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Vortex solitons at the interface separating square and hexagonal lattices

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ABSTRACT

Vortex solitons at the interface separating two different photonic lattices – square and hexagonal – are demonstrated numerically. We consider the conditions for the existence of discrete vortex states at such interfaces and develop a concise picture of different scenarios of the vortex solutions behavior. Various vortices with different size and topological charges are considered, as well as various lattice interfaces. A novel type of discrete vortex surface solitons in a form of five-lobe solution is observed. Besides stable three-lobe and six-lobe discrete surface modes propagating for long distances, we observe various oscillatory vortex surface solitons, as well as dynamical instabilities of different kinds of solutions and study their angular momentum. Dynamical instabilities occur for higher values of the propagation constant, or at higher beam powers.

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1. Introduction

Optical surface waves are a special type of localized waves existing at the interface between two media with different optical properties. They attract great attention with their possible application in surface sensing and probing, and have been the subject of intense study in diverse areas of physics [1]. Such surface waves were observed to exist in a variety of systems: between metal and a linear dielectric medium (plasmon waves) [2] at the boundary of semi-infinite periodic multilayer dielectric media [3], in Kerr media [4], waveguide arrays [5], metamaterials [6], optical amplifiers [7], etc.

Special attention has been devoted to the study of nonlinear optical surface waves, owing to the fact that the nonlinear response of materials makes possible the dynamic control of surface localization. The interplay of periodicity and nonlinearity can facilitate the formation of different types of surface modes localized at and near the surface, and a series of theoretical [8–15] and subsequent experimental [16–19] investigations have demonstrated nonlinearity-induced light localization at the interface and the formation of the so-called discrete surface solitons.

There has been a renewed interest in optical beams carrying angular momentum – vortex solitons – in many branches of science, including plasmas, Bose–Einstein condensates, superfluids, and nonlinear optics [20–22]. Vortex solitons are self-localized nonlinear waves that possess a phase singularity with a total phase accumulation of 2πTC for a closed circuit around the singularity. The integer number TC is the vorticity or topological charge of the vortex, and its sign defines the direction of the phase circulation. Nonlinear periodic systems such as photonic lattices can stabilize optical vortices in the form of stable discrete vortex solitons [21]. Recently, some examples of surface vortex solitons have been observed, at the boundaries of photonic lattices [23,24], or at the interface between two optical lattices with the same geometry but with different refractive index [25].

In this paper, we extend this analysis to the case of vortex solitons supported by different interfaces separating square and hexagonal photonic lattices [26,27]. We study a more general case investigating the interface separating two lattices of different symmetries, and observe vortex solitons at such interface. In particular, we determine the conditions for the existence of discrete vortex states at such interface and also study their stability. The existence domains of interface vortex solitons as well as the regions of stability are observed. A new kind of five-lobe discrete vortex soliton is observed for the first time, and different topological charges and phase structures of such solutions are considered. Also, we focus more attention to the study of extensively oscillating interface vortex solitons and their angular momentum transfer, as well as on the dynamical instabilities of such solitons.

The paper is organized as follows. In Section 2 we introduce the theoretical model which describes the vortex propagation at the interface between two different photonic lattices. Section 3 summarizes our numerical results for different kinds of interface

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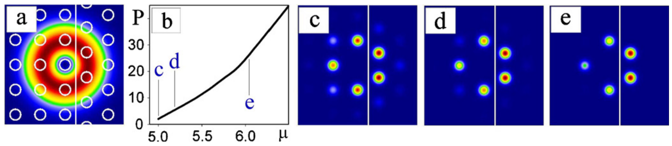

Fig. 1. Five-lobe interface vortex solitons. Input vortex beam is shown with the layout of the lattices beams indicated by open circles (a). The line depicts the interface separating two lattices. (b) Power diagram for the existence of five-lobe vortex solitons. The corresponding intensity distributions for interface vortex solutions are presented in (c), (d), (e). Parameters: $\Gamma = 11$, input lattice intensities $V_{0s} = V_{0h} = 2.5$, input vortex beam intensity $|A_0|^2 = 1$, vortex TC = 1.

surface states. In Section 4 we study oscillations and instabilities of such vortex solutions. Finally, Section 5 concludes the paper.

2. Modeling of vortex propagation at the lattice interfaces

The propagation of vortex beams at the interface separating square and hexagonal photonic lattice, is described using the scaled nonlinear Schrödinger equation for the optical electric field amplitude A [28]:

$$i\partial_z A + (\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2})A + \Gamma\frac{|A|^2 + V}{1 + |A|^2 + V}A = 0, \qquad (1)$$

where x, y and z are the transverse and longitudinal coordinates normalized to the characteristic beam width and diffraction length, Γ is the dimensionless strength of the nonlinearity, and $V(x, y)$ is the transverse lattice potential, given as a square potential $V_s(x, y)$ for $x < 0$, and a hexagonal potential $V_h(x, y)$ for $x > 0$, with the peak intensities V_{0s} and V_{0h}, respectively. A vortex beams, positioned at the corresponding interface lattice sites, are launched into the lattice, perpendicular to the input crystal face (see Fig. 1(a), Fig. 2(a) and Fig. 3(a)).

