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Fundamental and multipole solitons supported by one-dimensional multilayer photonic crystals potentials

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ABSTRACT

The existence and stability of solitons in one-dimensional multilayer photonic crystals potentials are reported. For all of the solitons, there exist cutoff points of the propagation constant below which the solitons vanish in the semi-infinite gap. The fundamental solitons are stable in the whole range where solitons exist. The antisymmetric dipole solitons can be stable when the propagation constant closes to the cutoff point. The range of stability for symmetric tripole solitons is changed with modulation depth and width of the multilayer photonic crystals potentials. The power of solitons increases with increasing of propagation constant and modulation width or decreasing of modulation depth of the potentials.

1. Introduction

Optical spatial solitons have been extensively investigated in various systems, including nonlocal nonlinearly [1–3], photonic crystals [4–6] and parity-time symmetric system [7,8]. Optically induced photonic lattices is of great interest to both fundamental physics and applications. In the linear spectrum, there exist band gap structures in such periodic systems. The bands are separated by gaps where periodic waves do not exist. Solitons emerge as defect modes whose propagation constants are located inside gaps. Novel optical phenomena is found in periodic photonic lattices nonlinear structures [9,10]. Various types of solitons appear as nonlinear defect modes residing in gaps of photonic lattices [11–13]. The applications about photonic crystals periodic photonic lattices have been deeply studied [4–6]. Recently, many researchers have paid much attention to composite multimode solitons. Many composite multimode solitons are associated with dipole and tripole solitons. In local Kerr-type media, fundamental solitons are stable, whereas multimode solitons are unstable. Otherwise, multimode solitons have been studied in nonlocal nonlinear media theoretically and experimentally [14]. Many people have focused on multimode solitons in optical lattices too [15–17]. In semi-infinite gap, it has been found that there exist mainly the symmetric solitons, and the antisymmetric solitons have not been found.

In this study, we have studied various solitons in multilayer photonic crystals potentials. Compared to the usual periodic potential, there exist more types of solitons including symmetric and antisymmetric solitons in the semi-infinite gap. The properties of propagation and the stability of solitons in these potentials are investigated.

2. Model

We consider optical propagation properties in self-focusing Kerr-nonlinear with multilayer photonic crystals potentials.

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

where U is the slowly varying complex field envelop, x and z are the transverse and longitudinal coordinates, respectively, $V(x)$ is the multilayer photonic crystals potentials. The depths of the potentials are U_1, U_2 and U_3 and the widths of them are d_1, d_2 and d_3, respectively.

The multilayer photonic crystals lattices profiles with $U_1=5$, $U_2=3$, $U_3=1$ and $d_1=\pi$, $d_2=\pi/2$, $d_3=\pi/2$ is displayed in Fig. 1(a). Linearizing Eq. (1) with $U(x, z)=f(x)\exp(ibz+ikx)$, where b is the propagation constant, k is a Bloch wave number, and $f(x)=f(x+T)$, in which T is the period of multilayer photonic crystals potential, we obtain the Bloch band structure by the plane wave expansion method for Fig. 1(a), which is shown in Fig. 1(b). One can see that the region of the semi-infinite gap is $b>0.72$, and the first and second gaps are $-0.5<b<0.58$ and $-2<b<-1.29$, respectively.

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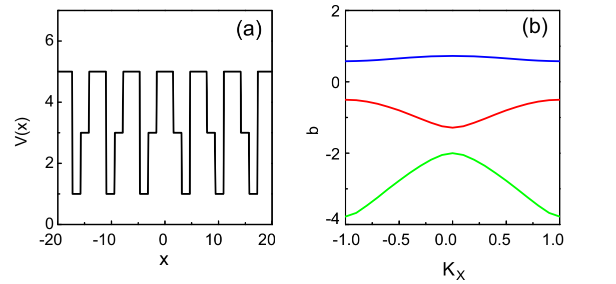

Fig. 1. (a) Lattice intensity profiles with $U_1=5$, $U_2=3$, $U_3=1$ and $d_1=\pi$, $d_2=\pi/2$, $d_3=\pi/2$; (b) band structure of the polybasic photonic crystals lattices which is corresponding to (a).

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

$$bf=\frac{1}{2}\frac{\partial^2 f}{\partial x^2}+V(x)f+|f|^2 f, \tag{2}$$

The solutions of solitons are gotten numerically from Eq. (2) and shown in Section 3.

To analyze the stability of solitons, we search for the perturbed solution to Eq. (1) in the form $U(x,z)=[f(x)+u(x,z)+iv(x,z)]\exp(ibz)$, where the real $[u(x,z)]$ and imaginary $[v(x,z)]$ parts of the perturbation can grow with a complex rate δ upon propagation. Substituting the perturbed soliton solution into Eq. (1) and linearization of it around the stationary solution $f(x)$ yields the eigenvalue problem

$$\delta v=\frac{1}{2}\frac{\partial^2 u}{\partial x^2}-bu+Vu+3f^2u, \tag{3}$$

$$\delta u=-\frac{1}{2}\frac{\partial^2 v}{\partial x^2}+bv-Vv-f^2v, \tag{4}$$

The above eigenvalue problem is solved numerically to find the maximum value of $Re(\delta)$. If $Re(\delta)>0$, solitons are unstable. Otherwise, they are stable.

