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Dipole solitons in an optical lattice with longitudinal modulation

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Abstract

In this paper, we numerically demonstrate the (1 + 1)-dimensional dipole solitons can exist in a new Kerr-type optical lattice with longitudinal modulation that fades away and boosts up alternately. The solitons whose two dipoles simultaneously located at one lattice site and at two adjacent lattice sites are investigated, respectively. The results show that, in the two cases, the dipole solitons can be stably trapped in this kind of lattice by properly adjusting lattice parameters and soliton parameters when the repulsive force of dipoles balances the centripetal force resulting from the lattice potential effect on dipole solitons. In addition, the trapping of dipole solitons with an incident angle or the initial center position is discussed.

Keywords: Dipole solitons; Existence; Optical lattice; Repulsive interaction

1. Introduction

Spatial solitons in optical lattices have been extensively studied in both theory and experiment because of potential applications in optical information processing such as all-optical soliton switching and routing [1–4]. Optical lattices with periodic modulation of the refractive index strongly affect the diffraction properties of light beams and lead to the formation of spatial solitons [1–7]. In recent years, optical lattices with longitudinal refractive index modulation have received significant attention [8–12]. Soliton steering, dragging and fission can be achieved by nonlinear lattices with longitudinal modulation [13–16]. Strong periodic longitudinal modulation and properly designed lattices segments can support nondiffractive propagation of light beams [14–16]. Optical lattices with longitudinal variation may provide more opportunities for the applications in all-optical devices based on spatial solitons.

Recently, many researches have focused on more complex structures and composite multimode solitons [17–30]. Dipole soliton (DS) with two symmetrical humps is the typical one. The existence of DSs was firstly predicted theoretically in Ref. [17] and soon observed experimentally in Ref. [18]. In general, the two humps of DSs are out of phase, which result in the repulsion between them. So DSs possess the inherent instability. Many works concentrate on the trapping and stabilizing of DSs by using the soliton-induced waveguides and optical lattices [23–25,29–31]. So far, most of researches focus on the (2 + 1)-dimensional (two transverse plus one longitudinal dimension) DSs. To our knowledge, there are few works on (1 + 1)-dimensional DSs except the investigation of the existence of (1 + 1)-dimensional DSs in the harmonic lattice in Ref. [31].

In this paper, we numerically demonstrate the DSs can exist in a new optical lattice with harmonic

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transverse modulation and periodic longitudinal modulation that fades away and boosts up alternately. We concretely consider the trapping of DSs, whose two dipoles are located at one lattice site and at two adjacent lattice sites, respectively. The results show that longitudinal modulation period strongly affects the capture of DSs. Under proper lattice parameters and soliton parameters, the DSs can be stably trapped when the repulsive force of dipoles balances the centripetal force resulting from the lattice potential effect on DSs. In addition, for the incident angle $\alpha \neq 0$ and the initial center position $\eta_0 \neq 0$, DSs can behave stable swing in the initial input channel.

2. Model

The theoretical model for light propagation in the focusing Kerr nonlinear medium with periodic modulation of the linear refractive index in both the transverse and the longitudinal directions is the following nonlinear Schrödinger equation [15,16]:

$$i\frac{\partial q}{\partial \xi} = -\frac{1}{2}\frac{\partial^2 q}{\partial \eta^2} - q|q^2| - pR(\eta,\xi)q \tag{1}$$

Here q is the dimensionless complex amplitude of light beam, η and ξ are the transverse and longitudinal coordinates scaled to the input beam width and the diffraction length, respectively. $R(\eta,\xi)$ describes the lattice profile and p is proportional to the modulation depth. Here we consider the lattice profile with the following form:

$$R(\eta,\xi) = \cos^2(\Omega_\eta \eta)\exp(-\delta_T \xi), \tag{2}$$

where $\delta_T = \begin{cases} \delta, & 2n\xi_T \leqslant \xi < (2n+1)\xi_T \\ -\delta, & (2n+1)\xi_T \leqslant \xi < (2n+2)\xi_T \end{cases}$, n is an integer, δ is the decrease (or increase) rate along the longitudinal direction, Ω_η and ξ_T denote the transverse modulation frequency and the longitudinal modulation period, respectively. Such kind of lattice, as shown in Fig. 1(a), can be constructed by the decreasing and increasing short segments of lattices, which can be technologically created by interference of plane waves in photorefractive crystals [2,3,15]. The lattice parameters, including the transverse frequency and the decrease (or increase) rate, can be experimentally tuned by changing the crystal temperature, intensities, intersection angles and carrying wavelength of lattice-forming plane waves [2–4,15,16].

