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Surface vortex solitons near boundaries of photonic lattices

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Abstract
We report on the existence and properties of vortex solitons at the edge and in the corner of two-dimensional triangular photonic lattices. We describe novel types of discrete vortex solitons, as well as the ring surface vortex solitons, localized in the lattice corners or at its edges. We observe that stable surface vortex solitons exist only in the form of a discrete six-lobe solution at the edge of the photonic lattice. Oscillations and irregular dynamics are observed for the ring vortex solutions and discrete two- and three-lobe solutions.

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(Some figures may appear in colour only in the online journal)

1. Introduction

Surface solitons propagating along the interface of two different media have attracted a great deal of interest in optical systems [1, 2]. It has been demonstrated that two-dimensional (2D) lattice interfaces support surface solitons [3]. Experimental observation of 2D solitons was reported at the boundaries of a finite optically induced photonic lattice [4, 5], at the interface between square and hexagonal waveguide arrays [6] and at the interface between a homogeneous lattice and a superlattice [7].

In recent years, special attention has been devoted to nonlinear surface vortex solitons. Such solitons are supported by the interface of two different optical lattices imprinted in Kerr-type focusing nonlinear media [8] and have been demonstrated experimentally at the surface of an optically induced 2D photonic lattice [9].

In this paper, we study the existence and properties of vortex solitons in truncated 2D photorefractive photonic lattices. Recent experimental results [9] predict the existence of stable vortex solitons at the edge of 2D square photonic lattice in the form of four-site vortex solitons. We extend the analysis to the triangular lattice and also include corner geometry. We describe novel types of discrete vortex solitons as well as ring surface vortex solitons, localized in the lattice corners or at its edges. Discrete vortex surface solitons are observed in the form of two-, three- or six-lobe solutions. We demonstrate that the lattice surface produces a strong stabilizing effect only on the discrete vortex solitons in the form of the six-lobe solution. Other types of discrete solitons are unstable during propagation; oscillations and irregular dynamics are observed with an increase in the the beam power or propagation constant.

2. Basic model equations

The behavior of vortex beams propagating in a photonic lattice is described by the wave equation in the paraxial approximation for the beam envelope in the photorefractive crystal. The model equation in the computational space is [10]

$$\mathrm{i}\,\partial_z U + \Delta U + \Gamma \frac{|U|^2 + I_g}{1 + |U|^2 + I_g} U = 0, \quad (1)$$

where z is the propagation distance, U is the slowly varying envelope of the propagating beam, Δ is the transverse Laplacian, Γ is the dimensionless beam coupling constant and $|U|^2$ is the laser light intensity measured in units of the background intensity I_d. I_g is the intensity distribution of the optically induced triangular photonic lattice.

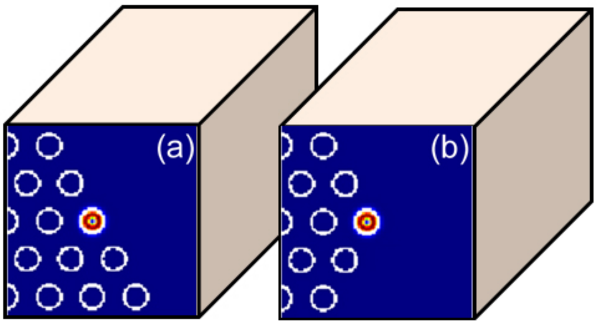

Figure 1. Problem geometry with input vortex beams at the edge (a) and in the corner (b) of the truncated triangular photonic lattice.

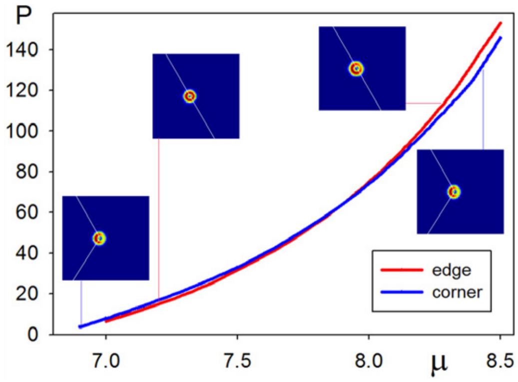

Figure 2. Power diagram for the existence of surface ring vortex solitons. The insets show the corresponding intensity distributions for corner and edge ring vortex solitons. Parameters: $\Gamma = 11$; maximum lattice intensity $I_0 = 1$.

