Interaction of Airy-Gaussian beams in photonic lattices with defects

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We investigate numerically the interaction between two finite Airy-Gaussian (AiG) beams in different media with the defected photonic lattices in one transverse dimension. We discuss that the beams with different intensities and phases launch into the different lattice structures but accelerate in opposite directions. During interactions, the interference fringe, breathers, and soliton pairs are observed. In the linear media, the initial deflection direction of the accelerated beams is changed by adjusting the phase shift and the beam interval. For a certain lattice period, the periodic interference fringe can form. A constructive or destructive interference can vary with the defect depth and phase shift. While the nonlinearity is introduced, the breathers is generated. Especially in the self-defocusing media, the appropriate AiG beam amplitude and lattice depth may lead to the formation of soliton pairs, On the contrary, the interaction of two Gaussian beams is diffraction.

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I. INTRODUCTION

Photonics and especially nonlinear photonics has experienced rapid development over the last few decades. In this growth, the novel accelerated Airy beams played one important role, and nonlinear effects such as soliton formation was the other key point. New fields of research have been opened completely because of combining both topics to study nonlinear interaction of accelerated beams. The Airy quantum wave packet of an infinite extent was introduced by Berry and Balazs as free-particle solutions of the Schrödinger equation [1]. However, the initial Airy function is not realizable in practice.

In optics, because the Airy function can be realized in practice and exhibit self-accelerating, nondiffracting, and self-healing properties during propagation, the Airy optical beams which retain a finite energy were widely investigated theoretically and experimentally since Siviloglou *et al.* [2,3] discussed them by using different methods. In the past decade, such self-accelerating optical beams have been studied, mostly in uniform media which include linear media [2–10], Kerr nonlinear dielectrics [11–15], photorefractive media [16], nonlocal nonlinear media [17,18], and quadratic media [11,19]. Because of the existence of nonlinearity, optical solitons can be formed with the Airy beams in different nonlinear media [20–24]. At the same time, a few people studied the propagation properties of optical Airy beams in nonuniform structures [25–31]. Efremidis and Chremmos first showed that an engineered accelerating beam can be generated in a periodic lattice [25,26]. Christodoulides *et al.* identified nondiffracting beams in two-dimensional periodic systems, exhibiting symmetry properties and phase structure characteristic of the band(s) they are associated with [27]. Chen *et al.* studied the behavior of Airy beams propagating from a nonlinear medium to a linear medium [28] and demonstrated both experimentally and theoretically one- and two-dimensional Airy beams in optically induced refractive-index potentials [29], respectively. Recently, Jović *et al.* reported that the propagation dynamics and beam acceleration are controlled with positive and negative defects and appropriate refractive index change [32]. Moreover, they analyzed how an optically induced photonic lattice affects and modifies the acceleration of Airy beams [33] and demonstrated the acceleration of two-dimensional Airy beams propagating in optically induced photonic lattices [34].

As a generalized form of the Airy beams, AiG beams can carry finite energy and maintain the diffraction-free propagation properties within a finite propagation distance [35]. Many researchers studied the AiG beams both theoretically and experimentally [35–40]. Deng *et al.* investigated the propagation of the AiG beam in uniaxial crystals [36], strongly nonlocal nonlinear media [37], and Kerr media [38]. Ez-Zariy [39] and Zhou *et al.* [40] discussed propagation characteristics of finite Airy-Gaussian beams through an apertured misaligned first order ABCD optical system and the fractional Fourier transform plane, respectively. Similarly asymptotic preservation of a self-accelerating property is observed with AiG beams in different media.

The above-mentioned papers have investigated dynamics and properties of single accelerating beams. Moreover, similarly to the interactions of solitons [41–44], interactions between Airy beams have gradually attracted the attention of researchers. Interactions between Airy pulse and temporal solitons at the same center wavelength [45] or at a different wavelength [46] were studied. The interaction of an accelerating Airy beam and a solitary wave was also investigated in various media [47]. Wolfersberger *et al.* analyzed the dynamics of two incoherent counterpropagating Airy beams interacting in a photorefractive crystal under focusing conditions [48,49]. Zhang *et al.* [50,51] and Deng *et al.* [52,53] studied numerically interactions of Airy and AiG beams in nonlinear media in one transverse dimension, respectively. Based on the effect of nonlocality, Shen *et al.* obtained stationary bound states of in-phase as well as out-of-phase Airy beams in nonlocal nonlinear media [54,55]. The interaction between a broad accelerating Airy beam and an intense Gaussian

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beam was also investigated numerically and experimentally to demonstrate gravitational dynamics in a nonlocal thermal nonlinearity [56]. Thus far, interactions of self-accelerating beams in uniform media were reported. However, interactions of self-accelerating beams in the waveguide arrays, especially in the photonic lattices with defects, have not been mentioned.

In this paper, we will numerically study the interactions dynamics of AiG beams in one-dimensional photonic lattices including defects. We realize different lattices with defects by embedding the positive and negative defects into the regular lattice and research the influence of the different physical parameters on the AiG beam interaction. The organization of the paper is as follows. We briefly introduce the theoretical model and basic equations in Sec. II; in Sec. III, we discuss numerically interactions of two AiG beams in photonic lattices with defects in detail. Section IV concludes the paper.