For the case of $p = 0$, corresponding homogeneous media, Eq. (1) admits the stationary soliton solution $q(n,\xi) = A\mathrm{sech}[A(\eta-\eta_0)] \times \exp[i\alpha(\eta-\eta_0)+i\beta\xi]$, where A depicts the soliton amplitude and inverse width , η_0 and α characterize the center position and the incident angle, respectively. β is the propagation constant of longitudinal direction [13]. For $p \neq 0$ and $\delta = 0$, corresponding the harmonic lattices, the authors of Ref. [31] presented the stationary solution of DSs by multiplying it with sine function. For $p \neq 0$ and $\delta \neq 0$, corresponding the lattice with longitudinal modulation, it is difficult to find the stationary solution of DSs. To search for the stable DSs in the lattice (2), here we adopt the following form of DSs [31]:

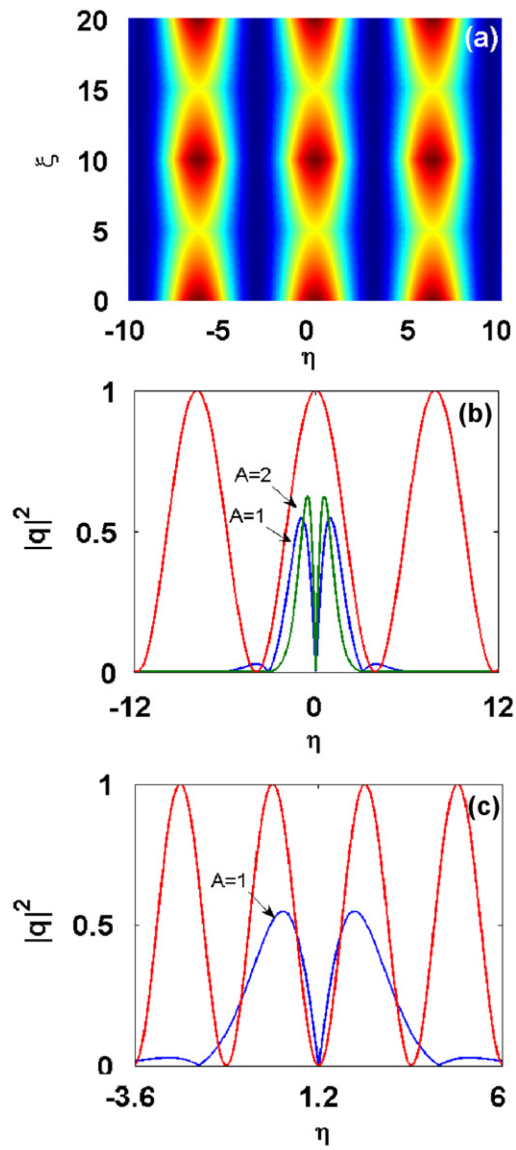

Fig. 1. (a) Profile of the lattice (2) with $\Omega_\eta = 0.5$, $\xi_T = 5$ and $\delta = 0.1$; Profiles of DSs (3) whose two dipoles are located at (b) one lattice site with $\Omega_\eta = 0.4$, $A = 1$, $A = 2$; and (c) two adjacent lattice sites with $\Omega_\eta = 1.3$, $A = 1$.

$$q(\eta,\xi=0) = A\sec h[A(\eta-\eta_0)]\sin(\eta-\eta_0)\exp[i\alpha(\eta-\eta_0)] \tag{3}$$

The soliton with the form of (3) has two out-phase symmetrical humps and they form the two dipoles of soliton. Here we consider two cases that two dipoles of