Counterpropagating self-trapped beams in optical photonic lattices

M. Belić[1,2], D. Jović[2], S. Prvanović[2], D. Arsenović[2], and M. Petrović[2]
[1] *Texas A&M University at Qatar, P.O. Box 5825 Doha, Qatar*
[2] *Institute of Physics, P.O. Box 57, 11001 Belgrade, Serbia*
jovic@phy.bg.ac.yu

Abstract: Dynamical properties of counterpropagating (CP) mutually incoherent self-trapped beams in optically induced photonic lattices are investigated numerically. A local model with saturable Kerr-like nonlinearity is adopted for the photorefractive media, and an optically generated two-dimensional fixed photonic lattice introduced in the crystal. Different incident beam structures are considered, such as Gaussians and vortices of different topological charge. We observe spontaneous symmetry breaking of the head-on propagating Gaussian beams as the coupling strength is increased, resulting in the splitup transition of CP components. We see discrete diffraction, leading to the formation of discrete CP vector solitons. In the case of vortices, we find beam filamentation, as well as increased stability of the central vortex ring. A strong pinning of filaments to the lattice sites is noted. The angular momentum of vortices is not conserved, either along the propagation direction or in time, and, unlike the case without lattice, the rotation of filaments is not as readily observed.

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1. Introduction

An intense interest was generated recently in the propagation and interactions of self-focused light in photonic lattices imbedded in photorefractive (PR) crystals, giving rise to the discrete diffraction and offering intriguing waveguiding possibilities [1-3]. Periodic two-dimensional (2D) arrays of optically induced waveguides allowed for the observation of novel self-trapped optical structures – the so-called discrete or lattice solitons, including the discrete vortex solitons [4-6]. In principle, different phenomena are observed if one considers propagation along the invariant (axial) lattice direction or perpendicular to it, in the plane of symmetry direction. Typically, one is more interested in the waveguiding aspects (i.e. propagating modes) of the lattice array in the former case, and more in the bandgap aspects (i.e. nonpropagating modes) of the photonic crystal in the latter case.

Of special concern are the modes connected with defects embedded in a perfect infinite or finite lattice [5-7]. An especially interesting geometry from the applications point of view is the photonic crystal fiber (PCF), in which a finite hexagonal lattice of holes is infused into a silica fiber, with the central hole absent [8]. Such a 2D PCF with a central defect, also referred to as the "holey fiber", offers a different scenario of waveguiding from the perfectly periodic infinite photonic crystal (PC) with dielectric rods or beams of light, in that it displays huge refractive index step, and that the light is pinned to the defect.

The formation and interactions of spatial solitons, within or without lattice, have been studied mostly in the copropagation geometry, with a few exceptions [9-13]. In these references the counterpropagating (CP) solitons were considered theoretically in one transverse dimension (1D), in Kerr and local PR media, and in the steady state. In Refs. [14-16] we studied numerically 2D CP vector solitons and displayed some novel dynamical beam structures in PR crystals. In Refs. [17-19] experimental results are presented, and in Ref. [20] numerical study of CP vortices is performed. Nowhere in the literature could we find reference to the CP lattice solitons.

Here we introduce, to the best of our knowledge for the first time, 2D CP vector lattice solitons in an optically induced photonic lattice, and present some of their intriguing properties. We display stable transverse symmetry-breaking splitup transitions of CP lattice solitons, as well as dynamically symmetry-broken splitup transitions, where no definitive patterns are visible. We demonstrate that CP vortices generally break up into filaments that are pinned to the lattice sites, but also that the stability of vortex cores can be enhanced in the presence of lattice defects. The angular momentum of vortices is not conserved, as it should not be in a symmetry-breaking transition. For some values of the coupling strength an indefinite rotation of the central vortex filaments is observed.

2. The model

To understand the behavior of CP vector solitons we formulated a time-dependent model for the formation of self-trapped CP optical beams [14, 15], based on the theory of PR effect. The model consists of wave equations in the paraxial approximation for the propagation of CP beams and a relaxation equation for the generation of the space charge field in the PR crystal, in the isotropic approximation. The model equations in the computational space are of the form:

$$i\partial_z F = -\Delta F + \Gamma EF \ , \qquad -i\partial_z B = -\Delta B + \Gamma EB \ , \tag{1}$$

$$\tau\partial_t E + E = -\frac{I}{1+I} \ , \tag{2}$$

where F and B are the forward and the backward propagating beam envelopes, Δ is the transverse Laplacian, Γ is the dimensionless coupling constant, and E the homogenous part of the space charge field. The relaxation time of the crystal τ also depends on the total intensity, $\tau=\tau_0/(1+I)$. The quantity $I=|F|^2+|B|^2$ is the laser light intensity, measured in units of the background intensity. A scaling $x/x_0 \rightarrow x$, $y/x_0 \rightarrow y$, $z/L_D \rightarrow z$, is utilized in the writing of dimensionless propagation equations, where x_0 is the typical FWHM beam waist and L_D is the diffraction length. The assumption, appropriate to the experimental conditions at hand, is that the mutually incoherent CP components interact only through the intensity-dependent space charge field. To make matters simple, we did not account for the temperature (diffusion) effects, although they are found to influence the interaction of CP beams [13]. In the experiment [17-19], these effects were compensated for by focusing the input B beam at the place of the exit and in the direction of the output F beam.