II. THE THEORETICAL MODEL AND BASIC EQUATIONS

To study the interaction characteristics of AiG beams in photonic lattices with defects, along the propagation distance z, we consider that the scale equation for the propagation of a slowly varying envelope q of the optical electric field in one transverse dimension in the paraxial approximation is of the nonlinear Schrödinger equation

$$i\frac{\partial q(X,Z)}{\partial Z}+\frac{1}{2}\frac{\partial^2 q(X,Z)}{\partial X^2} + V(X)q(X,Z)+\gamma|q(X,Z)|^2q(X,Z)=0, \qquad (1)$$

where $X=x/w_0$ is the dimensionless transverse coordinates scaled by the characteristic length w_0, $Z=z/kw_0^2$ with $k=2\pi/\lambda$, $V(X)=A_n\cos^2(\pi X w_0/T)[1+\delta n\exp(-X^2)]$ is the periodic refractive-index profile of the array with the lattice period T, A_n is the lattice modulation depth, and δn is the defect depth. Here we assume $w_0=10\,\mu$m and the wave length $\lambda=600$ nm. In Kerr media, the beams are self-focusing ($\gamma=1$) when the nonlinear refractive index is greater than zero and self-defocusing ($\gamma=-1$) when the nonlinear refractive index is smaller than zero. It is well known that the spatial solitons can be steadily transmitting in the (1+1)D local Kerr medium when the nonlinear effect balances the diffraction effect. Considering an AiG beam, its initial field distribution can be read as [36–40,52,53]

$$q(X,0)=A_0\mathrm{Ai}(X)\exp(\alpha X)\exp(-QX^2), \qquad (2)$$

where A_0 denotes the constant amplitude, Ai(·) is the Airy function, $\alpha=0.01$ in the exponential function is a parameter associated with the truncation of the AiG beams, and Q is the distribution factor controlling the beam that will tend to the Gaussian beam with a larger value and the Airy beam with a smaller value. The expression (2) of the initial field q is the single-beam solution of Eq. (1). To investigate the AiG beam interactions, we should construct more complex incident beams, made up of two shifted single beams, launched in parallel but accelerating in opposite directions. Thus, we assume that the incident beam will be composed of two shifted AiG beams with a fixed relative phase and different amplitudes

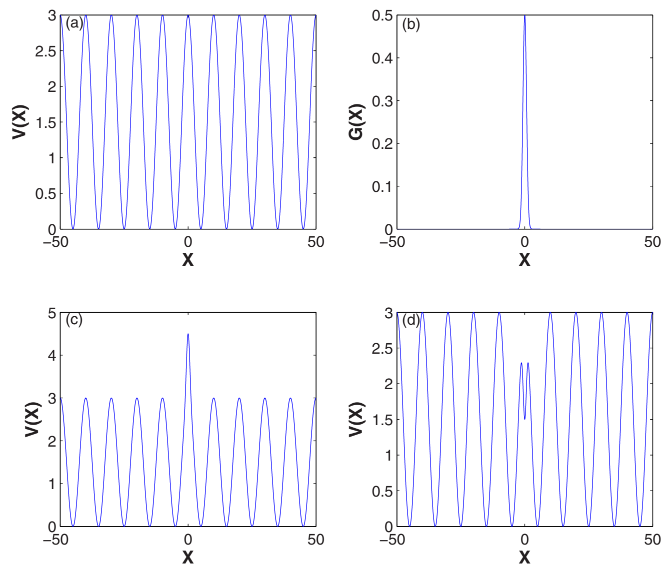

FIG. 1. Defect generation in an optical photonic lattice. (a) The regular lattice distribution ($\delta n=0$). (b) The Gaussian beam intensity distribution $G(X)$. Numerical realization of (c) positive ($\delta n=0.5$) and (d) negative ($\delta n=-0.5$) defect lattices. The other physical parameters $A_1=A_2=2$, $A_n=3$, $T=0.1$ mm, $\delta\phi=0$, $D=3$, $Q=0.05$, and $\gamma=0$.

between them [50–55],

$$q(X,0)=A_1Ai(X-D)\exp(\alpha(X-D))\exp(-Q(X-D)^2) + A_2Ai(-X-D)\exp[\alpha(-X-D)] \times\exp[-Q(-X-D)^2]\exp(i\delta\phi), \qquad (3)$$

where A_1 and A_2 are the amplitude of the two AiG beams, D is the parameter controlling the beam separations, and $\delta\phi$ is the parameter controlling the phase shift with $\delta\phi=0$ and $\delta\phi=\pi$ describing in-phase and out-of-phase AiG beams, respectively. To investigate the interaction of the two AiG beams for different beam factors, we have implemented comprehensive split-step Fourier methods to solve Eq. (1) and model the light propagation in photonic lattices with defects V. The propagation equation (1) is evaluated numerically, taking Eq. (3) as the initial input AiG beam. Figure 1 shows the basic scheme of the defect realization using a Gaussian beam. The regular lattice distribution ($\delta n=0$) and Gaussian beam intensity distribution $G(X)=\delta n\exp[-(X^2)]$ are illustrated in Figs. 1(a) and 1(b), respectively. Figures 1(c) and 1(d) show the calculated refractive index modulation results for both the positive ($\delta n=0.5$) and negative ($\delta n=-0.5$) lattices with defects.

