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Abstract: We demonstrate self-trapping of singly-charged vortices at the surface of an optically induced two-dimensional photonic lattice. Under appropriate conditions of self-focusing nonlinearity, a singly-charged vortex beam can self-trap into a stable semi-infinite gap surface vortex soliton through a four-site excitation. However, a single-site excitation leads to a quasi-localized state in the first photonic gap, and our theoretical analysis illustrates that such a bandgap surface vortex soliton is always unstable. Our experimental results of stable and unstable topological surface solitons are corroborated by direct numerical simulations and linear stability analysis.

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References and links

1. Introduction

In recent years, there has been an increased interest in the study of nonlinear discrete surface waves in periodic structures [1,2]. Discrete surface solitons were first proposed and experimentally demonstrated at the edge of one-dimensional (1d) photonic lattices [3–7], and subsequently they were also suggested and observed in 2D optical settings [8–10]. In fact, the phenomena of nonlinear surface states were enriched by prediction and demonstration of a variety of surface or interface solitons in the 2D domain, including multipole mode surface solitons [11], angular surface solitons [12], lattice interface solitons [13], and surface soliton arrays [14], to name just a few. Despite of these efforts on surface solitons, to our knowledge, no experimental work has investigated self-trapping of optical vortices at the surfaces of optical periodic structures. Thus far, there has been only limited theoretical work on surface vortex solitons: in one case, it was shown that in a discrete model of nonlinear Schrödinger equation surface vortex solitons could not exist exactly at the interface between a periodic medium and a homogeneous medium [15]. In another case, however, the solutions of lattice vortex solitons were found at the interface between two periodic media with different modulation indices [16]. While discrete vortex solitons propagating inside an otherwise uniform photonic lattice were predicted [17–20] and demonstrated successfully in a number of experiments [21–24], it is natural to ask whether vortex solitons be established at the surfaces or interfaces of optical periodic structures.

In the present work, we investigate both experimentally and theoretically the self-trapping of singly-charged vortex (SCV) beams at the surface of 2D photonic lattices with a self-focusing nonlinearity. In our experiment, two different excitation schemes (single-site [23] or four-site [21,22] depending on whether the vortex ring covers one surface site or four nearest lattice sites near the surface) lead to different features of nonlinear self-trapped vortices. Specifically, a SCV beam under the four-site excitation can evolve into a stable discrete surface vortex soliton in the semi-infinite gap. We also found the solution for such a surface vortex soliton in our numerical simulation of the continuum model with periodic potentials, which was not captured by the discrete model in previous work [15]. On the other hand, a SCV beam under the single-site excitation evolves into a quasi-localized surface state in the first photonic bandgap. However, in this latter case, our theoretical results from both direct evolution of the system and bifurcation analysis indicate that such self-trapped surface vortices are unstable.

2. Experimental results

Our experimental setup is similar to that used earlier [9,14], except that now the probe beam is a vortex beam. An interface between a 2D optical lattice (~30µm spacing) and a homogenous medium is established by optical induction in a SBN:61 photorefractive crystal.
After the Talbot effect of the periodic intensity pattern is suppressed, a sharp interface is generated at the crystal input [Fig. 1(a)], but it diffracts after 10 mm of linear propagation through the crystal [Fig. 1(b)]. With an appropriate level of nonlinearity, the lattice surface restores and remains nearly invariant through the crystal [Fig. 1(c)]. An extraordinarily-polarized SCV beam [Fig. 1(d)] is created with a computer-generated vortex mask, and is sent to propagate collinearly with the lattice beam along the surface. The size of the input vortex beam can be varied in order to cover either a single site or four sites on or close to the surface.

Fig. 1. Optically induced semi-infinite square lattices. Shown are the lattice beam at (a) input, (b) linear output, and (c) nonlinear output. (d) zoom-in interference pattern of an input vortex beam at the surface with an inclined plane wave.