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

$$\tau\partial_t E + E = -\frac{I+I_g}{1+I+I_g} \ , \tag{2a}$$

where I_g is formed by positioning Gaussian beams at the sites of the lattice, normalized by the dark irradiance I_d . For the lattice array we choose a hexagonal arrangement of beams, with variable intensities, and with the central beam absent. Such an arrangement is reminiscent of the holey fibers [8], except that there are no holes here, but laser beams that modulate the index of refraction. The beams are assumed to be degenerate and incoherent with the forward and backward components. We also assume that the array beams are far enough from each other, so that the interaction between them can be neglected, and that the influence of CP beams on the lattice beams is negligible.

The propagation equations are solved numerically, concurrently with the temporal equations, in the manner described in Ref. [16] and references cited therein. The dynamics is such that the space charge field builds up towards the steady state, which depends on the light distribution, which in turn is slaved to the change in the space charge field. As it will be seen, this simple type of dynamics does not preclude a more complicated dynamical behavior.

3. Counterpropagating Gaussian beams

A striking feature of CP self-trapped beams is noted as soon as the beams are launched in a PR medium with sufficient nonlinearity – the spontaneous transverse splitup instability [15, 16]. Providing for an explanation of the nature and the cause of the splitup transition turned out to be a more difficult problem. In Refs. [15, 16] we presented a simple theory of beam displacement - derived in two independent ways - that can account for such transverse shifts. In Ref. [18] we attempted to utilize the standard theory of modulational instabilities (MI) to obtain a threshold curve for the CP beams splitup that at least qualitatively agrees with the experimental and numerical results. In doing so, we were aware of the fact that, although both are symmetry-breaking phenomena, the pattern forming MI represents a spontaneous breaking of the translational symmetry of a homogeneous state, whereas the splitup transition is the breaking of the rotational symmetry of an isolated CP soliton. Thus, MI involves an appearance of transverse waves at a critical value of kc, whereas the splitup instability involves a jump of the peaked structure in the transverse inverse space for some value of kc. The two values of kc might, but need not be connected.

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An optical waveguide array embedded in a PR crystal considerably changes the behavior of CP beams, as compared to the wave behavior in bulk media, however the splitup instability stays there. The continuous O(2) rotational symmetry of the system in the transverse plane is substituted by a discrete point symmetry, and that has bearing on the symmetry-breaking splitup transition. Ours is an axially-invariant photonic lattice, with a planar D_6 symmetry and a central defect, and the axially-propagating beams undergoing symmetry breaking must comply with the sub-symmetries of the plane group. In our case the symmetry breaking usually proceeds along the D_2 – C_1 subgroup chain. In addition, the presence of a central defect introduces further differences in the discrete self-focusing, as compared to the infinite lattice, in that the localized optical structures are helped by and pinned to the defect.

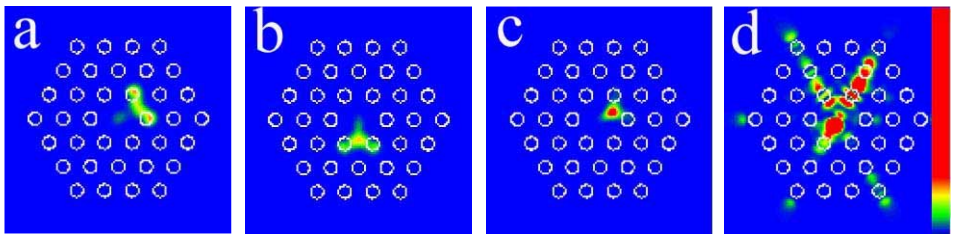

Fig. 1. Movies of the intensity distributions of the backward field at its output face, for various FWHM of input beams: (a) *11 µm* (768 KB), (b) *9 µm* (745 KB), (c) *7 µm* (602 KB), (d) *5 µm* (1.1 MB). For FWHM=*5 µm* no steady state is observed. Parameters: lattice spacing *28 µm*, FWHM of lattice beams *9 µm*, maximum lattice intensity $I_g=10I_d$, $\Gamma=19.3$, $L=2L_D=8$ *mm*, $|F_0|^2=|B_L|^2=10$.

