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Surface defect gap solitons in superlattices with self-defocusing nonlinearity

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ABSTRACT

We put forward the existence and stability of defect surface gap solitons at the interface between uniform media and an superlattice with self-defocusing nonlinearity. We reveal that the defect plays the significant role in controlling the region of solitons existing. Various solitons are found to be existed in different gaps for different defects. For positive defects, fundamental solitons can exist stably in the semi-infinite gap, and dipole solitons can exist stably in the first gap but they are unstable in the second gap. For zero or negative defects, fundamental and dipole solitons can exist stably in the first gap and the second gap, respectively.

1. Introduction

Surface waves are a special type of waves, which are confined at the interface separated by two media with different properties. They appear in diverse areas of physics, chemistry, biology, and display properties that have no counterpart in the bulk, and have unique properties as well as potential for application, such as surface characterization, optical sensing, and switching [1]. Truncation of otherwise periodic structures can create an interface between uniform and periodic media, which can support lattice surface solitons. Experiments show that surface lattice solitons can exist not only in focusing but also in defocusing media [2–6]. Interfaces between lattices with defocusing nonlinearity and uniform media can support surface gap solitons and surface kink solitons [4–7]. The studies of surface waves at lattice interfaces were extended to quadratic, saturable, nonlocal nonlinear materials and to interfaces between complex periodic [8–12].

Defects and defect states exist in a variety of linear and nonlinear systems, including solid state physics, photonic crystals, and Bose–Einstein condensates [13,14]. In particular, various defect solitons that appear as defect nonlinear modes in the nonlinear systems have been found, such as vector gap solitons [15], surface-defect gap solitons [16], etc. Defects surface solitons in the supperlattices with saturable nonlinear have been studied in [17], and solitons can mainly exist in the semi-infinite gap and the first gap. Moreover, surface solitons in a simple lattice and a superlattice were observed experimentally in photorefractive crystal [18]. This raises the question of whether surface defect gap solitons in uniform media and supperlattices with self-defocusing nonlinear have new properties. In self-defocusing nonlinear periodic media, partially incoherent multi-gap solitons can exist [19]. If the refractive index decreases with light intensity due to nonlinear response of the material, the beam normally experiences broadening due to the self-defocusing. However, in periodic photonic structures, the same type of nonlinearity allows for beam localization [20]. Therefore it is worthy to study the properties of surface gap solitons in supperlattices with self-defocusing nonlinearity.

In this paper, we study surface defect gap solitons in superlattice with self-defocusing nonlinearity. The properties of surface defect solitons in the self-defocusing media are quite different from those in self-focusing media. It is found that fundamental and multipole solitons can exist in the semi-infinite gap, the first gap and the second gap. The defect plays the significant role in controlling the region of solitons existing.

2. Theoretical model

We consider beam propagation at the interface of uniform and periodic media with Kerr-type self-defocusing nonlinearity. The evolution of complex amplitude U of the light fields can be

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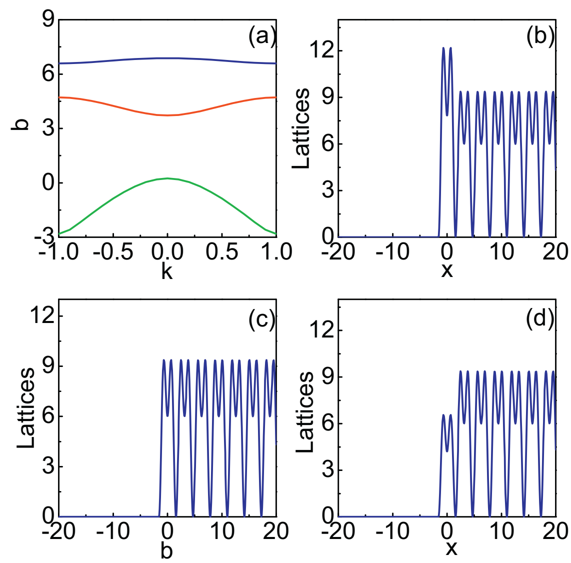

Fig. 1. (a) Band structure of the surface superlattice. (b)–(d) Surface superlattice intensity profiles with (b) $a = 0.3$, (c) $a = 0$, and (d) $a = -0.3$, respectively. For all cases $p = 12$ and $\epsilon = 0.5$.

