Counterpropagating optical vortices in photorefractive crystals

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Abstract: We present a comprehensive numerical study of (2+1)D counterpropagating incoherent vortices in photorefractive crystals, in both space and time. We consider a local isotropic dynamical model with Kerr-type saturable nonlinearity, and identify the corresponding conserved quantities. We show, both analytically and numerically, that stable beam structures conserve angular momentum, as long as their stability is preserved. As soon as the beams loose stability, owing to radiation or non-elastic collisions, their angular momentum becomes non-conserved. We discover novel types of rotating beam structures that have no counterparts in the copropagating geometry. We consider the counterpropagation of more complex beam arrangements, such as regular arrays of vortices. We follow the transition from a few beam propagation behavior to the transverse pattern formation dynamics.

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

References and links

1. Introduction

There has been a renewed interest in optical beams carrying angular momentum [1-3], ever since the realization that they can be associated with spatial optical solitons [4,5]. Although sometimes colloquially referred to as the spinning solitons, their actual spin is more properly connected to their polarization state. In nonlinear self-focusing settings they appear as ring-like beams, displaying a phase singularity at the beam’s center: the intensity is vanishing at the center (and at the transverse infinity), and the phase is increasing counter-clockwise from zero to $\pi$. The nagging problem in the studies of propagation of such soliton-like structures has been their stability [6].

Self-trapped beams of light propagating without change in a diffractive nonlinear medium, better known as spatial solitons, have become much investigated objects in nonlinear optics [4]. Of considerable importance in al-optical information processing, they come in a variety of forms - as bullets, screening, quadratic, photovoltaic, and lattice solitons, or as bright, dark, and grey [5,6]. They are generated in different media, by different nonlinear mechanisms, but the self-focusing effect, produced by light-induced changes in the medium’s index of refraction, appears as a common thread to all mechanisms. Self-focusing in photorefractive (PR) crystals is achieved through the generation of space charge field, which is caused by the photo-induced redistribution of charges that modifies the index of refraction. Application of an external DC electric field across the crystal and an additional uniform illumination are found necessary for a more effective soliton formation process.

So far the formation and interactions of spatial screening solitons have been studied mostly in the copropagation geometry, with a variety of phenomena observed, such as the soliton spiraling [7], fusion [8], and filamentation [9]. The "dynamics" of all of these phenomena have been considered with respect to $z$, the propagation direction; no real time has been involved. Temporal development of copropagating solitons was considered in only a few
publications and in one transverse dimension (1D), displaying approach to steady state [10]. Counterpropagating (CP) solitons were considered in a few publications [11-15] as well, in 1D, in Kerr and local PR media, and in the steady state. However, one can easily envision applicative interest in 2D CP solitons, for example, for achieving a bidirectional link between two bundles of fibers across a PR crystal, with the possibility of including transverse control signals. In Refs. [16-19] we studied numerically 2D CP vector solitons and displayed some novel dynamical beam structures in PR crystals.

The copropagating vortex solitons have been considered in a number of papers [20-25], with mostly their (in)stability in focus. It has been found that single or pairs of interacting vortices can not remain stable as they propagate. They break up into a number (two, three, four, five) of fragments, after a propagation of several diffraction lengths. Different mechanisms have been proposed for improving their stability, for example the inclusion of nonlocal interaction in the medium [25]. In some of our publications [17-19] we presented a collision of two CP vortices carrying unit topological charges, as an example. They were also found to be unstable, generally breaking up into fragments within one diffraction length.

Here we present a comprehensive numerical study of (2+1)D counterpropagating vortices in photorefractive crystals. We consider CP incoherent vortices in both space and time. We evaluate the dynamical conserved quantities for the CP vortices. We show, both analytically and numerically, that stable beam structures conserve angular momentum, as long as their stability is preserved. As soon as they loose stability, owing to radiation or non-elastic collisions, their angular momentum starts to change, in both \( z \) and \( t \). Novel types of rotating beam structures are discovered that have no counterpart in the copropagating geometry. The propagation of more complex CP beam arrangements, such as regular arrays of vortices, is also considered, and the transition from a few beam propagation behavior to the transverse pattern formation dynamics is followed.