First, we use the single-site excitation so the vortex ring covers only one lattice site. This excitation scheme is similar to that used for demonstration of second band vortex solitons [23] except that the excitation here is at the surface [Fig. 2(a)]. The vortex beam exhibits asymmetric discrete diffraction when its intensity is low but self-traps at the surface site when its intensity is high while keeping the bias field (2.2kV/cm) unchanged. Typical experimental results are presented in Fig. 2. When the nonlinearity is absent (the vortex-to-lattice beam intensity ratio is less than 1:10), the vortex beam diffracts as shown in Fig. 2(b). The diffraction tails have double intensity peaks at each lattice site [Fig. 2(b)], indicating the excitation of second band Bloch modes. The tail going into the lattice is much longer than that at the lattice surface, owing to surface enhanced reflection [4,9]. (Note that the diffraction could be much stronger if the lattice potential is reduced or the crystal length increased). As we increase the intensity ratio to 1:3, self-trapping of the vortex at the lattice surface occurs when the vortex confines more at the site of initial excitation, maintaining a donut-shaped pattern [Fig. 2(c)]. To verify its phase singularity, a tilted plane wave is introduced to interfere with the surface vortex beam. The single fork remains in the interferogram [Fig. 2(d)], indicating that the phase singularity is preserved during the 1 cm experimental propagation length. Since the input vortex beam is tightly focused, its initial $k$-space spectrum extends beyond the first Brillouin zone (BZ) [23]. Such input condition excites high band Bloch modes. In the case of the self-focusing nonlinearity, this leads to that the power spectrum is concentrated at the normal diffraction regions outside the first BZ but close to the high-symmetry X-points, as shown in Fig. 2(e). Apparently, such self-trapped vortex states arise from excitation of Bloch modes near the X-points of the second Bloch band. These experimental observations are compared with numerical results obtained from beam propagation simulations using experimental conditions. The numerical model we used is a nonlinear wave equation with a 2D square lattice potential under the self-focusing saturable nonlinearity [8,9], and the simulation results (Fig. 2, bottom) agree well with experimental observations. Although this agreement is obtained within 1 cm of crystal length, our theoretical analysis below shows that these quasi-localized surface states residing in the first photonic bandgap are unstable and thus would break up upon long distance propagation. In addition, what we demonstrated here is nonlinear surface modes, as our numerical simulation shows that the vortex cannot evolve into a single-site linear surface mode when the surface is deformed as in Fig. 1(c).
Fig. 2. Experimental (top) and numerical (bottom) results of vortex self-trapping under single-site surface excitation. (a) Lattice beam superimposed with the vortex beam, (b) linear and (c) nonlinear output of the vortex beam, where blue dashed line indicates the surface location, (d) zoom-in interferogram of (c) with an inclined plane wave, and (e) $k$-space spectrum of (c). The dashed square in (e) marks the boundary of the first Brillouin zone.

Next, we use the four-site excitation so the vortex ring is expanded to cover four nearest lattice sites at the surface [the vortex core sits in the index minimum as off-site excitation, as shown in Fig. 3(a)] Under appropriate nonlinear conditions, the SCV self-traps into a discrete surface vortex soliton. Typical experimental results are presented in Fig. 3. At low nonlinearity, the vortex beam exhibits discrete diffraction [Fig. 3(b)]. Notice that in this case the diffracted intensity pattern does not have fine features of double-peak in each lattice site, different from that of single-site excitation [Fig. 2(b)]. This suggests that, under this lattice condition, the expanded vortex excites the first band Bloch modes. At high nonlinearity, self-trapping of the vortex beam into a four-spot pattern is achieved [Fig. 3(c)]. Due to that the induced surface is slightly deformed [Fig. 1(c), the four-spot does not match a perfect square pattern. For comparison, the vortex nonlinear output in a homogeneous crystal (i.e., without the induced lattice) under the same bias condition is shown in the insert of Fig. 3(c), where the vortex breaks up into two diverging and rotating spots due to azimuthal modulation instability. To monitor the phase structure of the self-trapped vortex, an inclined plane wave was again introduced for interference, and the vortex singularity persists clearly in the nonlinear output [Fig. 3(d)]. The nonlinear spectrum [Fig. 3(e)] is also different from that of single-site excitation shown in Fig. 2(e), since now most of the energy is concentrated in the central region of normal diffraction within the first BZ. This indicates that the surface vortex soliton is formed in the semi-infinite gap with modes primarily from near the $\Gamma$-point of the first Bloch band. Our numerical simulation (Fig. 3, bottom) of vortex propagation under the

