Self-trapping and flipping of double-charged vortices in optically induced photonic lattices

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We report what is believed to be the first observation of self-trapping and charge-flipping of double-charged optical vortices in two-dimensional photonic lattices. Both on- and off-site excitations lead to the formation of rotating quasi-vortex solitons, reversing the topological charges and the direction of rotation through a quadrupolelike transition state. Experimental results are corroborated with numerical simulations. © 2006 Optical Society of America

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Optical waveguide arrays and photonic lattices have served as a test bench for studying many fascinating light behaviors in periodic systems.[1,2] One of the interesting phenomena is the propagation of optical vortices in two-dimensional (2D) lattices. Both theory[3,4] and experiments[5,6] have demonstrated the existence of self-trapped single-charged vortices (SCVs) as discrete vortex solitons. Unlike vortex solitons in continuum media that typically need self-defocusing nonlinearity,[7,8] those discrete vortex solitons in lattices were demonstrated with self-focusing nonlinearity. Recently, vortex dynamics associated with the angular momentum carried by the vortex beam, including charge-flipping,[9] topological transmutation and transformation,[10,11] and angular momentum transfer[12] in photonic lattices, has also attracted attention.

High-order vortices (with a phase accumulation of $2m\pi$ around a singular point, where m is the topological charge) are of particular interest for creating soliton clusters. Even during linear propagation a high-order vortex tends to break up into multiple SCVs ($m=1$). In isotropic continuous media with a saturable self-focusing nonlinearity, the vortex beam suffers from azimuthal modulational instabilities and breaks up into multiple soliton filaments that fly away from the vortex ring.[13] In nonlinear optical discrete media, the existence and stability of high-order vortex solitons has been a subject of mainly theoretical interest,[14,15] although necklacelike quasi-vortex solitons (without round-trip phase accumulation) have been demonstrated.[16] In particular, it has been suggested that, unlike stable lattice dipole, quadrupole, and cross-coupled dipole solitons,[17,18] true doubly charged vortices (DCVs) with a 4π helical phase structure ($m=2$) around the singular point cannot form stable solitons in 2D square lattices, and they tend to break up into either SCVs or filaments in a quadrupolelike style.

In this Letter, we present both experimental and numerical results of self-trapped DCVs in 2D square lattices that are optically induced with partially coherent light. We show that both on- and off-site excitations lead to the formation of dynamic quasi-vortex solitons, characterized by a rotating four-spot intensity pattern with both the direction of rotation and the helical phase structure reversing during propagation. The switching between clockwise ($m=+2$) and anticlockwise ($m=-2$) rotational modes of the vortex occurs periodically through a transition state, in which the vortex turns into a quadrupolelike structure with no phase variation across each intensity spot. We discuss the possible mechanism for such rotation and charge-flipping, in comparison with that of SCVs.

The experimental setup for this work is similar to that used in our earlier demonstrations of discrete solitons in lattices.[5,11,12] A biased photorefractive crystal [SBN:61 5 mm (a axis) $\times$ 10 mm (b axis) $\times$ 5 mm (c axis)] is employed to provide a saturable self-focusing nonlinearity. To generate a 2D square lattice, we use an amplitude mask to spatially modulate a partially spatially incoherent beam (488 nm) generated by use of a rotating diffuser. The mask is then imaged onto the input face of the crystal, creating a pixellike intensity pattern. The lattice beam is ordinarily polarized, so it induces a nearly linear waveguide array that remains invariant during propagation.[12] An extraordinarily polarized coherent beam passing through a phase mask of the DCV is used as a probe beam, propagating collinearly with the lattice. When needed, the vortex beam after exiting the crystal is sent into a Mach–Zehnder interferometer for phase measurement.

Typical experimental results are presented in Fig. 1, where both on- and off-site excitations with respect to lattice orientation are illustrated [Fig. 1(b)]. The intensity pattern of the input vortex beam and its interferogram with a plane wave are shown in Fig. 1(a), confirming the double topological charges ($m=2$). Without a bias field, the vortex breaks up into two SCVs during linear propagation. At a low bias field, the vortex undergoes discrete diffraction with its energy coupled to several lattice sites away from the vortex core, similar to that of a SCV ($m=1$).[5,6] Self-trapping of the DCV is achieved as the bias field is increased to above 2.0 kV/cm. As shown in [Fig. 1(c)], the vortex breaks up primarily into four intensity spots as for the discrete SCV soliton, but with a major difference in the phase structure. For the SCV soliton, it has been shown that the two diagonal spots are always out of phase. In fact, the relative phases