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 [16], based on the theory of PR effect. The model consists of wave equations in the paraxial approximation for the propagation of CP incoherent beams and a relaxation equation for the generation of space charge field in the PR crystal, in the local isotropic approximation. The nonlinearity is of the self-focusing saturable Kerr-type. The model equations in the computational space are of the form:

\[
\frac{i}{\tau} \partial_z F = -\Delta F + \Gamma E F, \quad -i \partial_z B = -\Delta B + \Gamma E B
\]

\[
\frac{\partial}{\partial t} E + E = -\frac{I}{1+I},
\]

where \( F \) and \( B \) are the forward and the backward propagating beam envelopes, \( \Delta \) is the transverse Laplacian, \( \Gamma \) is the dimensionless coupling strength, and \( E \) the homogenous part of the space charge field. The relaxation time of the crystal \( \tau \) also depends on the total intensity, \( \tau = \tau_0 / (1+I) \), where \( \tau_0 \) is the dielectric relaxation time under uniform background illumination. The quantity \( I = |F|^2 + |B|^2 \) is the laser light intensity, measured in units of the background intensity. A scaling \( x_0 \rightarrow x, y_0 \rightarrow y, z/L_D \rightarrow z \), is utilized in writing the propagation equations, where \( x_0 \) is the typical FWHM beam waist and \( L_D \) is the diffraction length. In our simulations we choose \( x_0 = 10 \mu m \), so that for the light from the Nd:YAG laser \( L_D \approx 5 \) mm. The assumption is that the counterpropagating 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 [14]. Likewise, the geometry of the beam interaction is chosen such that the anisotropy of the PR effect exerts a minimal influence [26].

Received 18 April 2005; revised 24 May 2005; accepted 24 May 2005

(C) 2005 OSA 13 June 2005 / Vol. 13, No. 12 / OPTICS EXPRESS 4381
The propagation equations are solved numerically, concurrently with the temporal equations, in the manner described in Ref. [18] 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. Some of our numerical results are presented in Figs. 1 – 11. In our simulations we discovered novel regular counter-propagating rotating structures in situations where normally they are not expected. To explain their features and behavior, we first investigate conditions for the existence of conserved quantities.

3. Conserved quantities

We should make a distinction between the quantities conserved in both space and time and the quantities conserved only in space. Space here means along the scaled propagation distance \( z \), integrated over the transverse coordinates, and time is the scaled \( t/\tau \). Applying the standard methods of dynamical analysis, we identify the following constants of motion.

The first and simplest one is the total intensity \( I_{\text{tot}} \). By noting that:

\[
\frac{\partial I^F}{\partial z} = 0 , \quad \frac{\partial I^B}{\partial z} = 0 ,
\]

where:

\[
I^F = \int \int dxdy (FF^*) , \quad I^B = \int \int dxdy (BB^*) ,
\]

we see that \( I_{\text{tot}} = I^F + I^B \) is independent of the propagation distance and time, and it does not depend on the input beam profiles.

The second constant is the total momentum of the system. It is independent of \( z \):

\[
\frac{\partial}{\partial z} \int \int dxdy (F^* \frac{\partial F}{\partial x} - B^* \frac{\partial B}{\partial x}) = \Gamma \int \int dxdy \left( F^* F + B^* B \right) = 0 ,
\]

if the space charge field \( E = E(I) = E(I(x,y,z)) \) depends only on the steady-state intensity. In this case, the total momentum is determined by the integral of input beam profiles only, and as they do not change in time, the total momentum also does not change in time.

The derivative of the total angular momentum \( L_{\text{tot}} \) along \( z \) axis is given by:

\[
\frac{\partial L_{\text{tot}}}{\partial z} = \frac{\partial L^F}{\partial z} + \frac{\partial L^B}{\partial z} = \int \int dxdy \left( x(-iF^* \frac{\partial F}{\partial y}) - y(-iF^* \frac{\partial F}{\partial x}) + x(iB^* \frac{\partial B}{\partial y}) - y(iB^* \frac{\partial B}{\partial x}) \right) ,
\]

or, in cylindrical coordinates \( x = \rho \cos \phi \), \( y = \rho \sin \phi \):

\[
\frac{\partial L_{\text{tot}}}{\partial z} = \int _0 ^{2\pi} d\phi \int _0 ^\infty d\rho \rho \frac{\partial}{\partial \phi} \left( F^* F + B^* B \right) .
\]

