Self-trapping of optical vortices in photonic lattices optically induced with self-defocusing nonlinearity

Daohong Song[1], Liqin Tang[1], Cibo Lou[1], Xiaosheng Wang[2], Jingjun Xu[1], and Zhigang Chen[1,2]
1. The Key Laboratory of Weak-Light Nonlinear Photonics, Ministry of Education and TEDA Applied Physical School, Nankai University, Tianjin 300457, China
2. Department. of Physics and Astronomy, San Francisco State University, San Francisco, CA 94132

H. Susanto, K. Law and P. G. Kevrekidis
Dept. of Mathematics and Statistics, University of Massachusetts, Amherst, MA 01003

Abstract: We demonstrate self-trapping of singly- and doubly-charged vortices in a self-defocusing "backbone" photonic lattice. While the singly-charged vortex can evolve into a gap vortex soliton, the doubly-charged tends to turn into quasi-vortex or quadrupole structure.

OCIS codes: (190.4420) Nonlinear optics, transverse effects in; (250.5530) Pulse propagation and solitons

Recently, spatial gap solitons have been demonstrated in a number of experiments in fabricated waveguide arrays and optically induced photonic lattices. However, gap vortices with their propagation constants located inside a true photonic bandgap due to Bragg-reflection have only been observed in a *self-focusing* lattice as second-band vortex solitons (bifurcating from the top of the second band at the Brillouin-zone edge where diffraction is normal) [1]. Gap vortex solitons in *self-defocusing* lattices have never been demonstrated to our knowledge, although they have been predicted to exist as spatially localized topological states in Bose-Einstein Condensates confined by an optical lattice [2] as well as in photorefractive crystals with an optically imprinted photonic lattice [3, 4].

Here we report the first experimental demonstration of 2D gap vortex solitons by on-axis excitation of a single vortex beam in a self-defocusing "backbone" photonic lattice. We show that a singly-charged (m=1) vortex can evolve into a gap vortex soliton, but a doubly-charged (m=2) vortex tends to turn into a quasi-vortex or quadrupole-like structure. The k-space spectra and interferograms (with a plane wave) of the self-trapped vortices from both experiments and numerical simulations are presented, and their stability is also studied numerically. Our theoretical analysis finds good agreement with experimental observations.

The experimental setup used for this study is similar to that used for observation of discrete (semi-infinite gap) vortex solitons in self-focusing lattices [5, 6], except that we now use self-defocusing lattices as we used recently for generation of gap soliton trains [7]. The lattice is induced in a photorefractive SBN crystal by a spatially modulated partially coherent light beam sent through an amplitude mask. The mask is appropriately imaged onto the input face of the crystal, creating a periodic input intensity pattern for lattice induction. With a negative bias voltage, the periodic intensity pattern induces a "backbone" waveguide lattice, as the crystal turns into a defocusing nonlinear medium. In all experiments, the lattice beam is ordinarily-polarized while the vortex beam is extraordinarily-polarized. Typical experimental results are summarized in Fig. 1, where off-site excitations (the vortex core on an index minimum) of both m=1 and m=2 vortices are illustrated. The interferograms of the input vortex beam with a plane wave are shown in Fig. 1(a), confirming the topological charge. Self-trapping of the vortices is achieved at a bias field of about -1.2kV/cm as shown in Fig. 1(b). Both singly- and doubly-charged vortices break up primarily into four intensity spots, similar to the discrete vortex solitons [5, 6] but with longer tails along principle axes. In order to identify their phase structures, a tilted plane wave is sent to interfere with the output vortex pattern [Fig.1(c)], and it is found that the vortices maintain the helical phase structure after 10 mm of propagation through the crystal. Sending a co-axial broad Gaussian beam as interfering beam, we can see clearly that the phase structures for self-trapped m=1 and m=2 vortices are different [Fig. 1(d)]. The measured k-space power spectra are shown in Fig. 1(e). Numerical beam-propagation simulation to longer propagation distance (up to 40 mm) indicates that the phase singularity can maintain for m=1 vortex, but not for m=2 vortex (the latter evolve into a quadrupole structure), and the k-space spectra concentrate into the edges (corners) for m=1 (m=2) vortex in the first Brillouin Zone.

