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Original research article

Interaction of Airy beams in a medium with parabolic potential

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ABSTRACT

The interaction of the Airy beams in a medium with parabolic potential is investigated. It is found that the interaction of the two in-phase beams under the action of the parabolic potential can form the breathers, and the period will be affected by the depth of the potential. It's also notable that the interval and the phase play an important role in the interaction. In addition, the influences of the initial amplitudes of the two beams are also studied.

1. Introduction

Since first found by Berry and Balazs within the context of quantum mechanics in 1979 [1] and experimental realized by Christodoulides et al. in optics in 2007 [2], Airy beam, which has unusual propagation features including weak diffraction, self-healing, and self-acceleration [3–5], has intrigued extensive research interests [6–16]. Besides the study of the single Airy beam, the interaction of the beams is also studied recently. For example, Zhang et al. have investigated the interactions of Airy beams in Kerr and saturable nonlinear media in 2013 and 2014 [17,18], and found that bound and unbound soliton pairs, as well as single solitons, can form in such interaction.

Here, we are specifically concerned with what will happen in an external parabolic potential. In Bose-Einstein condensates, this potential is frequently utilized as a harmonic trap, especially if the nonlinearity is weak and can be neglected. In addition, a widely used application of the parabolic potential is the propagation of pulse in graded-index(GRIN) fibers in optics. In 2015, Yiqi Zhang et al. have investigated the dynamics of finite energy Airy beams in the linear medium with an external parabolic potential theoretically and numerically [19]. Liping Zhang et al. have carefully studied the dynamics of the finite energy chirped Airy-Gaussian beam in a medium with parabolic potential in 2017 [20]. However, there are few papers investigating the interaction of the two Airy beams when considering the effects of parabolic potential.

In this paper, we are devoted to studying the interaction of the two Airy beams in the medium with external parabolic potential. The organization of the paper is as follows: in Section 2 we introduce the theoretical model; in Section 3 systematically investigate the propagation properties of the Airy beams when they transmit in the medium with parabolic potential; and we present our conclusion in Section 4.

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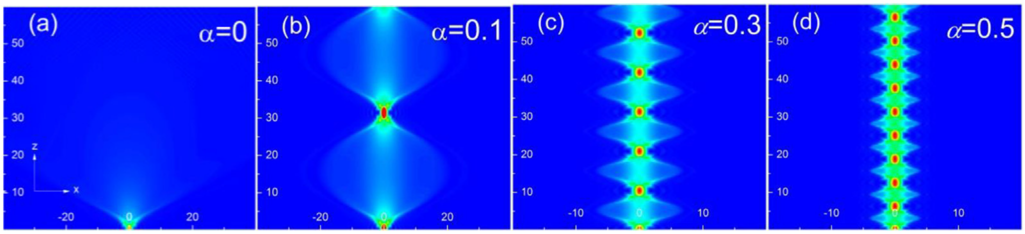

Fig. 1. The interaction of the two in-phase Airy beams with the same amplitude$A_1 = A_2 = 1$for differentα.

2. Model

We consider the propagation dynamics of the two Airy beams in the medium with an external parabolic potential, which can be described by the normalized one-dimensional linear parabolic (Schrodinger-like) equation,

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

Where U is the beam envelope, x and z are the dimensionless transverse coordinate and the propagation distance, respectively scaled by the parameters x_0 and kx_0^2. x_0 represents the transverse width and $kx_0^2$is the Rayleigh,$k = 2\pi n/\lambda_0$is the wavenumber, n is the ambient index of refraction, and$\lambda_0$is the wave length in free space. The potential expression is$V(x) = \alpha^2 x^2/2$, withαcorresponding to the depth of the parabolic potential.

Generally speaking, the initial Airy beam is in the form:

$$U(x) = A_0 Ai(x)\exp(ax) \quad (2)$$

where A_0 is the amplitude factor of the beam, $Ai(\bullet)$ represents the Airy function,$a$is an arbitrary positive real decay constant. Here, we take$a = 0.2$throughout.

For our initial profile, we mainly investigate the interaction of the Airy beams, and the initial beam is composed of two shifted linear Airy beams with different amplitudes between them,

$$U(x) = A_1 Ai(x - B)\exp(a(x - B)) + A_2 \exp(iQ)Ai(-(x + B))\exp(-a(x + B)) \quad (3)$$

where A_1 and A_2 are the initial amplitudes of the two beams, respectively. B is the interval between the two beams. $Q$is the parameter controlling the phase shift. $Q = 0$refers to in-phase of the two beams while the out-of-phase is represented by$Q = \pi$.

3. Numerical simulation

The interaction properties of the two Airy beams in the medium with an external parabolic potential are studied using the split-step Fourier method. In order to make a more comprehensive study of the interaction between the two Airy beams, the situations of $A_1 = A_2$and$A_1 \neq A_2$are both considered.

Fig. 1 shows the interaction of the two in-phase Airy beams in the medium with different parabolic potentials when$B = 1$. In Fig. 1(a), one can see that when the beams propagate in the linear medium, after a short interaction distance, the energy will radiate rapidly and can't transmit long distance due to the diffraction effect. When$\alpha \neq 0$, the beams are transmitted in the medium with parabolic potential. The energy of the two beams, which is radiated outward results of the diffraction effect, is rebounded after a parabolic potential well, and then radiates outward after interacting with each other. This process causes the beam to periodically broaden and compress to form the breathers finally. And as shown in Fig. 1(b)–(d), the width and the period also decrease with the increase of the potential.

Fig. 2 shows the maximum intensity versus the propagation distance when the beams interact in the medium with different parabolic potentials. When$\alpha = 0$, the intensity of the beams decays rapidly due to the diffraction effect after a short distance of interaction, which is consistent with the description in Fig. 1(a). When$\alpha \neq 0$, that is, the beams are transmitted in the medium with parabolic potential. As the potential well increases, the energy radiated outward by the diffraction effect is rapidly bounced back after encountering a strong potential well, so that the frequency of the breathers is accelerated, and the period is significantly reduced. However, the increase of the potential well does not affect the peak intensity, which indicates that the energy radiated outward can rebound well without obvious energy loss.

Fig. 3 shows the interaction of two in-phase Airy beams at different initial intervals. As the Airy beam shows a multi-lobed structure, its energy is mainly distributed in the main lobe, side lobe energy is relatively weak. The two in-phase beams attract each other. When $B = -2$, the energy of the main lobes converges to form the breathers near the center position, and the energy of the side lobes, radiated outward due to the weak attraction, is bounced back after encountering the potential well, and leads to the symmetrical tailing on both sides of the breathers. With the decrease of the interval between the main lobes, the energy of part of the side lobes also converges to the central position to form the breathers, making the trailing