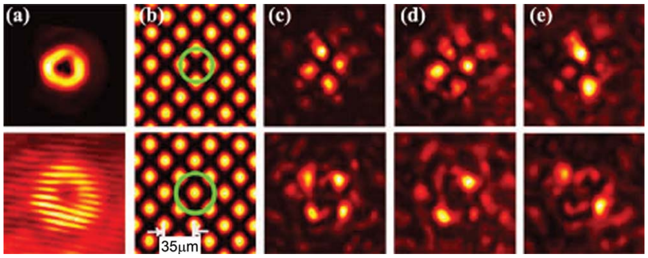

Fig. 1. (Color online) Experimental results of self-trapping of an off-site (top row) and an on-site (bottom row) double-charged vortex. (a) Input intensity pattern and interferogram of the vortex. (b) Lattice pattern with the vortex input position marked by the green circles. (c) Self-trapping of the vortex at bias field of 3.4 kV/cm. (d), (e) Interference between (c) and a broad beam (quasi-plane wave) with two different phase delays, showing two diagonal spots that are always in phase.

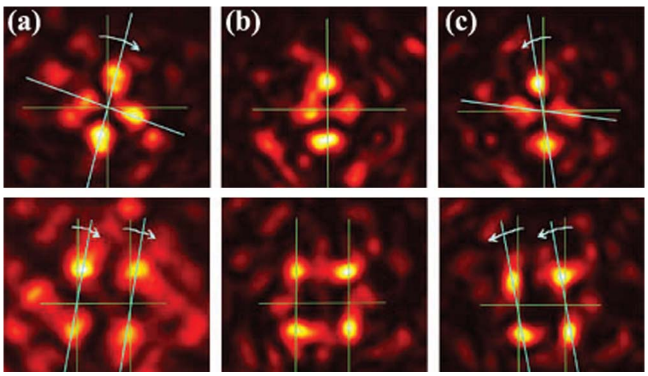

Fig. 2. (Color online) Experimental results of reversing rotation for off-site (top row) and on-site (bottom row) self-trapped vortices. (a)–(c) Output vortex patterns as the nonlinearity is increased gradually.

among the four spots changes in steps of $\pi/2$, and such a step-phase structure is frozen during propagation, confirming a true vortex soliton.[5] For the self-trapped DCV, a similar experiment shows that the two diagonal spots are always in phase [Fig. 1(d) and 1(e)]. Furthermore, the interferograms show that the two spots in one diagonal are out-of-phase with the other two spots in the other diagonal for both on- and off-site excitations. We note that, from Fig. 1(d) to Fig. 1(e), the relative phase between the vortex beam and the plane wave is changed by slightly moving a piezoelectric transducer mirror installed in the interferometer[5] while keeping all other experimental conditions unchanged. (The background noise is mainly from the plane wave.) From these measurements, it appears that the vortex beam breaks up into a quadrupole structure in lattices.

When the DCV breaks up into four spots in lattices, experimentally it is a challenge to distinguish between a true $m=2$ vortex and a quadrupole soliton: The interferogram in Figs. 1(d) and 1(e) would show similar results, while the interferogram in Fig. 1(a) could not be obtained with good visibility because of weak central intensity and background noise. Fortunately, the vortex carries angular momentum while the quadrupole does not. Based on that, we examine the four-spot pattern resulting from the vortex breakup at different levels of nonlinearity. By changing the vortex-beam intensity or the bias field (both controls the photorefractive nonlinearity), we observe that the four-spot pattern rotates slightly clockwise and then reverses the direction of rotation to counterclockwise as the strength of the nonlinearity is increased. Typical experimental results are shown in Fig. 2, where the on-site excitation was obtained by increasing the bias field and the off-site excitation was obtained by increasing the vortex intensity. These observations suggest that the vortex beam should undergo charge-flipping since the direction of rotation is related to the sign of the net topological charge.[9–12] Such rotation and flipping are attributed to the nonlinearity-induced momentum exchange between the vortex and the lattice, which would not occur for a quadrupole lattice soliton without vorticity.[17]

