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Surface defect solitons at interfaces between dual-frequency and simple lattices

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ABSTRACT

We reveal theoretically the existence and stability of surface defect solitons (SDSs) at interfaces between dual-frequency and simple lattices with focusing saturable nonlinearity. Solitons with some unique properties exist in such composite structures with the change of defect intensity. For zero defect or positive defect, the surface solitons exist at the semi-infinite gap and cannot exist in the first gap, and solitons are stable at lower power but unstable at high power. For the case of negative defect, the surface solitons exist not only in the semi-infinite gap, but also in the first gap. With increasing the defect depth, the stable region of surface solitons becomes narrower in the semi-infinite gap, these solitons are stable within a moderate power region in the first gap within unstable solitons in the entire semi-infinite gap.

1. Introduction

Surface solitons are special waves localized the interfaces between two different media or different refractive index modulations. The existence of surface solitons at the interfaces has attracted special attention due to their novel and unique characteristics in diverse areas of physics such as for exploration of intrinsic and extrinsic surface characteristics, as well as potential applications in optical sensing and switching [1,2]. The interfaces between different medias support different types of surface solitons such as optical surface waves [3], scalar surface solitons [4,5], gap solitons [6–8], vector discrete surface solitons [9,10], discrete surface solitons [11], multipole mode surface solitons [12], polychromatic surface solitons [13]. Moreover, vortex solitons can be captured stably by an interface between two optical lattices with different modulation depths [14–16]. Defects and defect states exist in a variety of linear and nonlinear systems, including solid state physics, photonic crystals, Bose–Einstein condensates, and the periodic structure. The introduced defects at interfaces between lattices can substantially modify the properties of solitons propagation. Defect solitons in lattices with specially designed defect have been applied extensively for steering of optical beams [17–19], switching [20], and filtering [21]. Recently, the research on defect solitons has become an interesting field. The existence and stability of defect solitons have been theoretically discussed in many systems such as simple optical lattices or superlattices [22–30]. In experiments, defect solitons in both one- and two-dimensional photonic lattices have been successfully observed [31–34].

Very recently, defect solitons excited at the interfaces between a simple lattice and a superlattice have been studied numerically and demonstrated experimentally [35]. Their work has not related to the case of defect at the interface. Moreover, the existence and stability of SDSs at the interface between an optically induced simple lattice and a superlattice have been investigated and discussed numerically [41]. Surface defect gap solitons in one-dimensional dual-frequency lattices and simple lattices have been discussed numerically [36]. However, defect solitons in complicated lattices will be one of the difficulty and emphases on the field of soliton in future. We report on the SDSs can exist at interfaces between mixed lattices with a defect when the defect strength (or defect intensity) is changed. The stability of SDSs is also studied analytically and numerically.

2. Model

We consider the probe beam propagating along the interface between one-dimensional dual-frequency and one-dimensional simple optical lattices in the focusing saturable nonlinear media. Light transmission is governed by the following nonlinear Schrödinger equation [22,23,27,28]:

$$i\frac{\partial U}{\partial z}+\frac{\partial^2 U}{\partial x^2}-\frac{E_0}{1+I_L+|U|^2}U=0 \quad (1)$$

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where U is the slowing varying amplitude of the probe beam and I_L is the intensity profile of the mixed optical lattice with a defect when $x < -\pi/2$,

$$I_0 \cdot 1.25 \cdot \sin^2[\Omega_1(x+\pi/2)] \times \sin^2[\Omega_2(x+\pi/2)] \tag{2}$$