If there is no azimuthal dependence, \( E \neq E(\phi) \), it follows \( \partial L^F / \partial z = \partial L^B / \partial z = 0 \), and hence the total angular momentum is a conserved quantity. In our model \( E \) depends on \( I \), and if \( I \neq I(\phi) \) then \( \partial L_{\text{tot}} / \partial z = 0 \). However, when the modulational instability (MI) sets in, there appear azimuthal instabilities, and the angular momentum becomes non-conserved. It acquires \( z \)-dependence, as well as \( t \)-dependence, as MI is not uniformly distributed.

If we consider the steady-state situation, \( E = E(I + I) \), we can write the Hamiltonian \( H \) for our system:
\[ H = \iint dxdy \left[ \frac{\partial F}{\partial x} \frac{\partial F^*}{\partial x} + \frac{\partial F}{\partial y} \frac{\partial F^*}{\partial y} + \frac{\partial B}{\partial x} \frac{\partial B^*}{\partial x} + \frac{\partial B}{\partial y} \frac{\partial B^*}{\partial y} \right] + \right. \\
\left. \iint dxdy \left[ \Gamma \ln(1 + FF^* + BB^*) - \Gamma(FF^* + BB^*) \right] \right].
\]

(8)

It is easy to demonstrate that \( \frac{\partial H}{\partial z} = 0 \), which means that in this case the Hamiltonian represents an integral of motion (as expected).

It is interesting to note that all integrals of motion, as written, which are constant in \( z \), are also constant in time. This is normal expectation when the transverse integrals are over the total transverse space. In numerics, however, the total integrated transverse space includes only the total computational space, and there is always some transverse leakage involved. There are situations where this leakage is minimal, as for the stable soliton propagation, but there are situations where the leakage is larger, as in the case when the system radiates. In our case, whenever we have a stable soliton-like propagation of vortices, there is practically no leakage, and whenever such propagation becomes unstable, due to MI or radiation losses, the leakage becomes noticeable, and the conservation in time is lost. This is most visible in the case of angular momentum, where even a tiny amount of radiation carries huge amount of momentum to transverse infinity. As mentioned, the momentum starts to vary in time, and also becomes \( z \)-dependent, as the radiation is not uniform along the \( z \)-axis. On symmetry grounds, when MI sets in the cylindrical symmetry is lost, and the angular momentum starts to change in \( z \). If the new symmetry of beams becomes a well defined discrete symmetry (tripole, quadrupole) one can define new conserved angular quasimomenta.

4. Transverse instabilities and stable structures

A general conclusion of our numerical studies is that the CP vortices in our model can not form stable CP vortex (i.e. ring-like) structures propagating indefinitely. For smaller values of \( l^* \) or propagation distance \( L \) we observe stable CP vortices. Nevertheless, when they break, they form very different stable filamented structures in propagating over finite distances, corresponding to typical photorefractive crystal thicknesses, which are of the order of few \( L_d \). In addition, they can form different stable dynamical structures, such as stable rotating dipoles. It should be noted that in CP geometries, the absolute stability of propagation over indefinite distance is of secondary importance; the influence of both input faces, at any distance, must be felt equally. Hence, stable steady or dynamical structures arising over finite distances are of considerable experimental interest.

Fig. 1. Typical behavior of CP vortices in the parameter plane. In the two cases shown the input vortices have the same topological charge +1, but different input intensities. Insets list the possible outcomes from vortex collisions.
Some typical examples are shown in Fig. 1, which represents the phase diagram in the plane of control parameters. To start with, we consider single head-on input vortices with the same topological charge $+1$. For lower values of $\Gamma$ or $L$ we see stable vortex propagation over the distances of interest (a few $L_D$). One can notice in the figure a narrow threshold region which separates the stable vortices from other structures. The shape of the threshold region follows the general $\Gamma L=\text{const.}$ form we derived earlier for the 1D case, in our papers [17,18]. Above this region we see stable dipoles, tripodes and quadrupoles, in the form of standing waves. This is another general feature in our numerical studies: CP vortices with the same topological charge tend to form standing waves, whereas the vortices with the opposite charges tend to form rotating structures. For higher values of the parameters, we identify the following quasi-stable situations: the transformation of a quasi-stable quadrupole into a stable tripole, several transformations of quadrupoles into quadrupoles, and a stable rotating dipole. Above the quasi-stable region, CP vortices produce unstable structures, i.e. constantly changing structures of unrecognizable shape.

