Counterpropagating surface solitons in two-dimensional photorefractive lattices

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Abstract: We study interaction of counterpropagating beams in truncated two-dimensional photonic lattices induced optically in photorefractive crystals, and demonstrate the existence of counterpropagating surface solitons localized in the lattice corners and at the edges. We display intriguing dynamical properties of such composite optical beams and reveal that the lattice surface provides a strong stabilization effect on the beam propagation. We also observe dynamical instabilities for stronger coupling and longer propagation distances in the form of beam splitting. No such instabilities exist in the single beam surface propagation.

OCIS codes: (190.5330) Photorefractive nonlinear optics; (190.5530) Pulse propagation and solitons.

References and links

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1. Introduction

Spatial surface solitons propagating in waveguide arrays and two-dimensional (2D) photonic lattices have attracted considerable attention recently for their potential in all-optical photonic applications [1, 2]. Most of attention has been focused on the single propagating beams [3, 4], even though such periodic structures tend to spontaneously produce backward propagating components [5]. Nonetheless, mutual interaction of two counterpropagating (CP) optical beams in a nonlinear medium is one of the simplest, yet very important nonlinear process in optics. Such seemingly simple geometry can give rise to complicated and sometimes counterintuitive beam dynamics, including both mutual and self trapping, and the formation of stationary states and spatiotemporal instabilities [6].

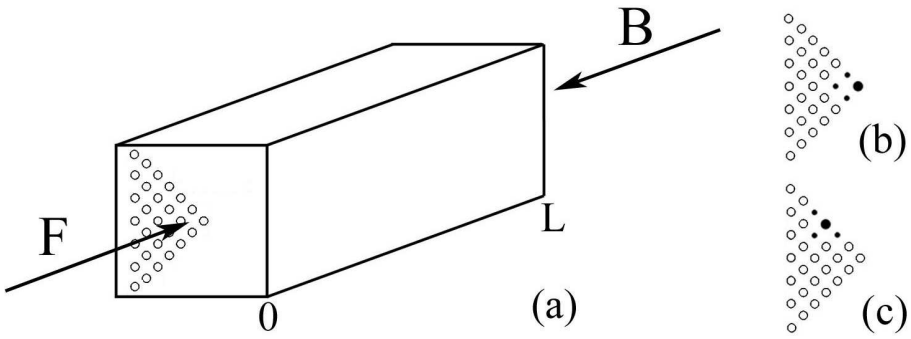

Fig. 1. (a) Problem geometry with the forward (F) and the backward (B) beams. (b,c) Sketches of the surface modes localized in the lattice corner or at the edge, respectively.

Interaction between solitons that propagate in the opposite directions enable mutual focusing, resulting from the interaction between the beams. The solitons interfere and give rise to an effective grating. Mutual trapping of two CP optical beams was shown to lead to the formation of a novel type of vector (or bimodal) solitons [7, 8], for both coherent and incoherent interactions. A more detailed analysis [9] revealed that these CP solitons may display a variety of instabilities accompanied by nontrivial temporal and spatial dynamics, and many subsequent theoretical and experimental studies were devoted to this subject [10].

The study of interaction of CP solitons in 1D [11] and 2D [12] nonlinear photonic lattices revealed the existence of *three different regimes*: stable propagation of vector solitons at low power, instability for intermediate powers, with a transverse shift of the solitons, and an irregular dynamical behavior of the two beams at high input powers. Nevertheless, both theoretical and experimental results suggest that spatiotemporal soliton instabilities are suppressed with the increasing strength of the optical lattice [11, 12].

In this paper we study the interaction of CP beams near the surface of a truncated 2D photonic lattice optically induced in a photorefractive crystal, and describe novel types of CP solitons, the so-called *counterpropagating surface solitons*, localized in the lattice corners or at its edges (see Fig. 1). We also study extensively the dynamical properties of such composite solitons and demonstrate that the lattice surface produces a strong stabilizing effect on such vectorial solitons.

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2. Model and basic equations

To study the CP surface solitons in optically-induced photonic lattices [3] in the geometry shown in Fig. 1(a), we consider a time-dependent model [9, 13] based on the theory of photorefractive effect. The model consists of the wave equations in the paraxial approximation for the propagation of mutually incoherent CP beams and a relaxation equation for the generation of the space charge field (SCF) in the photorefractive crystal,

$$i\frac{\partial F}{\partial z} = -\Delta F + \Gamma E F, \quad -i\frac{\partial B}{\partial z} = -\Delta B + \Gamma E B, \tag{1}$$

$$\tau\frac{\partial E}{\partial t} + E = -\frac{I}{(1+I)}, \tag{2}$$

where F and B are the forward and backward propagating beam envelopes, Δ is the transverse Laplacian, Γ is the dimensionless coupling constant, and E is the homogenous part of SCF. The relaxation time of the crystal τ also depends on the total intensity, $\tau = \tau_0(1+I)^{-1}$. The total intensity $I = |F|^2 + |B|^2$ is measured in units of the background intensity. A scaling $x/x_0 \to x$, $y/x_0 \to y$, $z/L_D \to z$, is utilized for the dimensionless equations, where x_0 is the typical FWHM beam waist and L_D is the diffraction length. We assume that mutually incoherent CP components interact through the intensity-dependent saturable SCF.