Our numerical modeling for propagation of DCVs in partially coherent lattices under conditions close to those from experiments presents a clear picture of undergoing dynamics. The partially coherent lattice is described by the so-called coherent density approach,[19] and the model is similar to that described in Ref. 20, except that the coherent Gaussian probe beam is replaced with a DCV beam. As in the experiment, two types of interferogram are generated at different propagation distances to obtain a picture of the phase profile of the DCV. In the first type, the vortex beam interferes with a tilted plane wave so as to allow us to examine the phase singularity at the vortex core [as in Fig. 1(a)]. Advantageously for numerical simulation, we can obtain such interferograms even when the vortex breaks up in lattices by uniformly increasing the amplitude of the vortex field so the vortex core has visible intensity. In the second type, the phase of the plane wave has been adjusted such that it is in phase with one of the four spots of the vortex filaments at chosen propagation distances. The latter type of interferogram enables the visualization of relative phase among the vortex filaments [as in Figs. 1(d) and 1(e)].

Typical numerical results using parameters from the experiment are presented in Figs. 3 and 4. Both on- and off-site excitations corresponding to Fig. 1 are illustrated in Fig. 3, where Fig. 3(a) shows the input phase structure and interferogram of the vortex. The ring-shaped DCV [Fig. 3(b)] breaks up and settles down into a stable four-spot pattern after

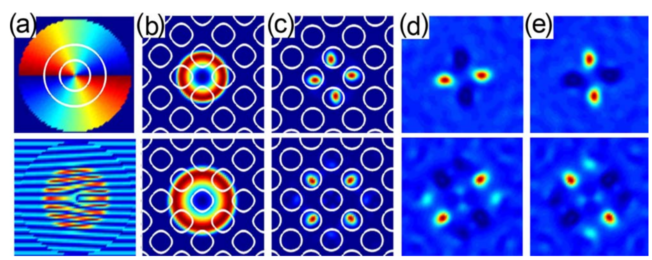

Fig. 3. (Color online) Numerical results of self-trapping of an off-site (top row) and an on-site (bottom row) vortex using parameters corresponding to those in Fig. 1. (a) Input phase diagram and interferogram of the vortex. (b), (c) Vortices at $z=0$ and $z=10$ mm, respectively (white contour lines indicate lattice structure). (d), (e) Interference output as in Figs. 1(d) and 1(e).

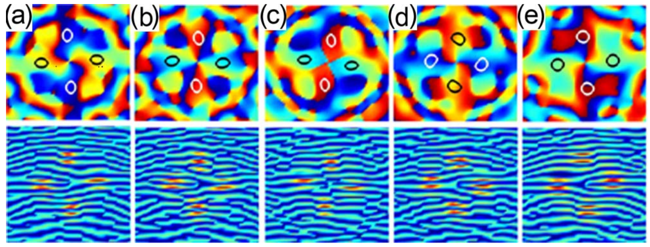

Fig. 4. (Color online) Snapshots of phase distribution (top) and interferograms (bottom) of the off-site vortex at different propagation distances. The circles in the phase diagrams correspond to vortex filaments. From (a) to (e), $z = 7.75, 8.25, 10.25, 10.75, 12.25$ mm. (c) Quadrupolelike state where the rotation starts to reverse.

about 5 mm of nonlinear propagation with the lattice beam. One snapshot of such an intensity pattern at 10 mm propagation distance is shown in [Fig. 3(c)]. Clearly the locations of the four spots match those of the four central lattice sites. Two interferograms corresponding to Figs. 1(d) and 1(e) are illustrated in Figs. 3(d) and 3(e), which clearly show that the two diagonal spots are in-phase with each other but out-of-phase with the two spots along the other diagonal, as observed in the experiment. Simulations to a longer propagation distance (>30 mm) with fixed parameters confirm that this relative phase distribution among four spots remains unchanged during propagation. However, the entire phase distribution of the vortex field varies during propagation, as represented by the periodic appearance of a $m=+2$ vortex, a quadrupole, and a $m=-2$ vortex. This is clearly illustrated by the phase diagrams and the aforementioned first-type interferograms shown in Fig. 4, where snapshots of the off-site DCV beam were taken at different propagation distances. The phase distribution shown in Figs. 4(a) and 4(b) indicates the existence of a vortex with a topological charge $m=+2$, rotating clockwise. A quadrupole, with a step phase rather than a graded phase around the center, is shown in Fig. 4(c), followed by the reappearance of the vortex with the opposite charge, $m=-2$, rotating counterclockwise [Fig. 4(d) and 4(e)]. In all cases the two spots in one diagonal remain in-phase with each other but out-of-phase with the spots in the other diagonal, as seen from these phase diagrams as well as from the interferograms of Figs. 3(d) and 3(e). Excitation of on-site DCVs shows similar behavior, but the rotation and flipping occur relatively slower.