III. THE NUMERICAL RESULTS OF INTERACTING AIG BEAMS IN PHOTONIC LATTICES WITH DEFECTS

If we assume $\gamma=0$ and $\delta n=0$ in Eq. (1), the "interaction" is actually a linear interference in the regular photonic lattices. We display the evolution of the incidence from Eq. (3)

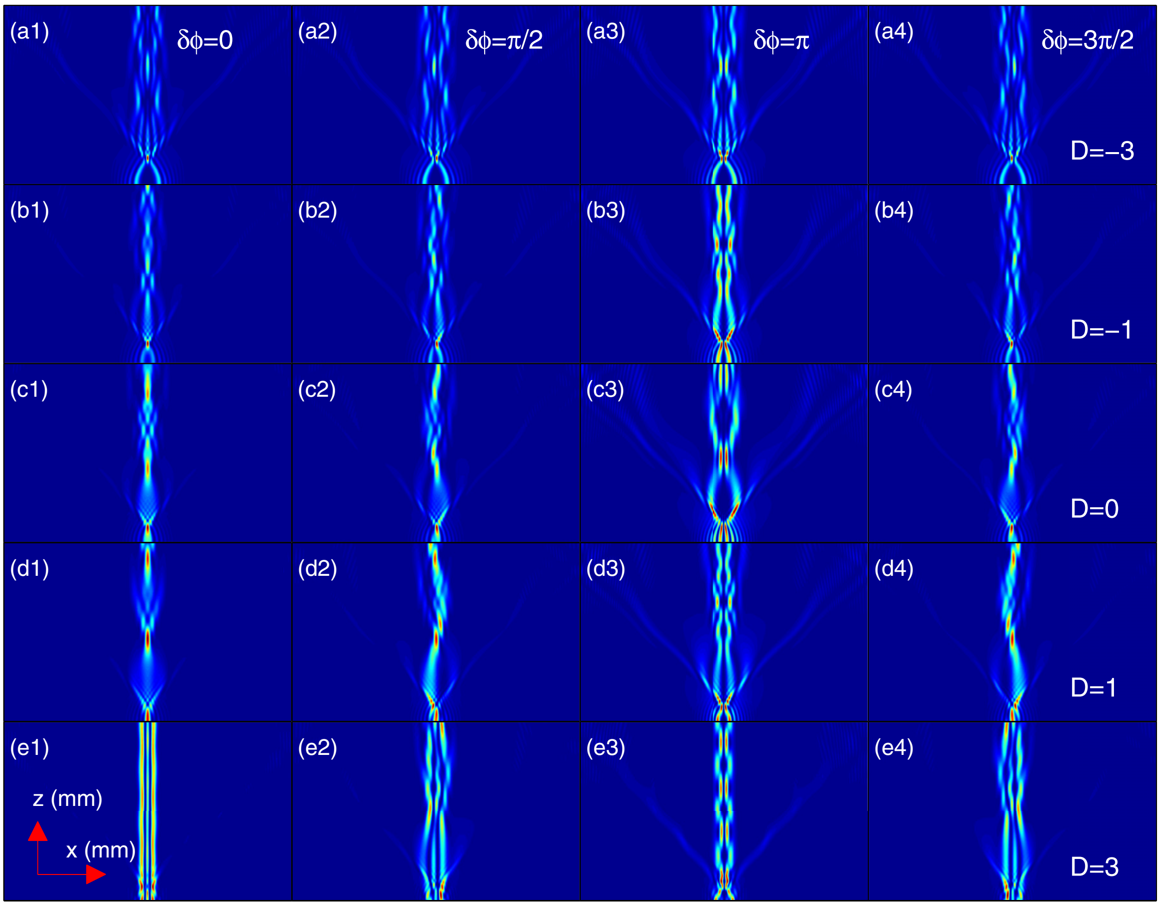

FIG. 2. The interaction of two AiG beams with changing the values of $\delta\phi$ and D for $A_1 = A_2 = 2$, $A_n = 3$, $T = 0.2$ mm, $\delta n = 0$, $Q = 0.01$, and $\gamma = 0$.

for different D and $\delta\phi$ in Fig. 2. The results shown in Figs. 2(a1)–2(e1) and 2(a3)–2(e3) are completely different from Fig. 2 in Ref. [51] because of the existence of the photonic lattices. However, the behavior of the central interference is similar. The central interference fringe in the in-phase case [Figs. 2(a1)–2(e1)] is bright, whereas in the out-of-phase case [Figs. 2(a3)–2(e3)] it is dark, as it should be for a constructive and destructive interference [51]. Some pseudo-periodic mutual focusing can be observed in the central region, especially when the interval of beams is closer, such as $D = 0$ [see Figs. 2(c1)–2(c4)]. This results from the diffraction, superposition, and interference of the curved accelerating beams as the beams propagate in the photonic lattices. Of course, no breathers can form.

When we change the phase shift $\delta\phi$, the beam direction varies simultaneously because the change of $\delta\phi$ influences the interaction of two beams. If $\delta\phi = \pi/2$, the direction of the accelerated beams will be first turned to the right; if $\delta\phi = 3\pi/2$, the accelerated beams will first go to the opposite direction. However, note that the case is the inverse when $D = 1$. This can be interpreted by Fig. 3. We can see that the intensity profile and value of the AiG beam with $D = 1$ are different from the other three profiles and values. Thus, the initial deflection direction of the accelerated beam with $D = 1$ is first left based on the interaction between the beam and lattice. As a result, we can say that the propagation direction of the beams can be changed by adjusting the values of the phase shift $\delta\phi$ and the beam interval D. Interestingly, the interaction of the two beams is the strongest with both in-phase and