Fig. 3. Experimental (top) and numerical (bottom) results of vortex self-trapping under four-site surface excitation. The insert in (c) shows the breakup of vortex beam into two spots without the induced lattice. Caption for (a-e) is the same as in Fig. 2.
Fig. 4. Numerical simulation of single- (top) and four-site (bottom) excitation of a SCV after 4-cm of nonlinear propagation. Shown are (a) vortex output intensity pattern and (b) its corresponding interferogram, and (c) side-view of the vortex propagation to z = 4 cm.

four-site excitation finds good agreement with experimental observation. As shown below, this four-site surface vortex soliton can be stable and thus remains intact for long distances.

3. Numerical results

Experimentally, it is a challenge to monitor the stability of above self-trapped surface vortices due to limited propagation distance along the edge of 2D induced photonic lattices as restricted by the crystal length. To address the stability issue, i.e., whether these self-trapped states can persist for longer propagation distances, we perform numerical simulations to much longer distances than the crystal length along with systematic linear stability analysis. We find that the single-site Bragg-reflection gap surface vortices are always unstable, whereas the four-site semi-infinite gap vortices can be stable within a certain parameter range. Results from beam propagation simulation up to 4 cm are shown in Fig. 4. There is an obvious difference in the output for two different excitation schemes. For the four-site excitation, the intensity pattern of the vortex consists of four equal-intensity lobes which remain invariant during propagation. The interferogram obtained by interfering the self-trapped vortex with an inclined plane wave shows clearly that the vortex singularity persists. On the other hand, the single-site vortex is unstable during nonlinear propagation, and the output intensity pattern tends to break up after certain propagation distance beyond the crystal length. We mention that stable second-band vortex solitons have been demonstrated inside uniform lattices [23].

Finally, we study the stability of the self-trapped vortices by means of linear stability analysis using the parameters corresponding to experimental conditions. The nonlinear model equation is

$$\left[i\partial_t + \nabla^2 + \beta + \frac{\sigma}{1 + |U|^2} \nabla U \right] U = 0,$$

where $U$ is the beam envelope, $\beta$ is the propagation constant, $\sigma = -21.6$, and $V = 5\cos^2[(x+y)/\sqrt{2}]\cos^2[(x-y)/\sqrt{2}]$ is the lattice potential when $y + \pi/\sqrt{2} > x$ but $V = 0$ elsewhere. We find the stationary soliton solutions, and then use ansatz $u(x, y, z) = U(x, y) + v(x, y)e^{i\xi} + w(x, y)e^{i\psi}$ for stability analysis. In Fig. 5, we showcase the results of our bifurcation computations for the exact stationary states through illustrating the optical power of the nonlinear waveforms as a function of the propagation constant, along with results of linear stability analysis for the obtained states by means of the maximal real part of the linearization eigenvalues $\lambda$, i.e., the instability growth rate. We find that the four-site surface vortex can indeed be stable [Fig. 5(a)] for sufficiently large propagation constant in the semi-infinite gap, while the single-site one in the first band-gap cannot [Figs. 5(d)–5(f)]. Additionally, the four-site vortex loses its stability while close to...
the band-edge [Figs. 5(b), 5(c)], and in some cases it breaks up into unstable quadrupolar structure. The single-site vortex [shown in Figs. 5(d), 5(e)] disappears at the second band-edge, and becomes more unstable when close to the edge of the first band [Fig. 5(f)]. The vortex tails are noticeable with Bloch mode characteristics when the propagation constants of single-site vortex solutions approach to the band edge. From Fig. 5, it should be noted that the four-site vortex, even when weakly unstable, has an instability typically much weaker in growth rate than that of the single-site vortex.

4. Conclusion

In summary, we have studied both experimentally and numerically self-trapping of singly-charged vortices at the surface of 2D optically induced photonic lattices with self-focusing nonlinearity. We show that the four-site SCV beam can self-trap into a stable discrete surface vortex soliton within the semi-infinite gap, while the single-site vortex in the photonic bandgap is always unstable in the whole existence region. Our experimental results are corroborated by direct numerical simulations and bifurcation analysis.

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