dipole lattice soliton [Fig. 2(c)]. Note that in the highly nonlinear regime, although some energy is radiated to the lattice sites away from the dipole, most of the energy is concentrated in the two sites matched by the input dipole. The initial phase structure is preserved after the dipole soliton is created, as seen from its output intensity pattern, in which destructive interference diminishes light between the two humps [Fig. 2(c)]. Should one of the two beams be turned off, the other forms a fundamental lattice soliton and redistributes the energy to its center as well as four neighboring sites along the principal axes of the lattice.[5,8] When the same dipole beam is launched into the crystal without the lattice, the dipole diverges [Fig. 2(d)] as expected.

The simulation and experimental results in Fig. 2 suggest that dipole solitons in theoretical model (1) may be stable. To investigate this issue, we first carry out a linear stability analysis for these solitons. For this purpose we perturb the solitons as $U = \exp(-\mu z)[u(x, y) + \tilde{U}(x, y, z)]$, where $u(x, y)$ is a dipole soliton and $\tilde{U} \ll 1$ is the infinitesimal perturbation. When this perturbed solution is substituted into Eq. (1), the linearized equation for $\tilde{U}$ can be derived. Starting with a random-noise initial condition, we simulated this linearized equation for long distances (hundreds of z units). If the solution grows exponentially, then the underlying dipole soliton will be linearly unstable, and the real part of the exponential constant (eigenvalue) will be the growth rate of infinitesimal perturbations. Otherwise, the dipole soliton would be linearly stable. We have carried out this stability analysis for all dipole solitons at two applied dc fields, $E_0 = 5$ and 6, and the growth-rate diagrams are plotted in Fig. 3 (left panel). We see immediately that the dipole solitons are linearly stable in the intermediate-intensity regime (and unstable otherwise). In particular, if $E_0 = 5$, these solitons are stable when $2.5I_d < I_p < 6.6I_d$. If E_0 increases to 6, these solitons become stable when $2.1I_d < I_p < 10I_d$, i.e, the stability region is almost doubled. Thus increasing the applied dc field stabilizes dipole solitons. Next we study the nonlinear evolution of dipole solitons under random-noise perturbations. The noise has a Gaussian distribution in the spectral k space with a FWHM that is 2 times larger than that of the soliton, and it has 5% of the soliton's power. To illustrate, we chose a linearly stable dipole soliton with

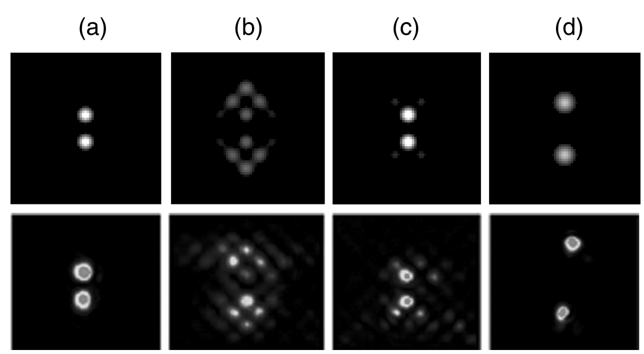

Fig. 2. Theoretical (top) and experimental (bottom) results of dipole solitons: (a) input; (b) output at low field; (c), (d) output at high field, with and without lattice.

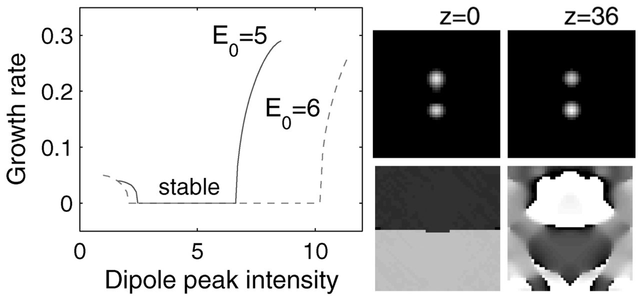

Fig. 3. Left panel, growth rates of infinitesimal perturbations on dipole solitons at $E_0 = 5$ and 6; right panel, intensities (top) and phases (bottom) of a dipole soliton with $E_0 = 6$ and peak intensity $I_p = 3I_d$ under 5% perturbations.