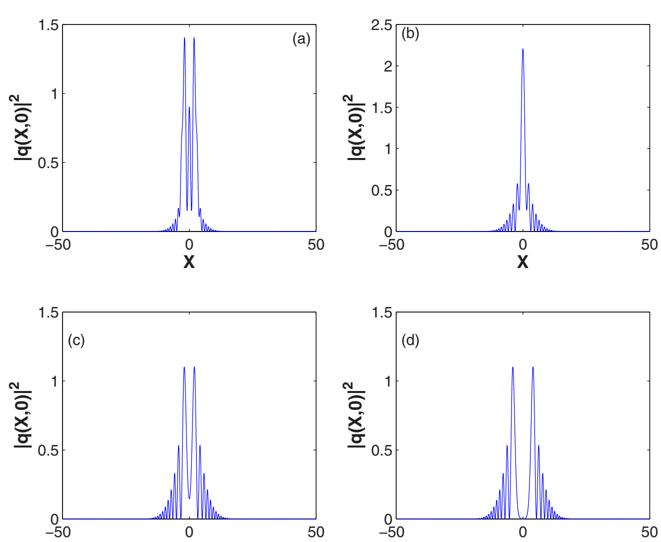

FIG. 3. Intensity profiles of AiG beams with $D = 3$ (a), $D = 1$ (b), $D = -1$ (c), and $D = -3$ (d) for $\delta\phi = \pi/2$. The other physical parameters are the same as Fig. 2.

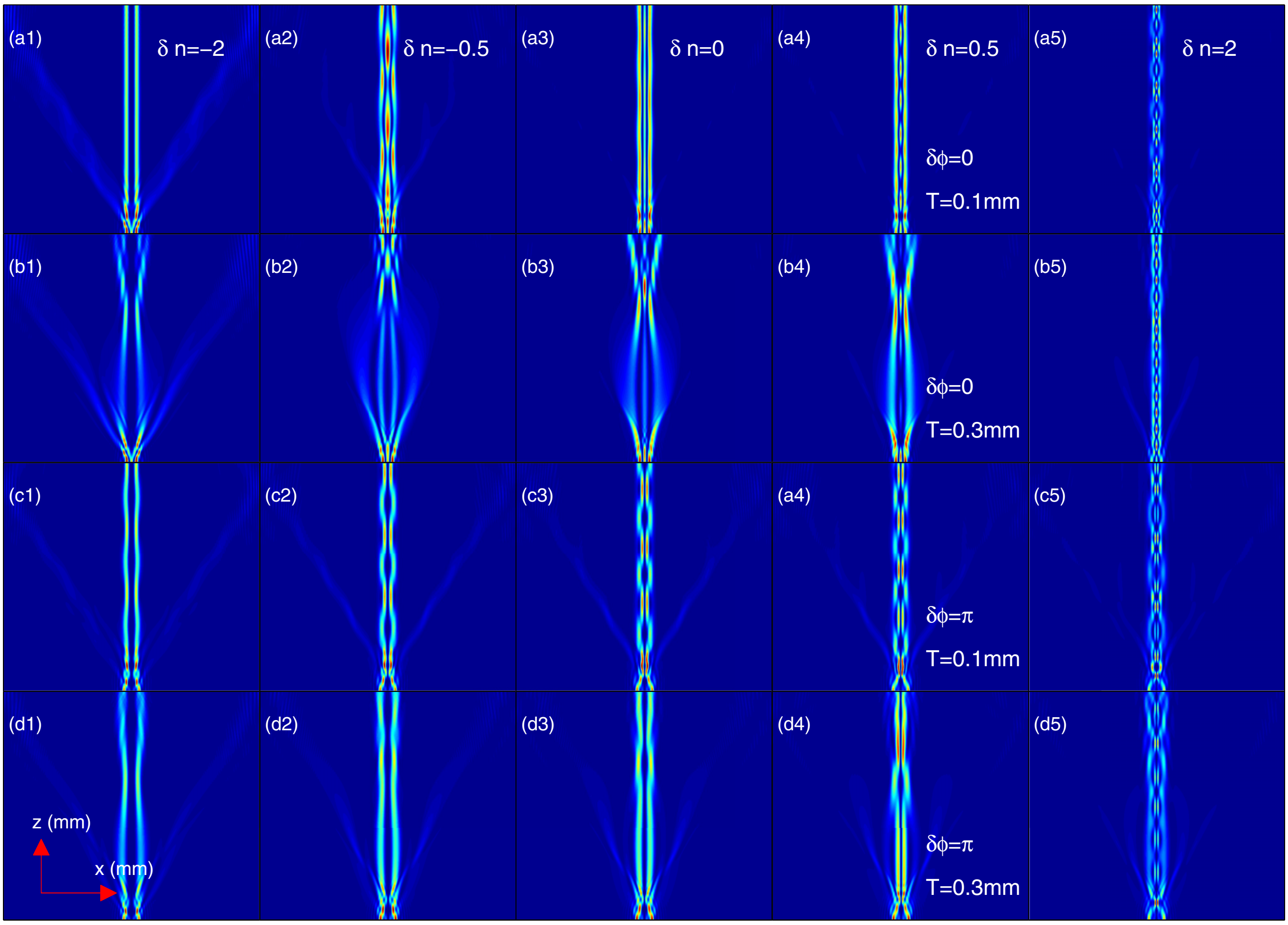

FIG. 4. The interaction of two AiG beams with changing the values of $\delta\phi$, δn, and T for $A_1 = A_2 = 2$, $A_n = 3$, $D = 3$, $Q = 0.01$, and $\gamma = 0$.

out-of-phase situations, so we will next study the interaction of the beams about two key cases.