The most characteristic cases from Fig. 1 are presented in Fig. 2, as movies in the transverse plane. The first, second and fourth columns represent a stable dipole, tripole and quadrupole, respectively. The third and fifth columns present quasi-stable structures, i.e. the structures that start evolving as one structure, but then transform into another, more stable structure (quadrupole into tripole and quadrupole into quadrupole). The first and second rows correspond to the exit face for the backward beam in the direct and inverse spaces, respectively. The third row shows time evolution of the backward beam’s total angular momentum, which is normalized to the total beam intensity. As advertised, the momentum is steady as long as the beams propagate steady, but starts to vary, in $t$ as well as in $z$, as soon as the propagation becomes unstable.

Fig. 2. Movies of the stable dipole (first column), the stable tripole (second column), a transformation of an unstable quadrupole into a stable tripole (third column), the stable quadrupole (fourth column) and a transformation of an unstable quadrupole into a stable quadrupole (fifth column). Output face of the backward beam is shown in the direct (a)-(e) (224KB, 320KB, 475KB, 491KB, 545KB), and the inverse space (f)-(j) (341KB, 288KB, 376KB, 366KB, 382KB). The lower row (k)-(o) (615KB, 432KB, 515KB, 575KB, 737KB) presents time evolution of the total angular momentum. Parameters $\Gamma$ and $L$ are given in the figures. The total input intensity of each beam in all cases is 1.

An interesting feature, discerned from Fig. 2, is the beam structure and dynamics in the transverse inverse space. It is seen that in the $k$ space a dipole remains a dipole, a tripole – a tripole (although with prominent hexagonal features), etc. This is not difficult to understand in terms of the modal decomposition of beams: a Gaussian remains a Gaussian in the inverse
space, although with different width and peak intensity. Also, the temporal dynamics and the dynamics in \( z \) remain highly correlated in the direct and the inverse space. This is the consequence of the assumed model: the optical field is slaved to the slow changes in the space-charge field. The dynamics of beams in both spaces is the image of the dynamics of the \( E \) field. However, as it will be seen below, the things considerably change when one considers the propagation of vortex arrays.

Figure 3 depicts spatial isosurfaces of the stable backward beams presented in Fig. 2, taken at \( \tau/\tau_v = 200 \). They do not change in time. One can clearly see, especially in the case of stable dipole, the spiraling of beam arms along the \( z \) axis, which has been described previously in a number of papers treating copropagating vortices and pairs of solitons \([6,7,27]\). The same phenomenon, evidently, appears in the case of CP vortices.

Fig. 4. Movies of stable rotating structures. (a) (474KB), (d) (415KB), (g) (490KB) Rotating dipole formed by the CP vortices of the same charge, (b) (837KB), (e) (429KB), (h) (715KB) rotating quadrupole formed by the CP vortices of the opposite charge, (c) (501KB), (f) (281KB), (i) (380KB) rotating soliton formed by the CP head-on Gaussian beams. The figure setup is as in Fig. 2.

5. Stable rotating structures

When the input vortices are of the opposite charge, as a rule, the resulting structures start to rotate. This situation is presented in Fig. 4, which displays the characteristic examples of
rotating dipoles and quadrupoles, and an uncharacteristic example of a rotating soliton. The last example is uncharacteristic in the sense that in all other cases - the dipoles, tripoles and quadrupoles – the structures are the result of the breakup of vortices, whereas in this case we have no vortices, but two Gaussian beams that carry no charge. Each beam collapses to a displaced soliton-like beam, which then starts to rotate indefinitely. What is very interesting here is that, after the displaced soliton-like beams are formed and start to rotate, their phases acquire topological defect charges $\pm 2\pi$ (so that the total momentum is still conserved). This feature is typical of vortices. The splitup behavior is similar to the typical behavior of CP head-on Gaussian beams, which are known [17-19] to display transverse displacements. However, the displacement transformations there are not followed by uniform rotation.