3. Numerical results

In the semi-infinite gap of multilayer photonic crystals lattices, we find two types of solitons, as shown in this section. The first type is symmetric solitons, including nodeless fundamental and multi-mode solitons whose profile of optical field is symmetric. The other type is antisymmetric solitons, mainly including dipole solitons, whose profile of optical field is antisymmetric.

We first investigate fundamental solitons in the multilayer photonic crystals potential, and the results are shown in Fig. 2. The power of solitons is defined as $P=\int_{-\infty}^{+\infty}|f(x)|^2dx$. Fig. 2(a) shows the power of solitons versus the propagation constant b. We can see that fundamental solitons exist in the semi-infinite gap, and the power of solitons increases almost linearly with increasing of b. There exists a cutoff point of the propagation constant below which the fundamental solitons vanish. The propagation constants of cutoff points increase with increasing the modulation depth. We find that fundamental solitons are stable in the whole regime where solitons exist in the semi-infinite gap.

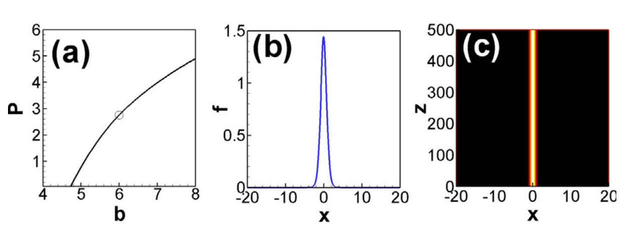

Fig. 2. (a) The power P versus propagation constant b of fundamental solitons with $U_1=5$, $U_2=3$, $U_3=1$ and $d_1=\pi$, $d_2=\pi/2$, $d_3=\pi/2$; (b) the field distribution of fundamental solitons for $b=6$; and (c) evolution of the soliton to (b).

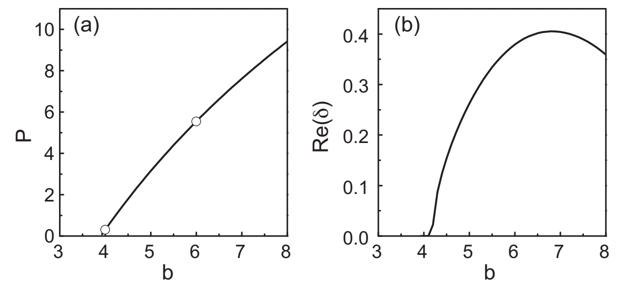

Fig. 3. (a) The power P versus propagation constant b of dipole solitons with $U_1=5$, $U_2=3$, $U_3=1$ and $d_1=\pi$, $d_2=\pi/2$, $d_3=\pi/2$; (b) Unstable growth rate $Re(\delta)$ versus propagation constant b for dipole solitons.

The field profile of fundamental solitons is shown in Fig. 2(b), which corresponds to the circle symbol in Fig. 2(a). Fig. 2(b) shows that symmetric fundamental solitons exit in the semi-infinite gap. The propagations of solitons are simulated based on Eq. (1), and 1% random-noise perturbations are added into the initial input to verify the results of linear stability analysis. The propagation corresponding to the soliton in Fig. 2(b) is shown in Fig. 2(c). We can see that symmetric fundamental solitons are stable in the semi-infinite gap.

Then, we investigate antisymmetric dipole solitons in the multilayer photonic crystals potential, and the results are shown in Figs. 3 and 4. The changes of the power versus b for dipole solitons are shown in Fig. 3(a). The power of solitons increases linearly with increasing of b and the cutoff point of the propagation constant below which the dipole solitons vanish is lower than that of the fundamental solitons. Fig. 3(b) is the perturbation growth rate versus propagation constant b. We can see that the dipole solitons exist stably only the propagation constant is close to the cutoff point.

The field profiles of dipole solitons are shown in Fig. 4(a) and (b) for different propagation constants, which correspond to the circle symbols in Fig. 3(a). Fig. 4(a) and (b) shows that antisymmetric solitons can exit in the semi-infinite gap. As the propagation constant increases, the power of solitons increases but the shape

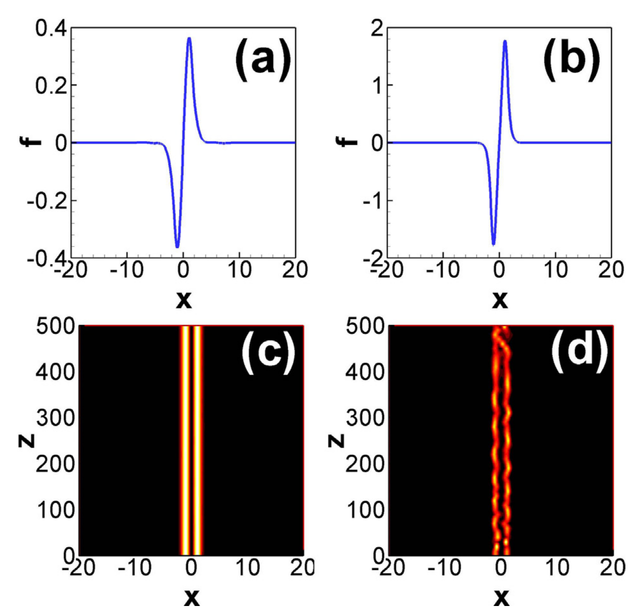

Fig. 4. The fields for dipole solitons in the semi-infinite gap at (a) $b=4$, and (b) $b=6$. (c) and (d) Evolutions of dipole solitons corresponding to (a) and (b), respectively.