Figure 4 shows the propagation distribution of the in-phase and out-of-phase AiG beams with the same amplitude for different $\delta\phi$, δn, and T. First, we discuss that the influence of the defect depth δn on the interaction of AiG beams [red dashed line in Fig. 5(a)] when the other parameters are constant. At $\delta\phi = 0$ and $T = 0.1$ mm, as shown in Figs. 4(a1)–4(a5), the interaction of the in-phase beams varies with δn. One can see that the "interaction" forms a linear interference in the photonic lattices with defects and the central interference fringe is bright except $\delta n = -2$. It is caused by the influence of the lattice with defects [see Fig. 5(b)] different from the other cases [see Figs. 5(c)–5(f)]. The negative defected lattice exists negative value, so the central interference fringe is dark. The central dark interference fringe also appears in Figs. 4(c1)–4(c5), where $\delta\phi = \pi$ and $T = 0.1$ mm, that is to say, two beams are out-of-phase. The difference of the initial input in-phase and out-of-phase beams is shown in Fig. 5(a). In particular, when $T = 0.1$ mm, one can find that some periodic mutual-focusing interference fringes, which are similar to breathers, take shape from Figs. 4(a1)–4(a5) and Figs. 4(c1)–4(c5). However, when T is bigger, such as $T = 0.3$ mm shown in Figs. 4(b1)–4(b5) and Figs. 4(d1)–4(d5), the mutual-focusing interference fringes is no longer periodic.

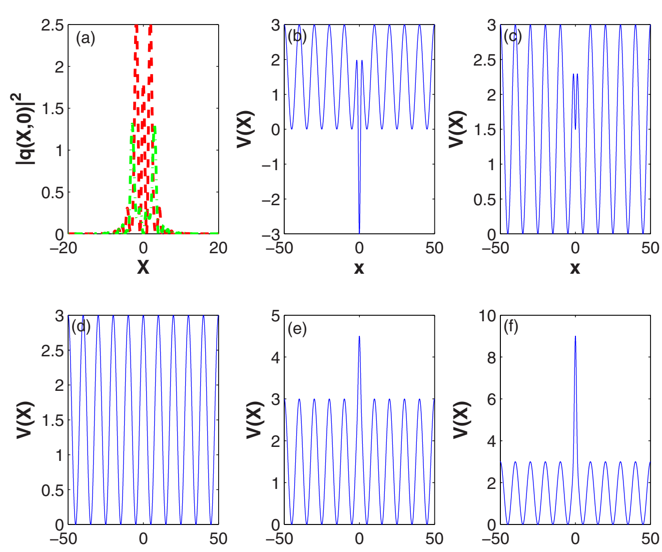

FIG. 5. (a) Intensity profiles of the initial input AiG beams with $\delta\phi = 0$ (red dashed line) and $\delta\phi = \pi$ (green dash-dotted line) for $\delta n = -2$ and $T = 0.1$ mm. The photonic lattices with defects with $\delta n = -2$ (b), $\delta n = -0.5$ (c), $\delta n = 0$ (d), $\delta n = 0.5$ (e), and $\delta n = 2$ (f) for $T = 0.1$ mm. The other physical parameters are the same as Fig. 4.

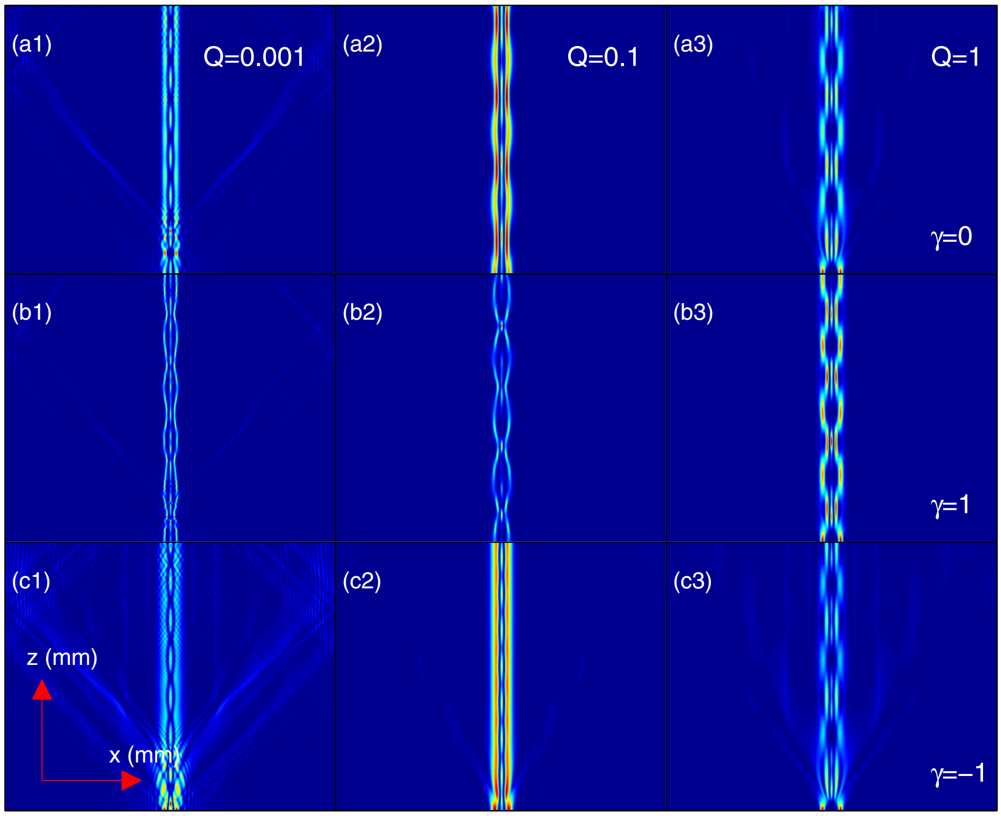

FIG. 6. The interaction of two AiG beams with changing the values of Q, and γ for $A_1 = A_2 = 4$, $A_n = 3$, $D = 3$, $Q = 0.01$, $\delta\phi = 0$, $T = 0.1$ mm, and $\delta n = 0.5$.

