

Observation of topological transformations of optical vortices in two-dimensional photonic lattices

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Abstract: We study interaction of a discrete vortex with a supporting photonic lattice and analyze how the combined action of the lattice periodicity and the medium nonlinearity can modify the vortex structure. In particular, we describe theoretically and observe in experiment, for the first time to our knowledge, the nontrivial topological transformations of the discrete vortex including the flipping of vortex charge and inversion of its orbital angular momentum. We also demonstrate the stabilizing effect of the interaction with the so-called “mixed” optically-induced photonic lattices on the vortex propagation and topological structure.

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OCIS codes: (190.4420) Nonlinear optics, transverse effects in; (190.5940) Self-action effects.

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1. Introduction

One of the fundamental properties of light is attributed to its angular momentum [1] which manifests itself in structural transformations of optical fields as well as in effective forces acting on particles [2, 3] and atoms [4]. The optical *orbital angular momentum* is associated with a beam vorticity or twisted flow of light around specific singular points or phase dislocations. In

dielectric media with a rotational symmetry, e.g. homogeneous and isotropic, the orbital angular momentum is a dynamical invariant (an integral of motion) of the system. Conservation of the angular momentum plays an important role for the structural stability of the vortex beams [5], including the diffracting Gauss-Laguerre optical modes of waveguides and the nondiffractive modes such as Bessel beams and their generalizations.

In nonlinear media, optical vortices appear as self-trapped spatially localized optical beams, or vortex solitons [6], and they suffer from azimuthal modulational instabilities [7, 8]. Several different physical mechanisms have been suggested for suppression the azimuthal instability [6]. Guiding the vortices in periodic structures such as photonic crystals or optical lattices offer an exciting opportunity to stabilize optical vortices in nonlinear media in the form of stable discrete vortex solitons [9, 10, 11], as recently demonstrated in experiment [12, 13]. However, stable discrete vortex solitons carry an angular momentum in a structural environment which does not support the conservation of the angular momentum because the medium periodicity breaks the rotational symmetry. As a result, novel types of the vortex dynamics such as the vortex charge flipping [14, 15] and vortex transmutations [16] should be observed.

In this paper, we study topological transformations of the discrete vortices propagating in photonic lattices due to the combined action of the lattice periodicity and the medium nonlinear response. We demonstrate, for the first time to our knowledge, both theoretically and experimentally, that such transformations can lead to the inversion of the vortex topological charge and the angular momentum while preserving its intensity structure. Furthermore, we suggest and demonstrate in experiment a novel approach to control a change of the angular momentum of the vortex beam by controlling elasticity of the lattice, and thus providing a possibility for a novel type of optical switching between the vortex states with opposite circulations.

2. Topological transformation: basic concepts

To illustrate the basic concept of the vortex topological transformations, we consider *three important examples* of the vortex propagation in nonlinear media. In Fig. 1(a) we show the well-known scenario of the symmetry-breaking azimuthal instability of a vortex soliton in bulk homogeneous media [7, 8]. The green iso-intensity surfaces indicate the half-maximum intensity, while the red isosurfaces visualize the dynamics of the phase dislocation (vortex core) in the transverse plane. After a metastable stationary propagation, the vortex ring breaks up into two fundamental solitons, while the core experiences splitting, illustrating the so-called unfolding of the phase dislocation [17]. In this case, the angular momentum is conserved, and it does not change its value even after the vortex breakup, as shown in Fig. 1(d). Instead, two soliton filaments carry the net orbital angular momentum moving away from the ring along the tangential trajectories [7].

Similar break-up dynamics of vortices can also be observed in the region of *linear instability* of the vortex propagation in periodic potentials [11]. The presence of the periodic potential, however, leads to the existence of stable vortex solitons in a square lattice when the *intensity and topological structure* of the vortex remain unchanged. This is demonstrated in Fig. 1(b) for an optically-induced photonic lattice created in an isotropic saturable medium [11]. The red “string” at the beam origin shows a robust dislocation, while the angular momentum exhibits small oscillations [see Fig. 1(d)] due to the soliton breathing. Following Ref. [14], we apply an asymmetric (elliptic) perturbation to the discrete vortex soliton by reducing the relative amplitude of a diagonal pair of the vortex sites by 10%, and in Fig. 1(c) observe periodic “bursts” of the vortex core [see also a movie IsoUnfoldings.avi, 2.2MB, where the white contour lines in the phase portrait correspond to the red surface in (c) indicating the shape and position of the vortex core]. These bursts correspond to the periodic unfoldings of the phase dislocation and vortex charge flipping, i.e. *the vortex topological structure becomes broken*.

