Optik 124 (2013) 2196–2199

Contents lists available at SciVerse ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Defect solitons in one-dimensional composite optical lattices

Guangyu Jiang [a,b,*], Youwen Liu [a]

[a] Department of Applied Physics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China
[b] College of measuring and optical engineering, Nanchang Hangkong University, Nanchang 330063, China

ARTICLE INFO

Article history:
Received 14 February 2012
Accepted 23 June 2012

Keywords:
Nonlinear optics
Soliton
Pulse propagation

ABSTRACT

The existence, stability and propagation dynamics of defect solitons at interfaces in one-dimensional composite optical lattices with focusing saturable nonlinearity are investigated numerically and analytically. Solitons show unique properties with the change of defect intensity. For a positive defect, the surface solitons only exist in the semi-infinite gap, and are stable at lower power but unstable at high power. For a negative defect, the surface solitons exist not only in the semi-infinite gap, but also in the first gap; the surface solitons show rich characteristics of instability in the entire semi-infinite gap.

1. Introduction

Since the soliton phenomenon was first described by John Scott Russell who observed a solitary wave in the Union Canal in Scotland [1]. Research on solitons has excited more interest in many branches of nonlinear science, including biology, photonic crystals, solid state physics, Bose–Einstein condensates, nonlinear optics. In particular, 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 attracted special attention due to their novel and unique characteristics in diverse areas of physics and been applied extensively for steering of optical beams [2–4], switching [5], and filtering [6]. Recently, the existence and stability of defect solitons have been theoretically discussed in many systems such as simple optical lattices or superlattices [7–15]. In experiments, defect solitons have been successfully observed in both one- and two-dimensional photonic lattices [16–19]. Defect solitons supported at the interfaces between a simple lattice and a superlattice have been studied numerically and demonstrated experimentally, in which the defects at the interface are not considered [20]. Moreover, the existence and stability of surface defect solitons (SDSs) at the interface between an optically induced simple lattice and a superlattice have been investigated and discussed numerically [21]. Very recently, surface defect gap solitons in one-dimensional dual-frequency lattices and simple lattices have been discussed numerically [24]. In this letter, we reveal that the SDSs can exist at interfaces between one-dimensional composite optical lattices with a defect when the defect strength (or defect intensity) is changed; the stability of SDSs in composite lattices with different intensity distributions is also studied analytically and numerically.

2. Model

We consider the probe beam propagating along the interface between one-dimensional composite optical lattices in the focusing saturable nonlinear media. Light transmission is governed by the following nonlinear Schrödinger equation [7,8,12,13]:

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

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

$$I_0\left\{\varepsilon_1\sin^2\left[\Omega_1\left(x+\frac{\pi}{2}\right)\right]+(1-\varepsilon_1)\sin^2\left[\Omega_2\left(x+\frac{\pi}{2}\right)\right]\right\} \quad (2)$$

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

$$0.858 I_0\sin^2\left[\Omega_1\left(x+\frac{\pi}{2}\right)\right]\left[1+\varepsilon\exp\left(\frac{-x^8}{128}\right)\right] \quad (3)$$

and for $x>\pi/2$,

$$1.45\cdot I_0\sin^2\left[\Omega_1\left(x+\frac{\pi}{2}\right)\right]\times\sin^2\left[\Omega_2\left(x+\frac{\pi}{2}\right)\right] \quad (4)$$

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

* Corresponding author at: Department of Applied Physics, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China.
E-mail address: jgy579@126.com (G. Jiang).

0030-4026/$ – see front matter © 2012 Elsevier GmbH. All rights reserved.
http://dx.doi.org/10.1016/j.ijleo.2012.06.100

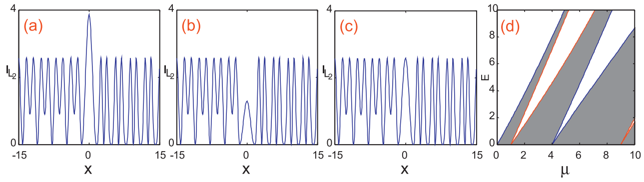

Fig. 1. Lattices intensity profile with $I_0 = 3$. (a) Positive defect $\varepsilon = 0.5$, (b) negative defect $\varepsilon = -0.5$, (c) without defect $\varepsilon = 0$, (d) applied dc field E_0 versus the propagation constant μ (gray regions corresponding to Bloch band).

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 $\pi^2/(k_0{}^2\, n^4{}_e\, D^2\gamma_{33})$) is the applied DC field voltage, where γ_{33} is the electrooptical coeffient of the crystal. ε is the modulation parameter of defect intensity, respectively. We take typical parameters in experimental conditions from Refs. [7–11]. Other parameters are $I_0 = 3$, $E_0 = 6$.The composite potential given by Eqs. (2)–(4) 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. The intensity distributions of composite optical lattices with a positive defect ($\varepsilon = 0.5$), a negative defect ($\varepsilon = -0.5$) and without defect ($\varepsilon = 0$) are displayed in Figs. 1(a)–(c) respectively. Using the above parameters, we obtain the region of the semi-infinite gap as $\mu \le 3.07$, and the first gap as$3.55 \le \mu \le 4.85$ by the plane wave expansion method, the bandgap's structure shown in Fig. 1(d).