These results account for the big effect of the lattices with defects on the beam interaction. In addition, we can also see that the beam minor lobes are more constraint when δn is from -2 to 2. Figure 6 shows the interaction of two in-phase AiG beams with the same amplitude for the different distribution factor Q and nonlinear parameter γ. The mutual-focusing distributions in the central regions are periodic for all cases, if we do not consider the influence of the numerical integration window on the distribution for $Q = 0.001$ in Figs. 6(a1)–6(c1). In a linear medium ($\gamma = 0$), when $Q = 0.001$, the AiG beam goes to the field distribution of Airy beams which hold some side lobes, so that the lattice with defects does not completely restrain the part of energy [see Fig. 6(a1)]. On the contrary, the field distribution of Gaussian beams has also been exhibited as $Q = 1$ [see Fig. 6(a3)]. The AiG beam is self-accelerating no longer, which is very similar to the propagation of the Gaussian beam in the linear media. Note that there exists some part energy in the other region apart from the central region in Fig. 6(a3) opposite to Fig. 6(a2). The reason can be explained in Fig. 7. At $Q = 1$, we can say that two independent Gaussian beams (green dash-dotted line) interact in the lattice with defects, so they also exist in the part diffraction. While $Q = 0.1$, the red dashed line shows that two AiG beams propagate hand-in-hand. This helps the lattice with defects so that all the energy can be restricted in the central region as shown in Fig. 6(a2). When we introduce the nonlinearity, the situation has changed. As the medium is the self-focusing nonlinear medium ($\gamma = 1$), we can see that the self-focusing nonlinearity further traps some energy and breathers has formed from Figs. 6(b1)–6(b3). However, while $\gamma = -1$, the self-defocusing nonlinearity increases the diffraction. Of course, the field distributions in

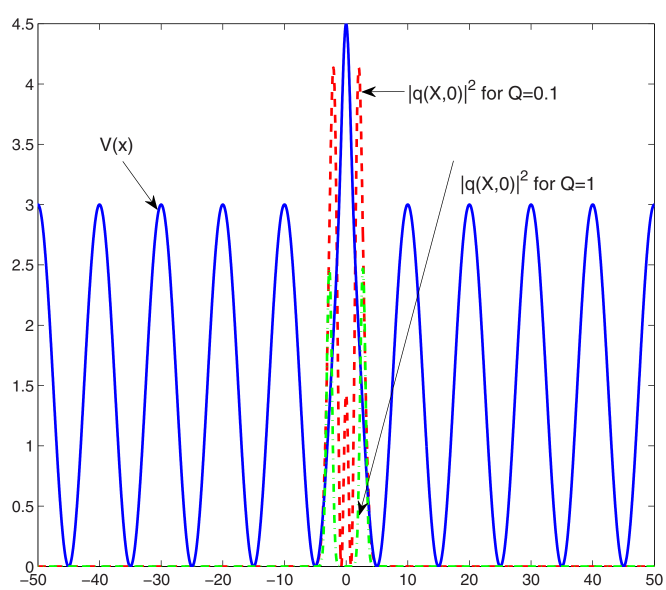

FIG. 7. Intensity profile of AiG beams $|q(X,0)|^2$ and the lattice with defects $V(X)$. The red dashed and green dash-dotted lines denote $|q(X,0)|^2$ at $Q = 0.1$ and $Q = 1$, respectively. The blue solid line shows $V(X)$. The other physical parameters are the same as Fig. 6.

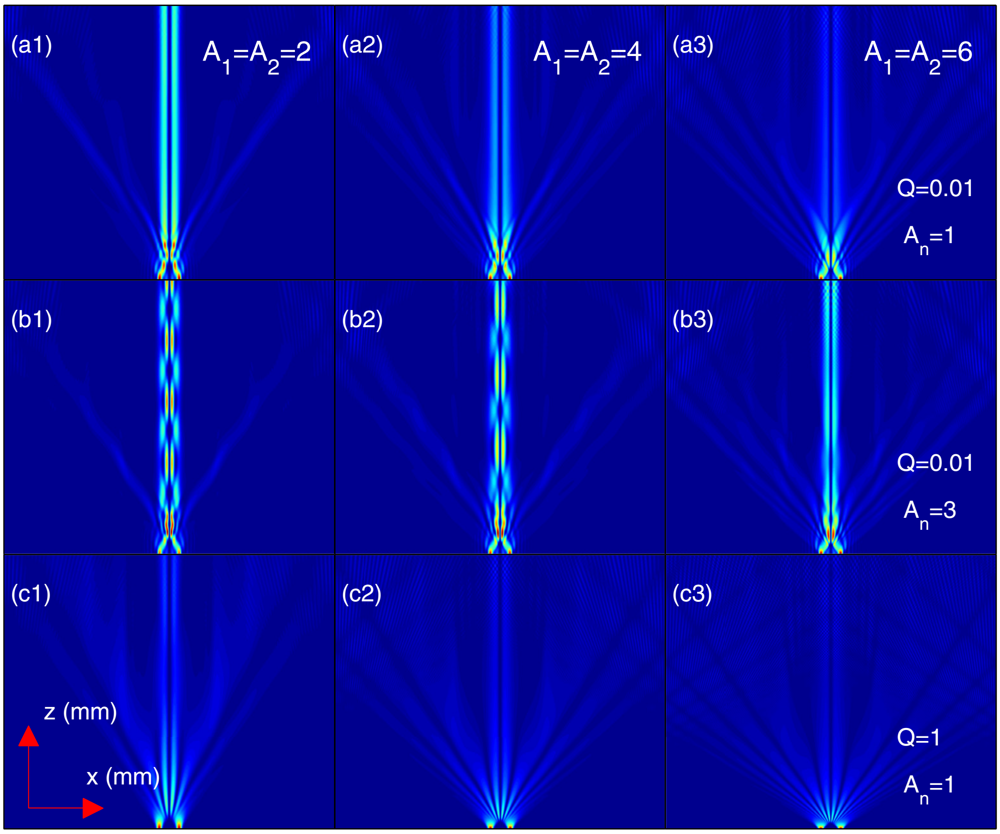

FIG. 8. The interaction of two AiG beams with changing the values of A_1, A_2, Q, and A_n for $T = 0.1$ mm, $\gamma = -1$, $D = 3$, $\delta\phi = \pi$, and $\delta n = 0.5$.