When the propagation in photonic lattices is considered, Eq. (2) is modified to include the transverse intensity distribution of the lattice array I_g, optically induced in the crystal

$$\tau\frac{\partial E}{\partial t} + E = -\frac{(I+I_g)}{(1+I+I_g)}. \tag{2a}$$

The form of I_g depends on the type of photonic lattice. For the square lattice, it is given by $I_g = I_0 sin^2[\pi(x+y)/(d\sqrt{2})] sin^2[\pi(x-y)/(d\sqrt{2})]$, where d is the lattice spacing. The propagation equations are solved numerically, concurrently with the temporal equation, in the manner described in Ref. [14]. The dynamics is such that the SCF builds up towards the steady state, which depends on the light distribution, which in turn is slaved to the change in SCF. In general, we found that the presence of photonic lattice exerts a stabilizing effect on the propagation of CP beams, as compared to the propagation in bulk. In our simulations we utilize experimental data from Ref. [3], and vary the coupling constant Γ, the propagation distance L, and the lattice and beam intensities. However, we confine our attention here to the cases with fixed lattice and input beam intensities. We choose the lattice intensity comparable but stronger than the beam intensities, in accordance with the experiment [3]. To check our numerics, we also simulated the cases of single beam propagation, to find steady surface states very similar to the ones found in experiment [3]. As compared to CP surface solitons, for identical other parameters the single beam surface solitons require slightly higher Γ to form, but display no instabilities.

3. Spatially localized surface states

First, we consider the *corner* states. Two mutually incoherent Gaussian beams of the same intensity are launched head-on from the opposite faces of a photorefractive crystal, in which an optically induced 2D photonic lattice is established [see Fig. 1(a)]. The beams are launched in the center of the corner unit cell. Some characteristic outcomes of the surface modes are presented in Fig. 2, after steady state is reached. The upper row in the figure displays intensity distributions of the forward beam at the exit face of the crystal. Insets depict the same situation in the inverse space; added squares mark the first Brillouin zone (BZ) of the full lattice. It is seen that with the increasing coupling constant, the beams focus into well defined CP solitons, close

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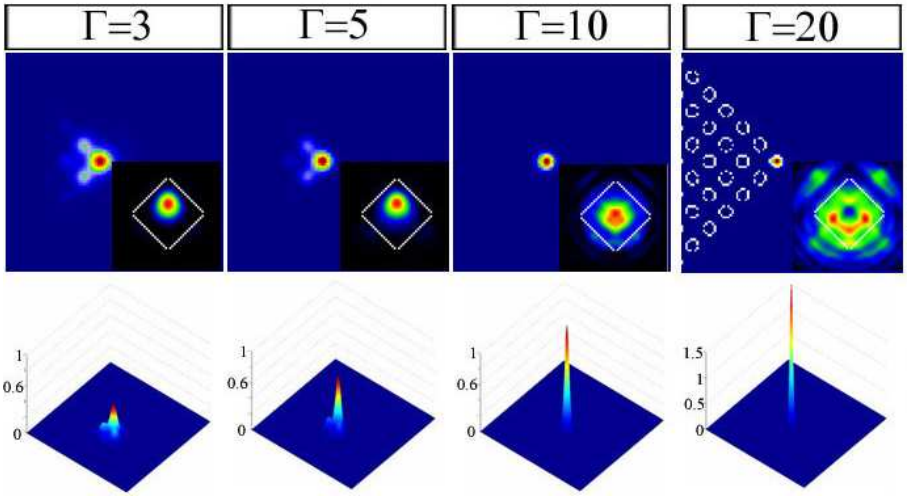

Fig. 2. Corner surface modes, for different coupling constants. Top row: Intensity distributions of the forward field at its output face in the direct space and in the inverse space (insets). The layout of the lattice beams is only shown in the last figure. Bottom row: The same intensity distributions in 3D. The propagation distance is $L = 2.5L_D = 10mm$. FWHM $= 14\ \mu m$ of the input Gaussian beams, lattice spacing $d = 23\ \mu m$, $|F_0|^2 = |B_L|^2 = 1$, the maximum lattice intensity $I_0 = 3$.

to the corner lattice site. As they focus in the direct space (the bottom row), they spread in the inverse space, spilling over the first BZ (insets). For larger Γ, the influence of the neighboring sites on the beam distribution is lost.