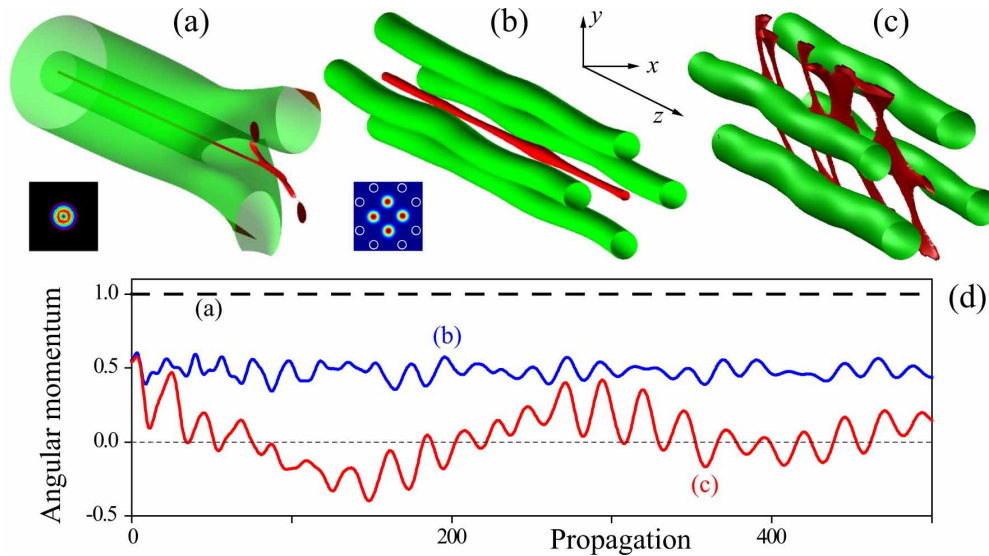


Fig. 1. Comparison between the structural and topological instabilities of optical vortices. (a) Linearly unstable vortex soliton in a saturable bulk medium. (b) Generation of a stable vortex soliton on a square photonic lattice. (c) Topological transformations of the asymmetrically perturbed discrete vortex on the lattice [movie IsoUnfoldings.avi, 2.2MB]. The isosurfaces are plotted at the half-peak intensity (green) and at a small value $\sim 10^{-2}$ (red). The red “string” in (b) shows the position of the vortex core, while bursts in (a) and (c) indicate the vortex unfoldings. (d) Dynamics of the angular momentum (normalized by the power) for all three cases.

We note that inversion of the topological charge of the free-propagating singular beam was predicted [18] and observed [19] for a single-charge “non-canonical” (i.e., elliptically deformed) vortex, as well as for higher-order singular beams focused by an astigmatic lens [20]. In these experiments, the intensity distribution of a vortex undergoes drastic deformation in the focus, where the charge-flipping occurs. In sharp contrast, in periodic media the vortex intensity distribution may practically remain the same. As it is seen in Fig. 1(c, green surfaces), the *intensity structure stays intact* during transformation, the feature which was commonly believed to guarantee the stability of phase topology as well [12, 13]. We conclude that in nonlinear periodic media the vortex beams demonstrate remarkable features of *topological transformations*: while the energy of the beam remains localized by the lattice, its phase structure changes substantially. This topological reaction results in a reverse of the vortex transverse energy flow, which is associated with flipping of the sign of the vortex angular momentum, see Fig. 1(d). Most probably, the topological transformations can be accurately described and explained by the presence and development of oscillatory instability (internal) modes of the discrete vortex solitons, similar to the breather solutions in discrete systems [21].

In analogy with the periodic lattices, the photonic structures with discrete rotational symmetries of a finite order received a special attention [22, 23]. Examples include the Bessel-type lattices [24, 25] and photonic crystal fibers [26, 27]. It was shown that while such structures do not allow for conservation of the angular momentum, they can be characterized by the so-called “angular Bloch momentum”, conserved during the evolution of spatially localized modes [22]. At the same time, these structures introduce essential limitations to the symmetry of the supported localized modes, e.g., the topological index of a vortex m can not exceed the cut-off

value $|m| \leq n/2$ [23], determined by the symmetry order n of the photonic structure. The selection rules then apply not only to the existence, but also to the stability properties of the discrete vortices [24]. The interplay between the symmetries of the angularly-modulated modes and corresponding waveguiding nonlinear structures leads to possibilities of the so-called vortex transmutations, where the initial individual vortex is mapped into another with a different topological charge [16].