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:

$$\frac{\partial^2 u}{\partial x^2} - \frac{E_0}{1 + I_L + |u|^2}u + \mu u = 0 \qquad (5)$$

The soliton solutions $u(x)$ can be solved numerically by a modified square-operator method [22]. The power of solitons is defined as $P = \int_{-\infty}^{+\infty} u^2(x)dx$. To confirm the stability properties of defect solitons in one-dimensional composite optical lattices, we search for the perturbed solutions of Eq. (1) in the form

$$U = \{u(x) + [v(x) - w(x)]\exp(\delta z) + [v(x) + w(x)]^* \exp(\delta^* z)\}\exp(-i\mu z) \qquad (6)$$

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. (6) into Eq. (1) and linearizing, the eigenvalues of the coupled equations are obtained as

$$\begin{cases} \delta v = -i\left[\dfrac{\partial^2 w}{\partial x^2} + \mu w - \dfrac{E_0 w}{1 + I_L + u^2}\right] \\[2ex] \delta w = -i\left[\dfrac{\partial^2 v}{\partial x^2} + \mu v - \dfrac{E_0 v(1 + I_L - u^2)}{(1 + I_L + u^2)^2}\right] \end{cases} \qquad (7)$$

which can be solved numerically [23,26].

3. Numerical results and discussion

To elucidate the results of the linear stability, we simulate 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 whose variance $\sigma^2 = 0.01$.For the case of $\varepsilon = 0$, SDSs only exist in the semi-infinite gap, the power P is monotonically decreasing with increase of μ and terminates at $\mu = 2.83$, as shown in Fig. 2(a). In the high power region: $\mu < 1.45$, surface solitons cannot stably exist. Fig. 2(c) plots the profile of soliton for $\mu = 1.42$ (point A in Fig. 2(a)). The corresponding soliton propagation is shown in Fig. 2(f). We can see in this figure that the unstable soliton can propagate for a certain distance at the interfaces, drift across the dual frequency lattices, and shift away from the interface to the inner lattice during propagation. In the moderate power region: $1.45 \le \mu \le 2.47$, the surface solitons can stably transmit. The surface solitons profile of a stable example ($\mu = 2.15$ point B in Fig. 2(a)) is showed in Fig. 2(d) and the soliton propagation for $\mu = 2.15$ is shown in Fig. 2(g). As an example for unstable soliton, we choose $\mu = 2.55$ (point C in Fig. 2(a)). In such case, the soliton profile is shown in Fig. 2(e) and the soliton propagation for $\mu = 2.55$ is showed in Fig. 2(h). The unstable soliton can propagate for a small distance at the interfaces, and decay apparently in dual frequency lattices. In addition, it can be seen from Fig. 2(c)–(e) that the shape of SDSs is centrosymmetric for $\mu = 1.42$ in the asymmetric spatial composite lattices; with the increasing of propagation constant μ, SDSs reduce in amplitude and its width is broadened, SDSs shape is noncentrosymmetric, and SDSs show pedestal in the dual frequency lattices. Fig. 2(b) shows the perturbation growth rate $Re(\delta)$ with propagation constant μ. The solitons cannot stably transmit for the $Re(\delta)$ larger than 0 in the regions: $\mu < 1.45$ and $2.47 < \mu \le 2.80$. However, we can see in Fig. 2(a) that the power of SDSs monotonically decreases with propagation constant when $\mu < 1.45$, namely their negative slope of power diagram ($dP/d\mu < 0$). In the region: $\mu < 1.45$, this instability is different from the Vakhitov–Kolokolov (VK) instability caused by the positive slope of power curve [24,25]. For the negative slope of power diagram ($dP/d\mu < 0$) and $Re(\delta) = 0$ in the region: $1.45 \le \mu \le 2.47$, the SDSs can stably exist, which accords with the VK criterion.

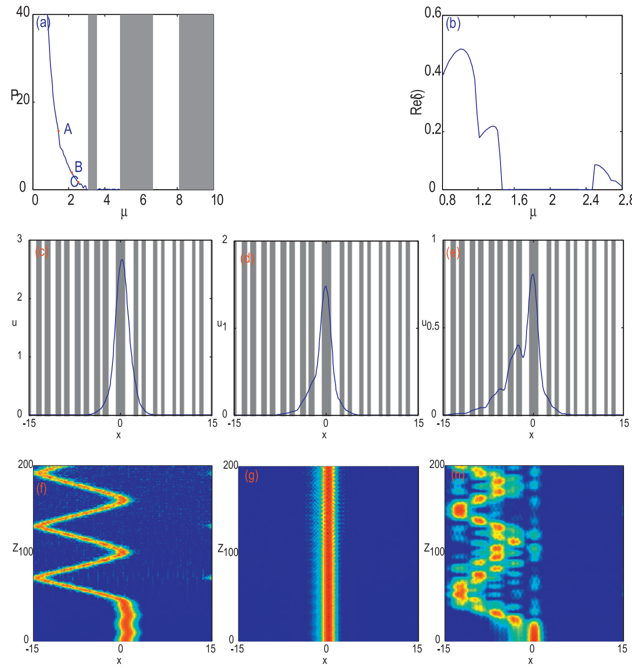

Fig. 2. ($\varepsilon = 0$) (a) The power versus the propagation constant (gray regions corresponding to Bloch bands). (b) $Re(\delta)$ versus the propagation constant. (c) Unstable SDS with $\mu = 1.42$ (point A in (a)). (d) Stable SDS with $\mu = 2.15$ (point B in (a)). (e) Stable SDS with $\mu = 2.55$ (point C in (a)). (f) SDS propagation for (c). (g) SDS propagation for (d). (h) SDS propagation for (e).

Fig. 3(a) presents the power P versus propagation constant μ for a positive defect ($\varepsilon = 0.5$). With the increase of defect depth, SDSs