First, we investigate the existence of vortex solitonic solutions. The above equation suggests their existence in the form $U = u(x, y)\mathrm{e}^{\mathrm{i}\mu z}$, where $u(x, y) = |u(x, y)| \exp[\mathrm{i}\varphi(x, y)]$ is a complex-valued function, $\varphi(x, y)$ is the phase distribution and μ is the propagation constant. After the substitution of the solitonic solution form into equation (1), it transforms into

$$-\mu u + \Delta u + \Gamma u \frac{|u|^2 + I_g}{1 + |u|^2 + I_g} = 0. \qquad (2)$$

The solitonic solutions can be found from equation (2) by using the modified Petviashvili's iteration method [11, 12]. We determine different classes of vortex surface solitons by launching vortex beams whose rings are covering one or more lattice sites near the boundaries of the photonic lattice. Vortex beams with topological charge equal to 1 are used as input. In this paper, we analyze four different classes of surface vortex solitons: the ring vortex and discrete solitons consisting of two, three and six lobes.

Next, to investigate the stability of such solutions, we use vortex surface solitons as input beams in equation (1). The numerical procedure is based on the fast-Fourier-transform split-step numerical algorithm.

3. Surface vortex states

To investigate vortex surface states, we choose the ring of the input vortex beam to cover the corresponding lattice sites at the edge and in the corner of the triangular photonic lattice (figure 1). Incident vortex beams covering only one lattice site are used for the investigation of the ring vortex surface states. Corner and edge vortex solitons are found in the same range of the propagation constant μ (figure 2). The corresponding power diagrams are presented, with characteristic outcomes as insets. Surface states with symmetric ring profiles exist only at the edge of the lattice and for lower values of the propagation constant. However, asymmetric surface vortex states are observed for both the corner and edge cases. All types of ring vortex surface solitons are unstable during propagation, similar to the experimental results [9].

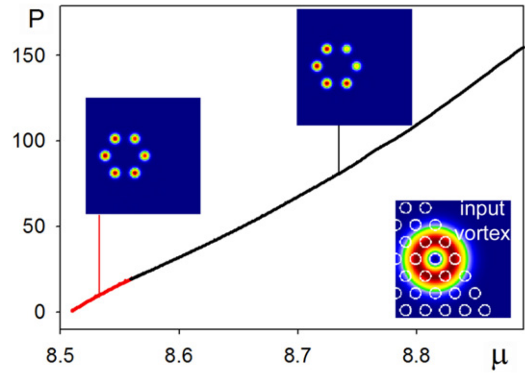

Figure 3. Six-lobe discrete surface vortex solitons. The power diagram is shown for the edge surface modes, with the corresponding solutions as insets. The region with stable symmetric six-lobe solutions is presented in red. The input vortex beam and the layout of lattice beams are also shown as an inset. The parameters are as in figure 2.