However, the point-like mapping of a single vortex into another, such as the vortex transmutation and charge-flipping, are not the only topological transformations which should be expected to occur in periodic lattices. Indeed, the generic property of optical vortices is their *nucleation*, in which vortices with opposite topological charges can be born or annihilate in pairs [17]. In the free-space propagation, a combination of a Gaussian beam and a multiple-charged optical vortex results in the spatial splitting of the single dislocation to a number of lowest order vortices [28]; similar generation of the rows of single-charge vortices is reported for elliptically-deformed high-charge vortex beam [20, 29]. Furthermore, the instabilities of high-charge dark vortex solitons in defocusing nonlinear media [6] also suggest that, a “generic” [5] structure which can arise during the topological transformation should involve configurations of several single-charge vortices, rather than a point-like phase dislocation of a high order.

Indeed, as we demonstrate below for the square photonic lattice induced optically in an anisotropic photorefractive medium, the evolution of a topologically unstable single-charge vortex beam results in the generation of an additional pair of vortices. This is in contrast to the above-described vortex charge flipping and vortex transmutations of a single phase dislocation in perfectly symmetric periodic potentials. Such a drastic difference can be explained by anisotropy of the nonlinear medium such as the anisotropy of an optical lattice induced in a photorefractive crystal. We can conclude that the multi-vortex configuration is a generic pattern towards which the topologically unstable vortices evolve, since the perturbations and asymmetries of the lattice are unavoidable in real experiments.

3. Experimental results

3.1. Experimental setup

To test experimentally the development of topological transformations of vortices in periodic structures, we used the experimental setup depicted in Fig. 2. We induced a two-dimensional (2D) optical lattice in a biased Strontium Barium Niobate (SBN) photorefractive crystal [30, 31] by spatially modulating a partially coherent optical beam (488 nm) created by a rotating diffuser (top channel in Fig. 2). Due to the strong electro-optic anisotropy in the biased SBN crystal, the ordinary polarized lattice beams will propagate nearly stationary along the 10 mm long crystal, forming a fixed periodic potential (*fixed lattice*) for any extraordinary-polarized probe beam (see inset in Fig. 2). In addition, 2D periodic potentials can be induced by the self-trapped extraordinary polarized periodic wave [31, 32, 33]. In the latter case, the nonlinear lattice can interact with the probe beams via cross-phase modulation [34, 35, 36]. As a result, the lattice wave deforms locally, creating a bound state with the probe beam, and we refer to these types of potentials as *flexible lattices*.

The 2D periodic pattern is oriented at 45° with respect to the c-axis of the crystal in order to achieve an identical refractive-index modulation along the two principle axes of the lattice. This choice of the lattice orientation allows to minimize the influence of anisotropy [32, 33]. However, the induced periodic refractive index modulation is essentially different from the isotropic approximation. Strictly speaking, the refractive index lattice has only one axis of reflection symmetry (perpendicular to the c-axis of the crystal). Furthermore, the nonlocality and saturation of photorefractive response significantly influence the resulting lattice profile. Thus, it is important to take into account these complications when model our system theoretically.

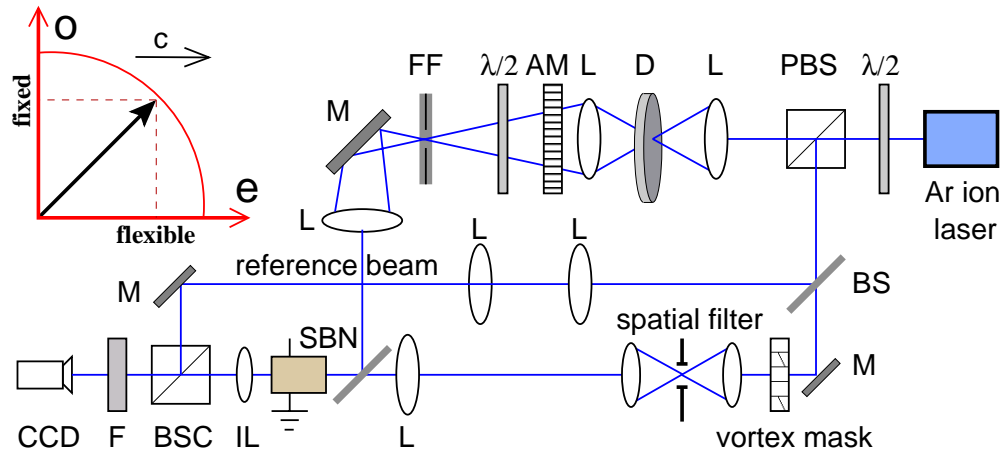


Fig. 2. Experimental setup: $\lambda/2$ - half-wave plate, PBS - polarising beam splitter, L - lenses, D - rotating diffuser, AM - amplitude mask of square array, FF - Fourier filtering of the four first diffraction orders, M - mirrors, BS - beam splitter, BSC - beam splitter cube, F - neutral density filter, SBN - Strontium Barium Niobate photorefractive crystal, and CCD - camera. Top left inset: schematic of the linear polarisation state of the lattice wave, forming its flexible and fixed components.