A typical example of the splitup symmetry-breaking transition in our photonic lattice is presented in Fig. 1. A relatively wide lattice is chosen, lattice spacing 28 µm, with relatively narrow beams of 9 µm. The width of CP components is varied. It is decreasing from 11 µm in Fig. 1(a) to 5 µm in Fig. 1(d). It is seen that the splitted component of the widest CP beam focused at the two adjacent lattice sites (Fig. 1(a)), whereas the components of more narrow CP beams focused in-between the two sites (Figs. 1(b)-(c)). The narrowest CP beam did not focus at all (Fig. 1(d)). It turned out to be unstable from the beginning, exciting initially the three 1D discrete solitonic modes, along the three main symmetry directions. It remained centrally-symmetric for awhile, with a clear hexagonal symmetry, but then became dynamically broken to C_1. Thereafter, the beam discretely diffracts in asymmetric bursts, at irregular times, along the two of the same 3 symmetry directions. This behavior is the analogue of the dynamic splitup transition observed earlier in CP vector solitons [18], but now with a strong discrete diffraction visible.

The similar tendency to focus on or in-between the lattice sites is noted if, instead of the component width, the coupling strength ΓL is increased (Fig. 2). Such even and odd discrete solitons are commonplace in periodic arrays of optical waveguides. The choice of the particular pair of adjacent lattice sites among the 6 is incidental, although the direction of the polarization of CP beams is horizontal. The situation here is steady-state, however the initial transient behavior lasts shorter with the increasing ΓL. Initially the beam jumps transversally and then rotates, until settling into a steady-state structure, accommodating the lattice's (sub)symmetry. Both CP beams execute the same dynamics, mirror-image of each other.

The splitup transition depicted in Fig. 2(b) is shown again in Fig. 2(c), as a three-dimensional picture along the crystal. It clearly displays the splitup of the forward and backward beams, depicted in green and red, into a discrete vector soliton that focuses onto the same two adjacent hexagonal sites on both ends of the crystal. The white rods represent the lattice beams. The green, forward beam enters from the left, in the middle of the central defect, and the red, backward beam enters from the right. In the middle of the crystal they cross each other and split into two beams, that focus onto the two adjacent lower lattice cites.

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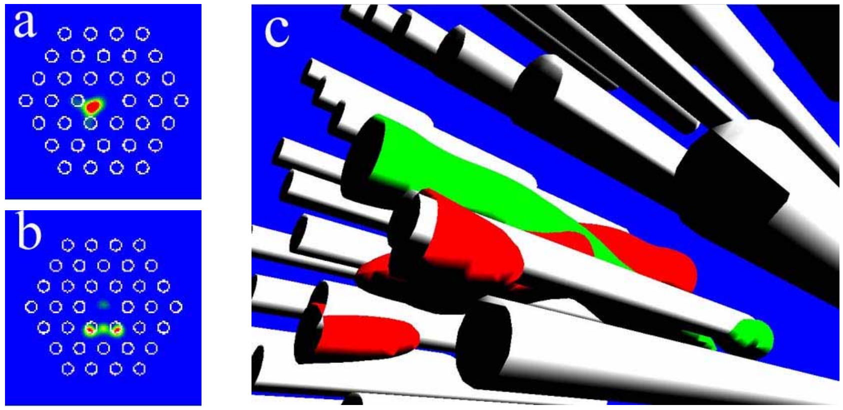

Fig. 2. Movies of the intensity distributions of the backward field at its output face for various coupling strengths: (a) $\Gamma=16.6$, $L=1.3L_D$, (755 KB) (b) $\Gamma=19.3$, $L=2.5L_D$ (603 KB). (c) Isosurface plots at 10% of maximum intensity for the case presented in Fig. 2(b) and in the steady state; green - forward beam, red - backward beam, white – lattice beams. Other parameters are as in Fig. 1(a).

4. Counterpropagating vortices

Concerning CP vortices, our general conclusion is that, similar to the propagation in bulk media, they can not remain stable over indefinite propagation distances [20]. They do not display transverse splitup transitions either, but break up into filaments. When the breakup occurs, the filaments conform to the symmetry of the lattice. Figure 3 represents head-on counterpropagation of two centered vortices, with different topological charges, overlapping with the waveguiding lattice. The values of charges are given in the parenthesis (forward, backward) on the top of each figure, and the width of input vortices is relatively large (26.2 µm). The filamented structures remain steady-state and strongly pinned to the lattice. The transient dynamics lasts relatively short. The angular momentum of CP vortices is not conserved. The system experiences a considerable loss of angular momentum, owing to the presence of the lattice.