Fig. 5. Isosurface plots of a rotating dipole from Fig. 4(a), shown at different times.

That the situation is as claimed, can be inferred from Figs. 5 and 6, which show the isosurfaces of the rotating dipole and the soliton. In the case of dipole one can clearly see the breakup phase, which initially proceeded in four filaments, but two of these are soon suppressed, whereas in the case of soliton no breakup is discernable, the initial Gaussian just focuses into one elongated spot. Additional information on the "rotating soliton" is gathered from the inverse space picture (Fig. 4(f)), where it is seen that the structure is not a single spot, but a deformed ring and a central spot.

Fig. 6. Isosurface plots of a rotating soliton from Fig. 4(c), at different times.

That each rule must have an exemption, is exemplified here by the rotating dipole: it is formed by the CP vortices of the same charge. Normally, the rotation of filaments is not expected in that case. Apparently, as the azimuthal instability sets in, some of the angular momentum is lost, and the momentum contributions of the forward and backward beams do not exactly cancel out, causing the resulting filaments to acquire some net momentum.

6. More complex beam structures

An intriguing question to ask is what happens when one launches more complex beam structures from the opposite sides of the crystal. We start addressing it by launching 2-by-2 vortex arrangements against each other, and comparing them to the basic head-on one-on-one arrangement. Then we will proceed to pixel-like many-on-many array arrangements, in which we have freedom to manipulate each of the vortex pixels. The interest in such lattice-like arrangements is many-fold, in that one can address each pixel (its phase and intensity), monitor the interaction of copropagating vortices by adjusting the distance between them, and control the interaction of CP beam arrays by choosing the distribution of charges and the
position of arrays relative to each other. An additional point of fundamental interest is to follow what goes on in the inverse space, as the geometry changes from few CP beams to many CP beams.

In the case of 4-on-4 beams, we choose square arrangements of vortices, with all of them in-phase, or pair-wise diagonally out-of-phase. It is easy to distinguish the two arrangements in Figs. 7 and 8: the in-phase fragments rotate in the same sense, the out-of-phase rotate in the opposite sense. We also choose the forward and backward fields to be of the opposite charges, and position individual vortices head-on. Such geometries allow for stable rotating structures.

Fig. 7. Rotating (4-on-4) vortices, backward field, out-of-phase: (a) Movie of intensity distribution in the real space (2.34 MB), (b) movie of intensity distribution in the inverse space (1.427 KB), (c) movie of phase distribution (1.623 MB), (d) the total angular momentum of the backward beam, (e) movie of time evolution of the angular momentum of the total field $F+B$ (624 KB).

One can follow in Figs. 7 and 8 the behavior of the in-phase and out-of-phase vortices. They form stable structures that rotate indefinitely. Parts (a), (b), (c) in each figure depict the transverse intensity distribution in the real space, in the inverse space, and the distribution of the phase, respectively. Parts (d), (e) depict the changes in the angular momentum of the backward field, and the angular momentum of the total field $F+B$, respectively. As it can be seen, because the angular moments of the forward and backward beams are symmetrical, the sum of the moments is not equal to the momentum of the sum. Also, large excursions in the moments are visible. This is expected in the system where four beams, each carrying a unit of momentum, collide, exchange momentum, and strongly radiate. There can be no question of angular momentum conservation in this strongly interacting nonintegrable system.

Fig. 8. Rotating (4-on-4) vortices, backward field, in-phase. Figure setup as in Fig. 7, (2.418 MB), (1.53 KB), (1.674 MB), (721KB).