the central region can also be regarded as breathers as shown in Figs. 6(c1)–6(c3).

In order to further study the effect of the nonlinearity and lattice on the interaction of two AiG beams, we will change the amplitude A_1 and A_2 and the lattice depth A_n. First, the propagation images of two out-of-phase beams with different distribution factor Q are shown in Fig. 8 in self-defocusing media. We assume that the value of A_1 and A_2 is the same and they change their value simultaneously. As $A_n = 1$, one can see that the soliton pairs forms as shown in Figs. 8(a1)–8(a3), especially at $A_1 = A_2 = 2$. This results from the role of the repulsive force of the self-defocusing nonlinearity and constraint force of the lattice with defects in the AiG beams. The result is similar to the interaction of two Gaussian beams, Fig. 6 in Ref. [42] and Figs. 4(b1)–(b2) in Ref. [44]. However, Ref. [42] and Ref. [44] discussed the interaction of two Gaussian beams in the self-focusing media. In our case, while $Q = 1$, two beams launch into the self-defocusing media, the beam diffraction arises, shown in Figs. 8(c1)–8(c3). If A_n is bigger, such as $A_n = 3$, one can see that the lattice with defects further constraints the beams and the breathers appear [see Figs. 8(b1) and 8(b2)]. More interestingly, when $A_1 = A_2 = 6$, soliton pairs can again form in Fig. 8(b3). While we increase the distance D between the two parts of the beam, such as $D = 5$ and $D = -5$ shown in Fig. 9, the results are very different. For AiG beams, the quasibreather dynamics has a larger spatial size and a longer periodicity; see Figs. 9(a) and 9(b). The interaction dynamics is different at $D = 5$ and $D = -5$ because of the different direction of the beam acceleration. However, for Gaussian beams, they diffuse obviously. In particular, they are same for the different distance ($D = 5$ and $D = -5$). The results illustrate again that the interaction dynamics excited by AiG beams and Gaussian beams is different.

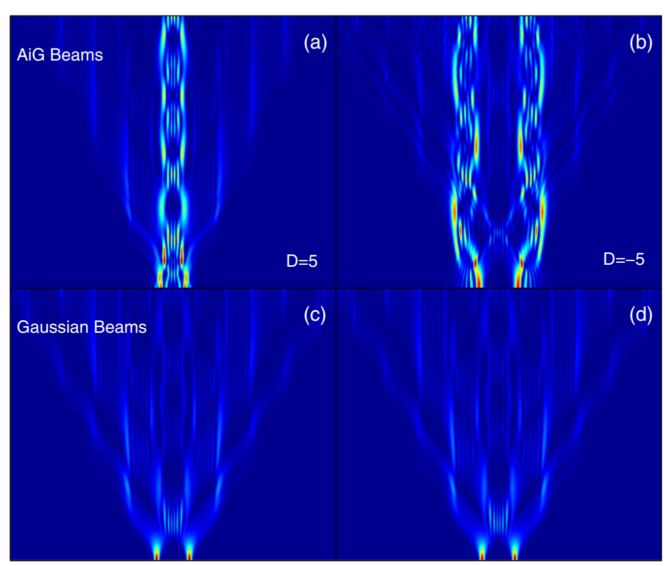

FIG. 9. The interaction of two AiG beams ((a) and (b)) or two Gaussian beams [(c) and (d)] for $D = 5$ (left column) and $D = -5$ (right column) at $A_1 = A_2 = 1$, $A_n = 5$, $T = 0.1$ mm, $\gamma = 1$, $\delta\phi = \pi$, and $\delta n = 0.5$.