An example of the surface mode structure that is not localized is the diffraction mode for small coupling constant (up to $\Gamma \approx 5$). Incident beams, in the form of narrow Gaussians, spread upon propagation, and the part of each beam is captured by the nearest lattice sites in the direct space. In the inverse space, the beams stay localized inside the first BZ. By increasing the coupling constant, the beams tightly overlap and the trapping becomes clearly visible; stable corner surface solitons form, and are observed between $\Gamma \approx 7.5$ and $\Gamma \approx 15$. By further increasing the coupling constant, instabilities take place. Upon propagation the incident beams mix and interact, and start repelling each other. After an initial transient they form a long-lived quasi-stable partly overlapping Gaussian-like mode; that is, a meta-stable 2D spatial vector soliton. In our earlier papers [9, 13, 14], even without the optical lattices, we observed a similar ejection phenomenon, and termed it the *splitup* transition. Here it appears in the localized modes in the corner of photonic lattice, and represents the simplest form of the dynamical beam instability. Such instabilities cannot occur in the single beam surface states.

The case $\Gamma = 20$ in Fig. 2 belongs to the unstable states; the splitup transition occurs there very fast during time evolution, and after that the steady state is reached. For this value of Γ only the steady state is presented, in which the Gaussian beams are slightly displaced after the splitup transition, but still strongly pinned to the lattice site. The splitup transition is easily identified in the inverse space; when it occurs, the beam crosses the edge of the first BZ; afterwards most of it focuses back inside and the steady state is reached. In the end, the beams loose their regular Gaussian shape along the propagation direction. Both CP beams execute the same behavior, being mirror-images of each other. Some cases from Fig. 2 are presented in Fig. 5 as movies.

Figure 3 summarize our results in the form of a phase diagram in the plane of control parameters L and Γ. The input intensities are kept fixed, as in Fig. 2. Three regions are visible in the diagram. For small coupling constants there exists a narrow region where no conversion

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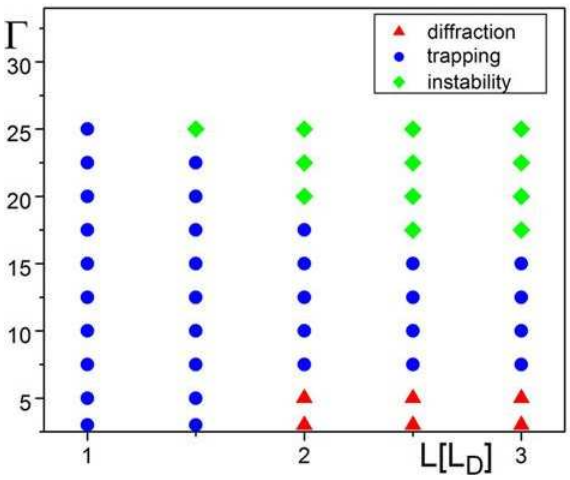

Fig. 3. Typical behavior of corner surface solitons. Symbols in the inset present possible outcomes. Blue dots denote the stable corner solitons, red triangles represent the diffracting modes, and green lozenges stand for the unstable modes.

to trapped surface modes is observed. We term these states the diffraction modes. The beams spread upon propagation, and overlap with the neighboring lattice sites (*cf.* Fig. 5). This regime is similar to the single beam experimental results at low bias field [3]. For higher values of Γ and L the region of stable corner solitons is observed. For still higher values of the parameters, the region of unstable modes is reached.

Similar results hold for the surface modes localized at the edge of photonic lattice. They are presented in Fig. 4. Again, only the cases when the coupling constant is varied are shown. For small coupling constants no strong localization at the edge is observed. Compared with the corner mode, the edge mode has different shape, because of different positions of the neighboring lattice sites; however, it again appears similar to the experimental results [3].