Numerically, we have found that the small phase gradient across each of the four spots, which results from the initial vortex field, is responsible for the rotation. Should we launch four individual spots with a flat phase across each spot (as in a quadrupole) instead of the DCV, no rotation will be observed. In fact, simulations under different conditions to longer distances show that the quadrupole, as shown in Fig. 4(c), always appears as a transition state before charge-flipping, in which the degree of rotation has reached a maximum. These novel vortex states with the vorticity flipping periodically arise from the nonlinearity-induced momentum exchange through the lattice, as also predicted for SCVs where perturbation and asymmetry are necessary to initiate such dynamics in isotropic media.[9] Should we use a fully anisotropic photorefractive model in our simulation, the DCV might break up into multiple SCVs during charge-flipping and topological transformation.[11]

In summary, we have demonstrated dynamic double-charged quasi-vortex solitons that undergo rotation and charge-flipping in optically induced partially coherent photonic lattices.

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References

1. D. N. Christodoulides, F. Lederer, and Y. Silberberg, Nature **424**, 817 (2003).
2. Y. S. Kivshar and G. P. Agrawal, *Optical Solitons* (Academic, 2003).
3. B. A. Malomed and P. G. Kevrekidis, Phys. Rev. E **64**, 026601 (2001).
4. J. Yang and Z. H. Musslimani, Opt. Lett. **28**, 2094 (2003).
5. D. N. Neshev, T. J. Alexander, E. A. Ostrovskaya, Yu. S. Kivshar, H. Martin, I. Makasyuk, and Z. Chen, Phys. Rev. Lett. **92**, 123903 (2004).
6. J. W. Fleischer, G. Bartal, O. Cohen, O. Manela, M. Segev, J. Hudock, and D. N. Christodoulides, Phys. Rev. Lett. **92**, 123904 (2004).
7. G. A. Swartzlander and C. T. Law, Phys. Rev. Lett. **69**, 2503 (1992).
8. A. S. Desyatnikov, Y. S. Kivshar, and L. Torner, in *Progress in Optics*, E. Wolf, ed. (North-Holland, 2005), Vol. 47, p. 219.
9. T. J. Alexander, A. A. Sukhorukov, and Yu. S. Kivshar, Phys. Rev. Lett. **93**, 063901 (2004).
10. A. Ferrando, M. Zacares, M. Garcia-March, J. A. Monsoriu, and P. F. de Cordoba, Phys. Rev. Lett. **95**, 123901 (2005).
11. A. Bezryadina, D. N. Neshev, A. S. Desyatnikov, J. Young, Z. Chen, and Yu. S. Kivshar, in *Conference on Lasers and Electro-Optics (CLEO)* (Optical Society of America, 2006), paper number QFB1.
12. Z. Chen, H. Martin, A. Bezryadina, D. N. Neshev, Y. S. Kivshar, and D. N. Christodoulides, J. Opt. Soc. Am. B **22**, 1305 (2005).
13. W. J. Firth and D. V. Skryabin, Phys. Rev. Lett. **79**, 2450 (1997).
14. P. G. Kevrekidis, B. A. Malomed, Z. Chen, and D. J. Frantzeskakis, Phys. Rev. E **70**, 056612 (2004).
15. H. Sakaguchi and B. A. Malomed, Europhys. Lett. **72**, 698 (2005).
16. J. Yang, I. Makasyuk, P. G. Kevrekidis, H. Martin, B. A. Malomed, D. J. Frantzeskakis, and Z. Chen, Phys. Rev. Lett. **94**, 113902 (2005).
17. J. Yang, I. Makasyuk, A. Bezryadina, and Z. Chen, Stud. Appl. Math. **113**, 389 (2004).
18. M. Rodas-Verde, H. Michinel, and Y. S. Kivshar, Opt. Lett. **31**, 607 (2006).
19. D. N. Christodoulides, T. H. Coskun, M. Mitchell, and M. Segev, Phys. Rev. Lett. **78**, 646 (1997).
20. H. Martin, E. Eugenieva, Z. Chen, and D. N. Christodoulides, Phys. Rev. Lett. **92**, 123901 (2004).