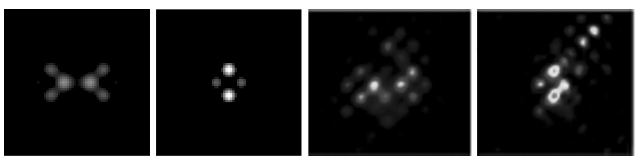

Fig. 4. Theoretical and experimental results of in-phase dipolelike solitons. From left to right, output at low and high fields from theory and the corresponding results from experiments.

$E_0 = 6$ and $I_p = 3I_d$. The simulation result is shown in Fig. 3 (right panel). The soliton does not break up even after 36 z units of propagation (corresponding to more than 80 mm in physical distance). In addition, the two lobes of the dipole remain OOP as in the input. This simulation result, as well as others that we have done with different parameters, shows that dipole solitons with intermediate intensities are both linearly and nonlinearly stable. This stability explains why dipole solitons are so robust in our experiment.

Finally, we mention that we have also discovered dipolelike solitons whose two peaks have the same phase. These in-phase dipolelike solitons are always linearly unstable, but this instability can be strongly suppressed in the regime of a high bias field. These solitons were observed in our numerical simulations and experiments under conditions analogous to those in Fig. 2, except that the two input beams are now in phase. Typical results are shown in Fig. 4. Details will be reported elsewhere. In comparison with Fig. 2, a clear distinction between the two types of soliton structure lies in the intensity redistribution for both discrete diffraction and nonlinear trapping.

In summary, we have demonstrated the formation of dipole solitons in 2D optically induced photonic lattices. The OOP dipole solitons are shown to be stable in a large region of the parameter space.

This work was supported in part by the U.S. Air Force Office of Scientific Research, NASA Experimental Program to Stimulate Competitive Research grants, the Natural Science Foundation of China (60328406), and the Research Corporation. J. Yang's e-mail address is jyang@emba.uvm.edu.

*Also with TEDA College, Nankai University, Tianjin, China.

References

1. D. N. Christodoulides, F. Lederer, and Y. Silberberg, Nature **424,** 817 (2003).
2. D. K. Campbell, S. Flach, and Y. S. Kivshar, Phys. Today **57**(1), 43 (2004).
3. H. S. Eisenberg, Y. Silberberg, R. Morandotti, A. R. Boyd, and J. S. Aitchison, Phys. Rev. Lett. **81,** 3383 (1998).
4. J. W. Fleischer, T. Carmon, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Phys. Rev. Lett. **90,** 023902 (2003).
5. J. W. Fleischer, M. Segev, N. K. Efremidis, and D. N. Christodoulides, Nature **422,** 147 (2003).
6. D. Neshev, E. Ostrovskaya, Y. Kivshar, and W. Krolikowski, Opt. Lett. **28,** 710 (2003).
7. J. Meier, J. Hudock, D. N. Christodoulides, G. Stegeman, Y. Silberberg, R. Morandotti, and J. S. Aitchison, Phys. Rev. Lett. **91,** 143907 (2003).
8. H. Martin, E. D. Eugenieva, Z. Chen, and D. N. Christodoulides, Phys. Rev. Lett. **92,** 123902 (2004).
9. B. A. Malomed and P. G. Kevrekidis, Phys. Rev. E **64,** 026601 (2001).
10. J. Yang and Z. Musslimani, Opt. Lett. **23,** 2094 (2003).
11. D. N. Neshev, T. J. Alexander, E. A. Ostrovskaya, Y. S. Kivshar, H. Martin, and Z. Chen, Phys. Rev. Lett. **92,** 123903 (2004).
12. J. W. Fleischer, G. Bartal, O. Cohen, O. Manela, M. Segev, J. Hudock, and D. N. Christodoulides, Phys. Rev. Lett. **92,** 123904 (2004).
13. J. S. Aitchison, A. M. Weiner, Y. Silberberg, D. E. Leaird, M. K. Oliver, J. L. Jackel, and P. W. E. Smith, Opt. Lett. **16,** 15 (1991).
14. Z. Chen and K. McCarthy, Opt. Lett. **27,** 2019 (2002).