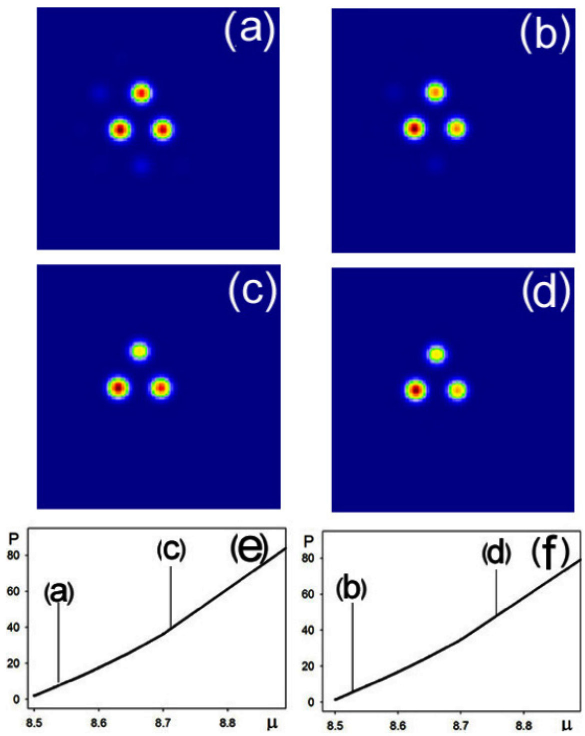

Figure 4. Three-lobe discrete surface vortex solitons. Different kinds of edge (left column) and corner (right column) solutions are presented with the corresponding power diagrams (e) and (f). The parameters are the same as in figure 2.

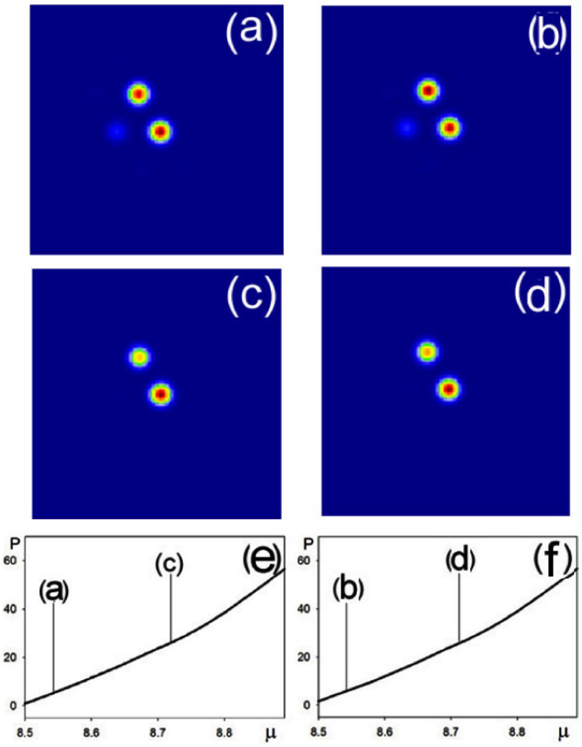

Figure 5. Two-lobe discrete surface vortex solitons. The figure layout is as in figure 4. The parameters are the same as in figure 2.

To investigate discrete surface vortex solitons, we choose broader input vortex beams, to cover more lattice sites at the lattice edge and in the corner. Figure 3 presents six-lobe discrete vortex solutions at the lattice edge. The edge surface modes are observed in the form of symmetric as well as asymmetric six-lobe discrete vortex solitons. But, in the corner, only asymmetric modes are found. The corresponding power diagram for the edge states is presented in figure 3, with characteristic solutions as insets. The input vortex beam with the layout of lattice beams is also presented. Investigating the stability of such vortex solitons, we find that only symmetric six-lobe edge solutions are stable during propagation, for long propagation distances. Such stable solutions are observed for lower values of the propagation constant, as well as for lower beam powers (the region marked with a red line in figure 3).

Figure 4 summarizes our results for the three-lobe surface vortex solitons. These solutions are observed using input vortex beams covering three neighboring lattice sites. Symmetric three-lobe vortex states are observed only at the lattice edge (figure 4(a)). Asymmetric edge states (figure 4(c)) are found by increasing the beam power. The corresponding power diagram for edge solutions is presented in figure 4(e). The corner surface modes are observed only as asymmetric solutions (figures 4(b) and (d)). Both corner and edge three-lobe solutions are not stable during propagation. Symmetric states show very regular oscillations, but asymmetric oscillations and irregular instabilities occur for higher beam powers.