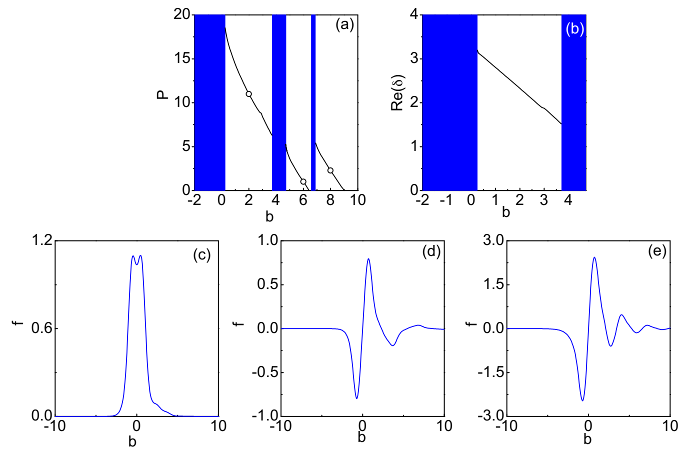

Fig. 2. (a) Soliton power versus propagation constant. (b) Unstable growth rate $Re(\delta)$ versus propagation constants for the dipole solitons in the second gap. (c)–(e) The distribution of field to the solitons, (c) in the semi-infinite gap with $b = 8$, (d) in the first gap with $b = 6$, (e) in the second gap with $b = 2$. (For all cases $a = 0.3$ and $p = 12$.)

described by following dimensionless nonlinear Schrödinger equation (NLSE),

$$i\frac{\partial U}{\partial z} + \frac{\partial^2 U}{\partial x^2} + pV(x)U - |U|^2 U = 0, \quad (1)$$

where the transverse x and longitudinal z coordinates are scaled in terms of beam width and diffraction length. The parameter p characterizes the depth of refractive-index modulation. Surface defect gap solitons can exist only when the lattice depth exceeds a threshold value [4], therefore, we fixed $p = 12$ throughout the paper to ensure the existing of surface gap solitons. The function $V(x)$ stands for the lattice refractive-index profile, which are assumed in this paper as

$$V(x) = \begin{cases} V_0[\epsilon\cos^2(x) + (1-\epsilon)\sin^2(2x)]\left[1 + a\exp\left(-\frac{x^8}{128}\right)\right], & x \geq -\frac{\pi}{2} \\ 0, & x < -\frac{\pi}{2} \end{cases} \quad (2)$$

Here a and ϵ represent the strength of the defect and the modulation parameter of superlattice, respectively. When $0.1 \leq \epsilon \leq 0.7$, Eq. (2) is the superlattice shape [16]. Without losing of generality, we take $\epsilon_1 = 0.5$ throughout the paper.

We search for stationary solutions to Eq. (1) in the form $U = f(x)\exp(ibz)$, where b is the constant propagation, and $f(x)$ is the complex function satisfies equations,

$$bf = \frac{\partial^2 f}{\partial x^2} + pV(x)f - |f|^2 f. \quad (3)$$

The solutions of defect solitons are gotten numerically from Eq. (3) and shown in the next section. The linear version of Eq. (3) is

$$bf = \frac{\partial^2 f}{\partial x^2} + pV(x)f. \quad (4)$$

The surface superlattices governed by Eq. (2) have a Bloch band structure when $a = 0$. To understand the main properties of gap surface solitons, it is important to consider first the Bloch spectrum of Eq. (4). We search the Bloch spectrum by substituting a solution $f(x) = q(x)\exp(ik_x)$ to Eq. (4), where k_x is the Bloch wave number, and $q(x)$ is complex period function, which satisfies equation,

$$bq = \frac{d^2 q}{dx^2} + 2ik_x\frac{dq}{dx} - k_x^2 q + pV(x)q. \quad (5)$$

We numerically solve Eq. (5) to obtain the Bloch spectrum by the plane wave expansion method, which are shown in Fig. 1(a). One can see that for $p = 12$ the region of the semi-infinite gap is $b > 6.87$, the first and the second gap are $4.71 < b < 6.59$ and $0.24 < b < 3.72$. Fig. 1(b)–(d) shows the intensity distributions of the surface superlattices potentials with the strength of the defect $a = 0.3$, $a = 0$ and $a = -0.3$, respectively. $a = 0$ corresponds to the uniform surface superlattice.

To elucidate the stability of surface defect solitons, we search for perturbed solution to Eq. (1) in the form $U(x, z) = [f(x) + u(x, z) + iv(x, z)]\exp(ibz)$, where $[u(x, z)]$ and $[v(x, z)]$ are real and imaginary parts of the perturbation which can grow with complex rate δ upon propagation. Linearization of Eq. (1) around $f(x)$ yields the eigenvalue problem

$$\delta v = \frac{\partial^2 u}{\partial x^2} - bu + pVu - 3f^2 u, \quad (6)$$

$$\delta u = -\frac{\partial^2 v}{\partial x^2} + bv - pVv + f^2 v, \quad (7)$$

which we solved numerically to find perturbation profiles and associated growth rate δ. If $Re(\delta) > 0$, solitons are unstable. Otherwise, they are stable.

3. Surface defect solitons

In the surface defective superlattices with self-defocusing nonlinearity, we find fundamental and dipole solitons in the semi-infinite gap, the first gap and the second gap, as shown in this section. The fundamental solitons can exist stably in the semi-infinite gap for positive defects or in the first gap for zero and negative defects. The dipole solitons can exist stably in the first