for $-\pi/2 \le x \le \pi/2$,

$$0.741 I_0 \sin^2[\Omega_1(x+\pi/2)][1+\varepsilon \exp(-x^8/128)] \tag{3}$$

and for $x > \pi/2$,

$$0.741 I_0 \sin^2[\Omega_1(x+\pi/2)] \tag{4}$$

Here I_0 is the peak intensity of optical lattices or superlattices.$\Omega_1 = 1$ (in unit of π/D) and $\Omega_2 = D/d$ (in unit of π/D) are the lattice wave vectors which describe lattices period and asymmetry, where D and d are their corresponding lattice spacings. x (in unit of D/π) and z (in unit of $2k_lD^2/\pi^2$) is the transverse and longitudinal scale, respectively, in which $k_l = k_0 n_e$, $k_0 = 2\pi/\lambda_0$ is the wave-number in vacuum (λ_0 is the wavelength in vacuum) and n_e is the unperturbed refractive index. E_0 (in unit of $\pi^2/(k_0{}^2 n_e{}^4 D^2 \gamma_{33})$) is the applied DC field voltage, where γ_{33} is the electrooptical coefficient of the crystal. ε is the modulation parameter of defect intensity, respectively. We take typical parameters in experimental conditions as shown in Refs. [25,26]: $D = 30\,\mu$m, $d = 5\,\mu$m, $\varepsilon_1 = 0.3$, $\lambda_0 = 0.5\,\mu$m, $n_e = 2.3$, and $\gamma_{33} = 280$ pm/V [22,24], then $x = 1$, $z = 1$, and $E_0 = 1$ correspond to 9.55 μm, 5.5 mm, and 8.86 V/mm. Other parameters are $I_0 = 3$, $E_0 = 6$. The dual frequency potential given by Eq. (2) can be induced optically by launching a beam into the amplitude mask whose intensity distribution of transmission light is the same as the superlattice potential.

We look for the stationary solitons of Eq. (1) in the form of $U(x,z) = u(x)\exp(-i\mu z)$, where μ is the propagation constant, and $u(x)$ is the real function representing the profile of the soliton solution. Substituting the expression into Eq. (1) yields the following ordinary differential equation:

$$\frac{\partial^2 u}{\partial x^2} - \frac{E_0}{1+I_L+|u|^2}u + \mu u = 0 \tag{6}$$

The power of solitons is defined as $P = \int_{-\infty}^{+\infty} u^2(x)dx$. The soliton solutions $u(x)$ can be solved numerically by a modified square-operator method [37,38]. We construct families of the soliton solutions, which are determined by the μ, D and d, and lattice-modulation parameters I_0 and ε.

To indicate the stability of defect solitons at the interfaces between dual-frequency and simple lattices with focusing saturable nonlinearity, we search for the perturbed solutions of Eq. (1) in the form

$$U = \{u(x) + [v(x) - w(x)]\exp(\delta z) + [v(x) + w(x)]^* \exp(\delta^* z)\} \times \exp(-i\mu z) \tag{7}$$

where $v(x)$ and $w(x)$ are the real and imaginary part of infinitesimal perturbations, respectively, with a complex instability growth rate δ. The superscript "*" means complex conjugation, and $v(x), w(x) \ll 1$. Substituting Eq. (4) into Eq. (1) and linearizing, the eigenvalues of the coupled equations are obtained as

$$\begin{aligned} \delta v &= -i\left[\frac{\partial^2 w}{\partial x^2} + \mu w - E_0 w/(1+I_L+u^2)\right] \\ \delta w &= -i\left[\frac{\partial^2 v}{\partial x^2} + \mu v - E_0 v(1+I_L-u^2)/(1+I_L+u^2)^2\right] \end{aligned} \tag{8}$$

These equations can be solved numerically to get the perturbation growth rate Re(δ).