Fig. 9. Isosurface plots of the rotating (4-on-4) vortices, from Fig. 8.
A curious feature is noted in the modal distributions in the inverse space: while in Fig. 7(b) one can still distinguish the grouping of spots resembling the distribution in the real space, this is almost gone in Fig. 8(b). There the distribution of spots is more the reflection of the lattice-like regular grouping of spots in the direct space. Although in both cases we deal with 4-on-4 vortices, which disintegrate into 4 fragments each, in the out-of-phase case the fragments conspire so that at any moment only 6 approximately hexagonal spots are highly visible, whereas in the in-phase case all 16 spots are visible at all times. This has consequence on the appearance of the inverse space distributions: in the out-of-phase case one still sees 6 prominent spots (and a number of satellites) reminiscent of the direct space distribution, whereas in the in-phase case one sees a square arrangement of spots, 4 of them more prominent, corresponding to the square-lattice-like arrangement in the direct space.

Figure 9 displays the isosurface plot of the 4-on-4 rotating filaments from Fig. 8, presented at different times.

7. Counterpropagating arrays of vortices

As mentioned above, counterpropagating arrays of vortices possess interesting qualities, from the applicative as well as fundamental points of view, and offer rich opportunities for multifaceted multi-parameter study of various phenomena. Here we address just one aspect – how the change in one parameter, the distance between vortices in arrays, affects the collective behavior of all beams.

It is clear that, at large distances, each pair of CP vortices will behave independently of the others, in the manner described above. As the distance is reduced, the interaction of co-propagating vortices starts to affect the interaction of CP vortices. As a rule, this interaction precipitates the, already present, instabilities of the basic CP two-beam system. In CP arrays, the filamentation of vortices happens sooner, at smaller z distances, and at lower values of the $\Gamma$ parameter. The vortices break into four-petal clusters, as in the basic CP system. In addition, the presence of arrays brings to the fore collective features of the behavior of the system. Its evolution starts to acquire the standard pattern formation characteristics [28], in that one can follow a reduction in the number of interacting transverse $k$ modes, corresponding to the symmetry of the lattice, and an increasingly sharp distribution of these spots in the inverse space. One can also follow the spatial and temporal chaotization of transverse patterns, as the driving parameters change. Some of these aspects are exemplified in Figs. 10 and 11.

Figure 10 shows a stable rotating 9-by-9 square array of vortices, behaving regularly in a periodic fashion. In the inverse space one can see the basic 4 square spots, at 45 degrees, corresponding to the basic interacting modes, and attendant higher order modes, arranged on the square lattice, all blinking in unison with the fundamental periodic motion of the array in...
the real space. In addition, each of the basic 4 spots is surrounded by a number of satellite beams, corresponding to the large-scale structure in the real space, and the satellites perform the same fundamental periodic motion of the whole lattice.

Figure 11 shows the same array at a reduced distance between the array elements. Now the system gradually becomes spatially chaotic, evolving into a granular structure, in which different regions seem to execute different quasi-periodic motion. The chaotization proceeds from the lattice corners inward, owing to strong edge effects. In the inverse space one still sees the same basic arrangement of spots, corresponding to the underlying square arrangement of the vortices, however now with more irregular distribution of the additional higher-order mode and satellite spots, and with the temporal periodicity less apparent.

Fig. 11. Unstable, increasingly chaotic, rotating 9-by-9 array, with a 45 μm, distance between vortices, at $t=130 \tau$. Movies in (a) (2,178 MB) direct space (13,851 MB version), and (b) inverse space (1,353 MB) show the distributions of the backward field. Other parameters are as in Fig. 4(b).

8. Conclusions

In summary, we reported on a detailed numerical study of (2+1)D counterpropagating vortices in photorefractive crystals. We consider CP vortices in both space and time. We show analytically and numerically that stable beam structures conserve angular momentum, as long as their stability is preserved. As soon as they loose stability, owing to radiation or non-elastic collisions, their angular momentum starts to change, in both $z$ and $t$. Novel types of rotating beam structures are discovered that have no counterpart in the copropagating geometry. The propagation of more complex CP beam arrangements, such as regular arrays of vortices, is also considered, and the transition from a few-beam propagation behavior to the transverse pattern formation dynamics is followed.

Acknowledgments

Work at the Institute of Physics is supported by the Ministry of Science and Environment Protection of the Republic of Serbia, under projects OI 1475 and OI 1478. MP acknowledges fellowship from the Belgian Federal Science Policy Office, under the S&T Cooperation Program with Central and Eastern Europe.