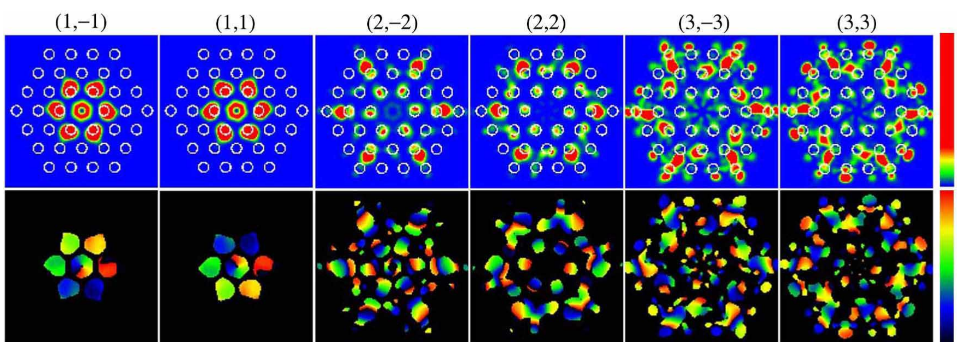

Fig. 3. Intensity (upper row) and phase (lower row) distributions of the backward field at its output face in the steady state, for different topological charges, recorded on the top of each figure. Parameters are as in Fig. 1, input FWHM of vortices is *26.2 µm*.

The filaments of low-order (1, ±1) vortices focus onto the first-order lattice sites, whereas the filaments of higher-order vortices mostly focus in-between the higher-order lattice sites. The size of the discrete-diffracted structures increases with the topological charge, however the phase distribution among the filaments reveals the typical vortex linear increase of phase, with branch-cut lines. There is practically no difference in intensity

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between the discrete (1, 1) and (1, –1) vortices, and only slight differences between the higher-order vortices. The plane symmetry of all these structures is C_6. Note the well-preserved core vortex at the central defect of (1, ±1) structures. This feature remains robust, even as the length of the crystal is increased. Stable vortices pinned to the defect could not be observed in the case without lattice, at such high values of the coupling strength ΓL.

The filamented structures could not be made to rotate as readily as in the case of CP vortices propagating in the absence of lattice. For this to happen, it was necessary to consider vortices of opposite charge, at higher values of ΓL, and at lower values of I_g. In Fig. 4 we present a tripole-like structure, produced from the (1,-1) vortices, that rotates indefinitely. The central core vortex has broken into 3 rotating filaments, while the other filaments remain pinned to and oscillate about their lattice sites. Unlike the case of CP vortices propagating in the absence of lattice [20], the angular momentum of the filamented structure is not conserved in time. Owing to the strong interaction with the lattice it oscillates back and forth, in accordance with the oscillatory motion about the lattice sites.

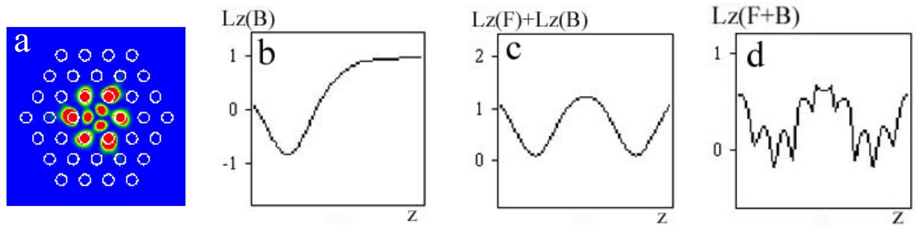

Fig. 4. Rotating vortex, backward field: (a) Movie of the intensity distribution in the real space (1.603 MB). (b) Movie of the time evolution of the total angular momentum of the backward beam (441 KB). (c) Movie of the time evolution of the sum of angular momenta of both fields (498 KB). (d) Movie of the time evolution of the angular momentum of the total field *F+B* (629 KB). Total angular momentum is normalized to the total beam intensity. Parameters: lattice spacing *28 μm,* FWHM of lattice beams *9 μm,* maximum lattice intensity $I_g=5I_d$, $\Gamma=16.55$, $L=2.5L_D=10$ *mm*, $|F_0|^2=|B_L|^2=5$, input FWHM of vortices *26.2 μm*.

5. Conclusions

In summary, we report on the various aspects of counterpropagation of self-trapped beams in isotropic local saturable photorefractive media, in the presence of an optically-induced photonic lattice. We display axial propagation of solitonic CP beams and vortices in an optical lattice with a central waveguiding defect. A peculiar dynamic behavior of localized beams is observed, in that the CP components suddenly change their transverse positions, and from an attracting interaction switch to repelling. Although sharing some common features with the counterpropagation in the absence of lattice, such as the splitup transition, the discrete diffraction brings novel moments into the picture, such as the appearance of discrete solitons, the discrete symmetry breaking, and the pinning to the central defect. In the case of CP vortices we observe the filamentation of beams. A strong pinning of filaments to the lattice is found, with an accompanying loss of angular momentum, and an improved stability of the vortex core. However, the vortex core can be destabilized at higher values of ΓL and lower values of I_g, sometimes producing a steady rotation of the resulting filaments.

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