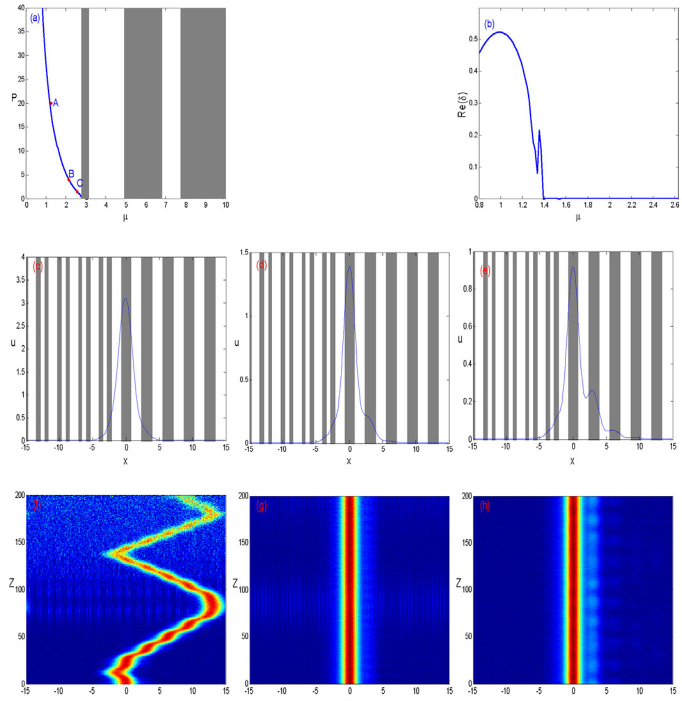

Fig. 1. ($\varepsilon = 0$) (a) The power versus the propagation constant (gray regions corresponding to Bloch bands). (b) Re(δ) versus the propagation constant. (c) Unstable SGS with $\mu = 1.25$ (point A in (a)). (d) Stable surface soliton with $\mu = 2.15$ (point B in (a)). (e) Stable surface soliton with $\mu = 2.55$ (point C in (a)). (f) Surface soliton propagation for (c). (g) Surface soliton propagation for (d). (h) Surface soliton propagation for (e).

3. Numerical results and discussion

To further study the SDSs' stability, the robustness on propagation of the soliton is tested in direct simulations of Eq. (1) by adding a noise to the inputted soliton by multiplying them with $[1+\rho(x)]$, where $\rho(x)$ is a Gaussian random function with $\langle\rho\rangle = 0$ and $\langle\rho^2\rangle = \sigma^2$ (The adopted σ is equal to 10% of the input soliton amplitude).

First of all, we study defect solitons at the interfaces between uniform compounded lattices. Fig. 1(a) shows the power diagram of SDSs versus propagation constant μ. For $\varepsilon = 0$, the SDSs only exist in the semi-infinite gap, the power P is monotonically decreasing with increase of μ. In the high power region: $\mu < 1.39$, surface solitons cannot stably exist. Fig. 1(c) plots the profile of soliton for $\mu = 1.25$ (point A in Fig. 1(a)). The corresponding soliton propagation is shown in Fig. 1(f). We can see in this figure that the unstable soliton can drift across the simple lattice, shift away from the interface to the inner lattice during propagation, and decay apparently after a certain distance. In the moderate power region: $1.39 \le \mu \le 2.63$, the surface solitons can stably transmit. The surface solitons profile of a stable example ($\mu = 2.15$ corresponds to point B in Fig. 1(a)) is shown in Fig. 1(d) and the soliton propagation for $\mu = 2.15$ is shown in Fig. 1(g). To further testify the stability of SDSs, we take ($\mu = 2.55$ corresponds to point C in Fig. 1(a)) for example. In such a case, the soliton profile is shown in Fig. 1(e) and soliton propagation for $\mu = 2.55$ are shown in Fig. 1(h). It can be seen from Fig. 1(c)–(e) that the shape of SDSs is centrosymmetric for the asymmetric spatial distribution of mixed lattice for $\mu = 1.25$; with the increasing of propagation constant, SDSs reduce in amplitude and its width is broadened, SDSs shape is noncentrosymmetric. In addition, we find that SDSs can stably propagate at the interfaces between uniform compounded lattices shown in Fig. 1(g)–(h). The above analytic results have been proved by means of using