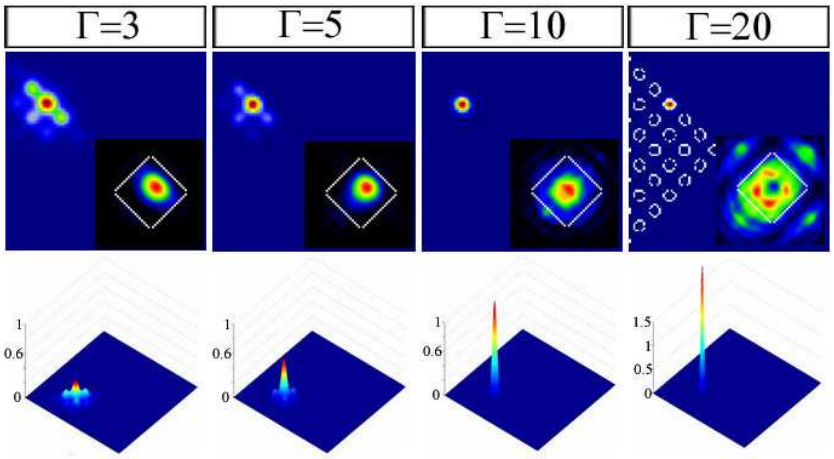

Fig. 4. Edge surface modes, as the coupling constant is increased. The figure layout is as in Fig. 2. The parameters are also as in Fig. 2.

For higher values of the coupling, highly localized stable trapped edge surface solitons are observed, for values of the coupling constant similar to those of the corner surface solitons.

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Similarly, for still higher values of Γ and L, we observe the development of instabilities, in the form of one or two subsequent splitup transitions. After the splitup transitions, the intertwined Gaussian-like beams are again strongly pinned to the lattice site. Characteristic cases from Fig. 4 are also presented as movies in the lower part of Fig. 5.

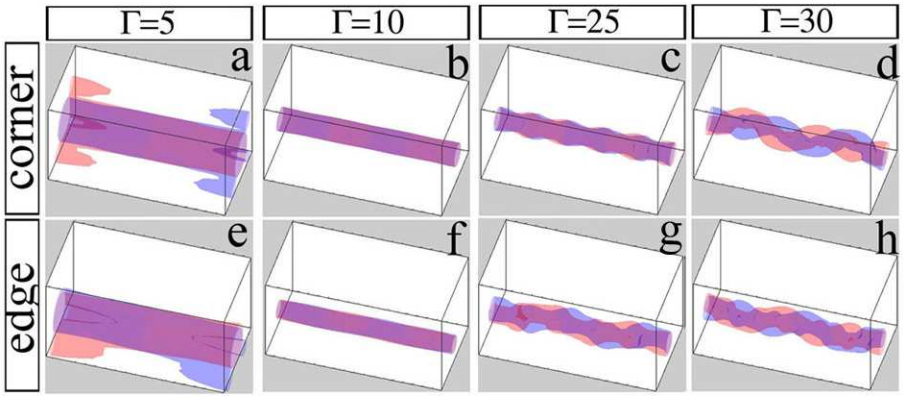

Fig. 5. Dynamical behavior of surface modes in two-dimensional lattice. Upper row: corner beams. Lower row: edge beams. Movies of the intensity distributions of both forward and backward fields are shown along the propagation direction, in time: (a) (Media1), (b) (Media2), (c) (Media3), (d) (Media4), (e) (Media5), (f) (Media6), (g) (Media7), (h)(Media8), for different coupling constants Γ. The cases (a) and (e) are zoomed, to display more clearly the diffraction of beams. Other parameters are as in Fig. 2.

4. Soliton instabilities

The most illustrative cases depicted in Figs. 2 and 4 are shown again in Fig. 5, but now as 3D movies along the photorefractive crystal. Both forward and backward beams are presented, depicted in blue and red. We observe that the stable corner [see Fig. 5(a)] and the edge [see Fig. 5(e)] surface states for $\Gamma = 5$ are not focused; they spread across the neighboring lattice sites. The cases for $\Gamma = 10$ form the stable surface solitons during time, but slightly change the transverse profile along the crystal; they represent breathing surface solitons. The cases for $\Gamma = 25$ are unstable (Media3 and Media6); splitup transitions are visible there. The examples with rich dynamics for $\Gamma = 30$ and the corresponding movies (Media4 and Media8) represent behavior with two consecutive splitup transitions. After those transitions the steady state is reached, but the beams display regular intertwined spiraling shapes along the crystal.

5. Conclusion

We have studied the interaction of CP optical beams in truncated 2D photorefractive photonic lattices and revealed the existence of novel types of CP optical surface solitons, localized in the lattice corners or at the edges. Beside stable bimodal surface modes, we have observed the development of transverse symmetry-breaking split-up instabilities of CP surface solitons. We have identified threshold conditions for such dynamical instabilities, and demonstrated that they occur for stronger couplings and longer propagation distances. Such instabilities are not possible in the surface states of single propagating beams. In general, the lattice provides a strong stabilization effect on the CP solitons, pinning them strongly to the lattice sites.

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