Similar results hold for the surface modes in the form of two-lobe vortex solitons (figure 5). Symmetric two-lobe vortex states are observed only at the lattice edge (figure 5(a)). There are no stable two-lobe corner and edge states during propagation.

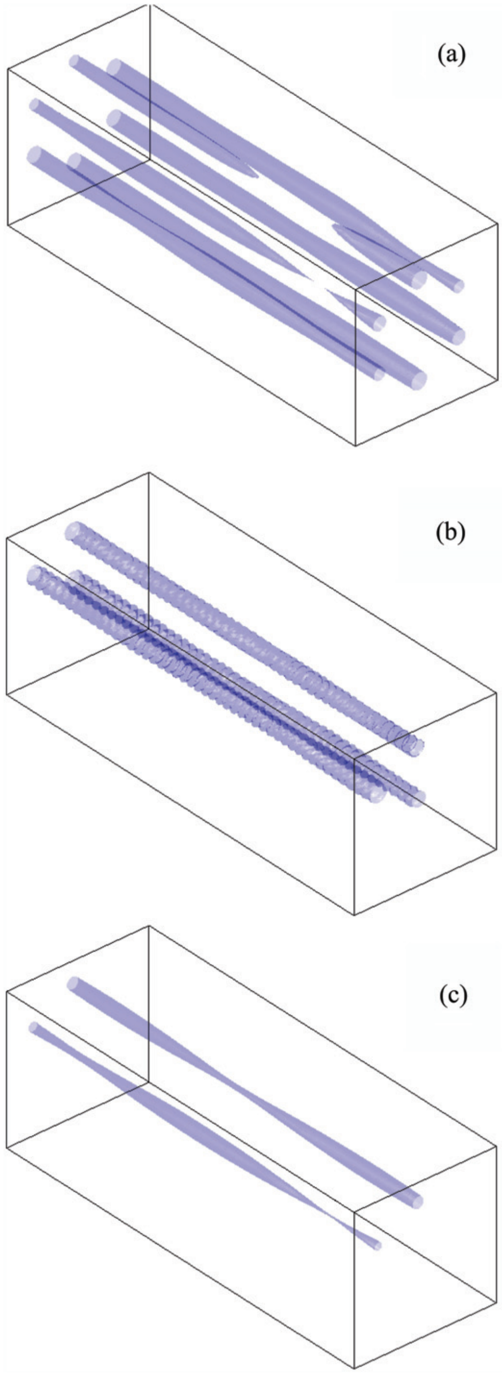

Figure 6. Typical discrete surface vortex solitons in propagation. The six-, three- and two-lobe solitons are shown along the propagation direction. The parameters are the same as in figure 2.

4. Surface vortex dynamics

Finally, we investigate the (in)stability of vortex surface solitons. Ring surface vortex solutions are always unstable during propagation. The ring shape of the vortex beam is broken very fast and irregular dynamics take place with propagation. The most illustrative cases of discrete surface vortex solitons are shown in figure 6 along the propagation distance. Figure 6(a) shows typical behavior of asymmetric six-lobe surface states during propagation. At the beginning, each lobe oscillates slightly with changing peak intensity. During propagation, neighboring lobes exchange more power and irregular oscillations take place. In the case of three-lobe discrete vortex solitons, we present the behavior of symmetric edge mode solutions during propagation (figure 6(b)). These solutions show very regular oscillations, but oscillations of each lobe around its initial position are more pronounced than the exchange of power between the neighboring lobes. The simplest case is the discrete solution with only two lobes (figure 6(c)), which oscillate during propagation.

5. Conclusion

We have reported on the existence and properties of vortex solitons at the edge and in the corner of 2D photonic lattices. Novel types of discrete vortex solitons, localized in the lattice corners or at its edges, have been observed. We have demonstrated that the lattice surface produces a strong stabilizing effect only on the discrete vortex solitons in the form of a six-lobe solution. Besides stable six-lobe discrete surface modes, we have observed oscillations of vortex surface solitons, as well as their dynamical instabilities.

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