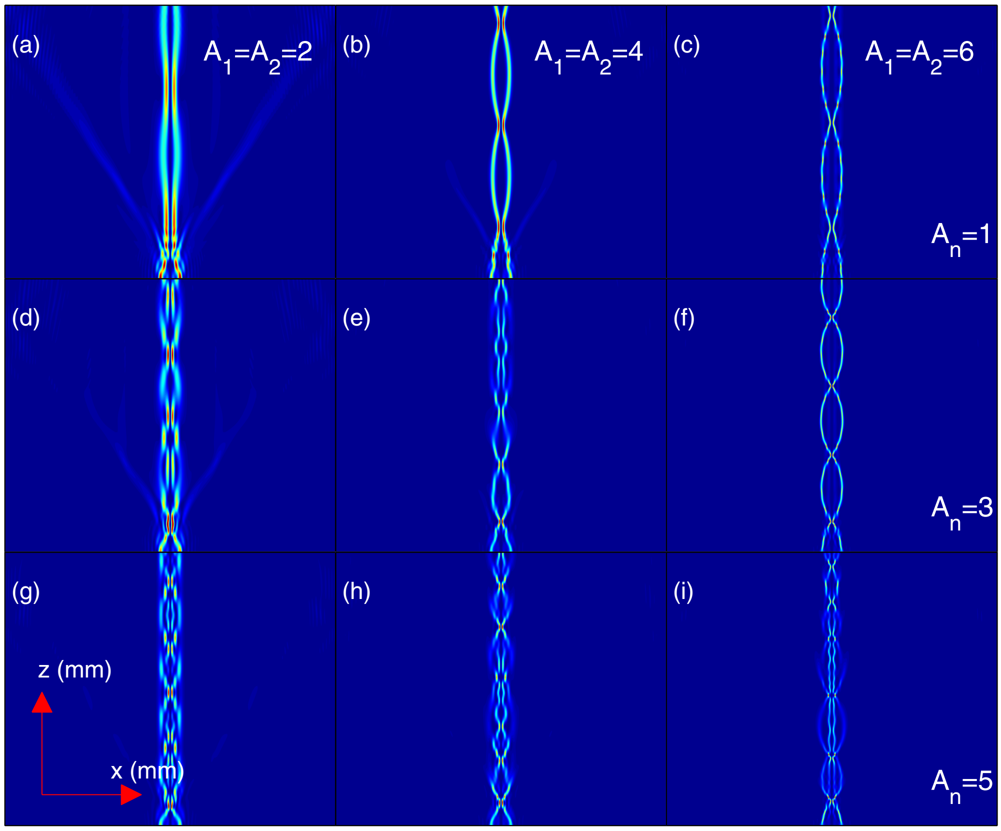

FIG. 10. The interaction of two AiG beams with changing the values of A_1, A_2, and A_n for $\gamma = 1$ and $Q = 0.01$. The other physical parameters are the same as in Fig. 8.

When we introduce the self-focusing nonlinearity, we find that breathers form instead of soliton pairs from Figs. 10(a)–10(c). At $A_n = 3$, when the self-focusing nonlinearity grows, the breathers are first destroyed shown in Fig. 10(d) and 10(e) for increasing the beam input power. Moreover, when $A_1 = A_2 = 6$, breathers can again form in Fig. 10(f) because the balance between the self-focusing nonlinearity and the lattice defect. Compared with Fig. 10(c), the period is smaller. In Figs. 10(g)–10(i), no breathers exists even though the beam power is bigger ($A_1 = A_2 = 6$) at $A_n = 5$. Second, we consider that the interaction of two in-phase beams for different A_1 and A_2 in self-focusing media, as shown in Fig. 11. The asymmetrical intensity distribution of the beams is formed by the interaction of the two AiG beams with $A_1 \neq A_2$. At this situation, the breathers are not discovered from Figs. 11(a) and 11(c). In addition, one can see that the deflecting direction is affected by the different intensity distributions [see Fig. 11(d)]. Compared Fig. 11(b) with Figs. 11(a) and 11(c), the breathers are symmetric because A_1 and A_2 are the same value.

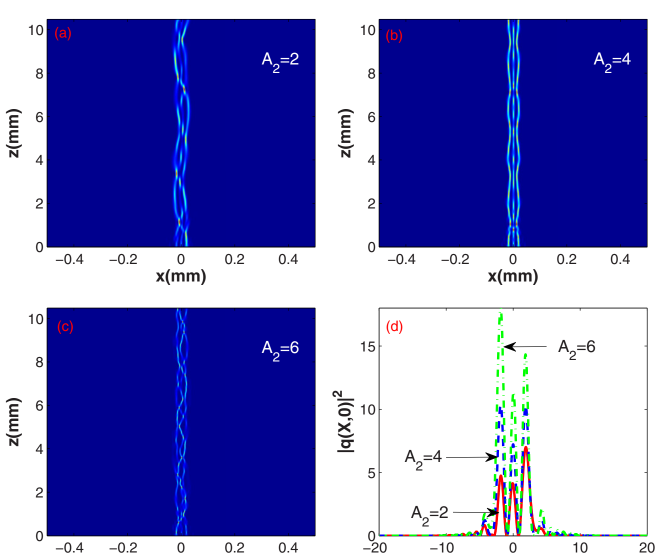

FIG. 11. The interaction (a)–(c) and intensity profiles of two AiG beams with changing the values of A_2 for $A_1 = 4$, $A_n = 3$, $T = 0.1$ mm, $\gamma = 1$, $D = 3$, $Q = 0.01$, $\delta\phi = 0$, and $\delta n = 0.5$.

IV. CONCLUSION

To conclude, we have investigated the interactions of two different amplitude and phase AiG beams in linear and nonlinear media with the lattices with defects by using the numerical simulations with the split-step Fourier method. We find that the interference fringe, breathers, and soliton pairs can be produced in these interactions. The generated interference fringe, breathers, and soliton pairs in the central region do not accelerate transversely, because their properties are determined by the underlying the media with lattices with defects and not by the incident beam from which they are generated. In the linear media, the phase shift and the beam interval can affect the initial deflection direction of the accelerated beams. In general, the central interference fringe in the in-phase case is bright, whereas in the out-of-phase case it is dark. Interestingly, when a lattice period is appropriate, the periodic interference fringe may be formed. A constructive or destructive interference can also be influenced by the defect depth. While the nonlinearity is introduced, the breathers are generated. As the medium is the self-focusing nonlinear medium, the self-focusing nonlinearity further traps some energy and breathers have formed. Though the self-defocusing nonlinearity increases the diffraction, the field distributions in the central region can also be regarded as breathers. In particular, when we select the appropriate beam amplitude and lattice depth, soliton pairs may be shaped. In addition, the interaction of the two AiG beams with different amplitudes can lead to the asymmetrical intensity distribution of the beams.

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