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

$$-\mu a + (\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2})a + \Gamma a\frac{|a|^2 + V}{1 + |a|^2 + V} = 0. \qquad (2)$$

The solitonic solutions can be found from Eq. (2) by using the modified Petviashvili's method [29,30]. This method is a modification of the Fourier iteration method proposed in [29], and it is based on the separation of linear and nonlinear terms in Eq. (2), and construction of the iteration scheme for an observation of different solitons. We determine different classes of vortex surface solitons by launching vortex beams whose rings are covering lattice sites near the interface separating two photonic lattices. We use input parameters $\Gamma = 11$ and input beam intensity $|A_0|^2 = 1$ but vary input lattice intensities V_{0s} and V_{0h}. Vortex beams with different topological charges (TCs) are used as input. In this paper, we analyze three different classes of interface vortex solitons: discrete solitons consisting of three, five and six lobes.

Next, to investigate the stability of such solutions, we use solitonic solutions obtained from Petviashvili's iteration method as input beams in Eq. (1). Then we solve numerically the propagation equation (1) employing a numerical approach developed earlier [28]. Numerical procedure is based on the fast-Fourier-transform split-step beam propagation numerical algorithm. With this procedure we could study the stability of our solitons as well as their dynamical behavior and AM transfer in the lattices.

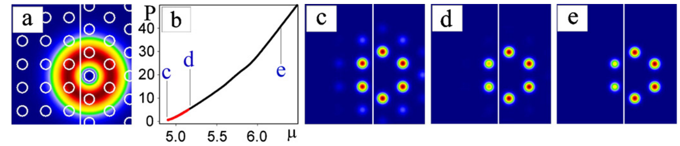

Fig. 2. Interface vortex solitons with six lobes. Input vortex beam is shown with the layout of the lattices beams indicated by open circles (a). (b) Power diagram for the existence of six-lobe vortex solitons (the region of stable solutions is marked with the red line). (c), (d), (e) The characteristic intensity distributions for six-lobe vortex solutions. Physical parameters are as in Fig. 1. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

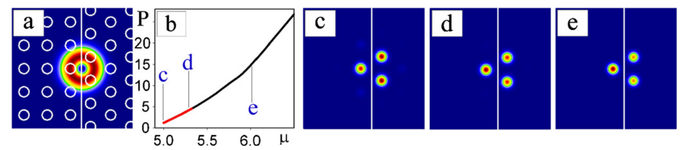

Fig. 3. Three-lobe interface vortex solitons. (a) Input vortex beam with the layout of the lattices beams indicated by open circles. (b) Corresponding power diagram for the existence of three-lobe vortex solitons (the region of stable solutions is marked with the red line). (c)–(e) Typical intensity distributions for three-lobe vortex solutions. Physical parameters are as in Fig. 1. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

3. Interface discrete vortex solitons

We start investigating the interface with the same lattice intensities ($V_{0s} = V_{0h}$) and search for spatially localized vortex soliton solutions. It is well known that the lattice induces confinement of the filaments approximately at the location of the incident vortex ring and the surrounding lattice sites. First, we choose the input ring vortex beam to cover the lattice sites adjacent to the square lattice part of the interface (Fig. 1(a)). The corresponding power diagram is presented in Fig. 1(b). The beam power for vortex solitons is given by the formula: $P = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}|a|^2 dxdy$. The characteristic outcomes in the form of five-lobe solution are shown in Fig. 1 (c), (d) and (e). Increasing the propagation constant μ leads to the asymmetry of the solitons, with stronger localization of the vortex energy in the hexagonal lattice part of the interface (Fig. 1 (d), (e)).

Next, we consider vortex beam positioned at the hexagonal lattice part of the interface; it is chosen input ring vortex beam to cover the lattice sites adjacent to the hexagonal lattice part of the interface (Fig. 2(a)). The surface vortex states are observed in a form of six-lobe discrete vortex solitons. The corresponding power diagram for such states is presented in Fig. 2(b). Typical outcomes are shown in Fig. 2 (c), (d) and (e). The symmetric interface vortex solitons with six lobes can exist for lower values of the propagation constant μ. But increasing the values of propagation constant, one can observe asymmetric solutions with stronger localization of the vortex energy in the hexagonal lattice part of the interface.

Fig. 3 presents three-lobe discrete vortex solutions at the interface separating square and hexagonal lattice. The asymmetry of the vortex soliton with higher power (c)–(e) is more pronounced than that of the vortex with lower power. It is interesting to note that three-lobe asymmetric solutions have stronger localization of the vortex energy in the square lattice part of the interface. The corresponding power diagram is presented in Fig. 3(b); they exist in almost the same range of the propagation constant as five and six-lobe solutions, but with lower powers. Power threshold has the lowest values for six-lobe solutions followed by the three-lobe and then five-lobe solutions.

Next, we want to put more attention to the investigation of five-lobe vortex solutions. We choose the same input ring vortex beam as in Fig. 1(a) but with different topological charges TC. Fig. 4 presents five different kinds of discrete vortex solutions at the interface separating square and hexagonal lattice, observed

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