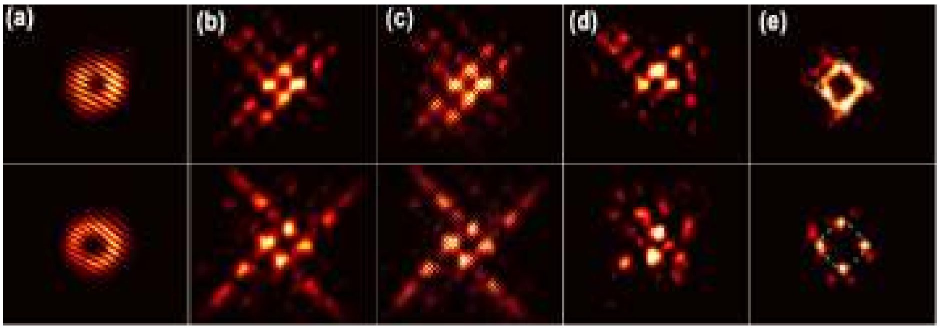

Fig. 1: Experimental results of self-trapping of singly-charged (top) and doubly-charged (bottom) vortices in a defocusing photonic lattice. (a) interferogram showing the phase of the vortex beam, (b) self-trapped vortex pattern, (c, d) interferogram between (b) and a tilted plane wave and an on-axis Gaussian beam, respectively, and (e) the k-space spectrum.

The above observations are further corroborated by numerical analysis using a model similar to that used in Ref. [8] but here a self-defocusing nonlinearity is employed. Figure 2 shows the numerical solutions illustrating a stationary vortex of m=1 and a stationary out-of-phase quadrupole (first column), corresponding to the experimental results in Fig. 1. The second column presents the phase structure of these solutions. The third column shows their Fourier spectra, indicating that the quadrupole bifurcates from the M-points in the first band at the corners of the first Brillouin Zone, but the m=1 gap vortex has much richer spectrum. Theoretically, we find that the m=1 vortex can be stable, i.e. the maximum instability growth rate satisfies $\max[\mathrm{Re}(\lambda)]=0$, in a wide fraction of its existence region (last column), but the quadrupole, which in a way can be interpreted as a m=2 quasi-vortex, are not unstable in its entire region of existence although such instability may not be observable with experimental crystal length.

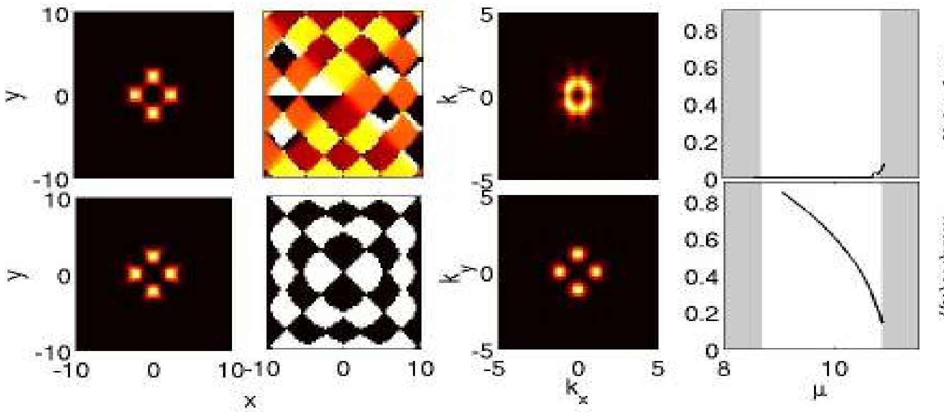

Fig. 2: Numerical results of self-trapped singly-charged vortices (top) and quadrupoles (bottom). Shown are typical stationary patterns (first column), corresponding phase structure (second column), Fourier spectra (third column), and maximal instability growth rate of the solutions (fourth column). Zero growth rates indicate that the self-trapped structure is linearly stable.

In summary, we have demonstrated 2D gap vortex solitons by on-axis excitation of a single vortex beam in an optically induced photonic lattice with self-defocusing nonlinearity. Our theoretical results are in good agreement with experimental observations.

This work was supported by the 973 Program, NSFC, PCSIRT, NSF and AFOSR. We thank J. Yang, C. Denz for discussions.

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