As a probe beam, we use an extraordinary polarized single-charge vortex created by a computer-generated hologram (vortex mask - bottom channel in Fig. 2). The generated vortex is passed through a spatial filter in order to clean up its mode structure and substantially focused onto the front face of the crystal by lens ($f=175$ mm). Due to its extraordinary polarisation, the vortex beam will experience strong self-focusing due to the photorefractive nonlinearity while propagating in the periodic potential induced by the lattice. In order to monitor the phase structure of the vortex transmitted through the lattice we interfered the vortex output with an inclined broad reference beam (middle channel in Fig. 2) and obtained the corresponding interferograms. The obtained interferograms allow to detect the position of the vortex phase dislocation by the presence of a fork in the interference lines [see, e.g., Fig. 3(a, bottom)]. In our experimental arrangement, an up-fork corresponds to a topological charge equal to $+1$.

We explored two different excitation conditions: (i) when the vortex beam is launched into off-site and (ii) on-site locations in the lattice. For both cases, we study the vortex dynamics in the fixed and flexible lattices by tuning the lattice polarization from ordinary to extraordinary (inset of Fig. 2), including several intermediate cases, referred below as *mixed lattices*. We summarize all experimental data by several representative examples: an off-site vortex on a fixed lattice (Fig. 3); on-site vortex interacting with a mixed lattice (Fig. 4); and off-site vortex on a flexible lattice.

3.2. Vortex charge flipping in fixed lattices

We begin with the case of an off-site vortex propagating on a fixed lattice induced when the crystal is biased with a DC external electric field of 4 kV/cm . The profile of the input vortex is shown in Fig. 3(a, top) as superimposed on a lattice with a period of $\sim 36\ \mu\text{m}$. The input vortex phase is shown in the bottom image, where the charge $+1$ of the vortex is identified by the up-fork of the interference lines. At low powers the vortex beam is trapped by the lattice and its intensity is located at the four spots placed on the lattice sites [see Fig. 3(b, top)] connected by a spiral phase front similar to that of the original vortex [see Fig. 3(b, bottom)]. As the

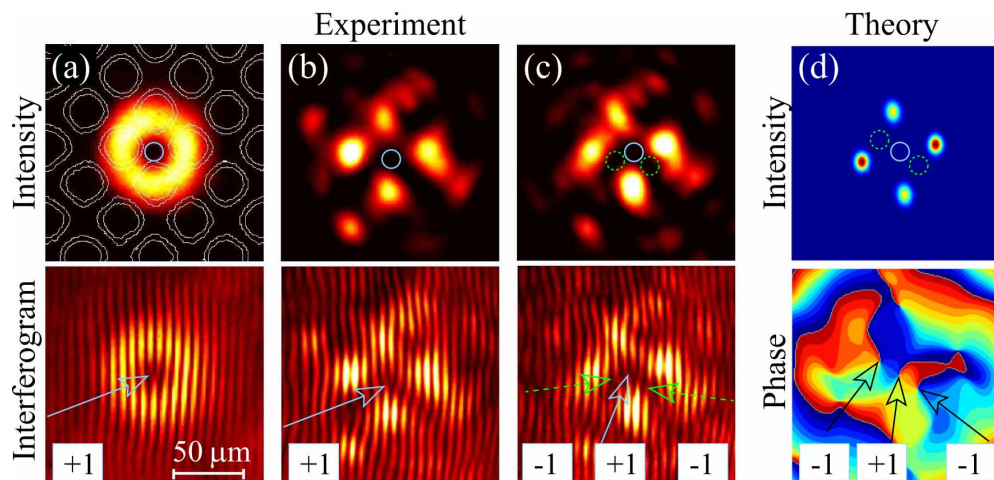


Fig. 3. Topological transformation of an off-site vortex in a fixed lattice (induced by an ordinary polarized lattice wave). Upper row – intensity distribution; bottom row – phase interferogram. (a) Input vortex in the lattice; (b) linear diffraction; (c) nonlinear output with a transformed phase structure. (d) corresponding numerical simulations confirming the nonlinear phase transformation [movie FixedOFF.avi, 6.2MB]. Arrows and circles indicate the position of the vortex dislocations. The total charge of the beam in (c) is -1 , i.e., it is inverted with respect to the initial charge $+1$.

vortex intensity is increased to $\sim 10\%$ of the lattice intensity, the anisotropic photorefractive nonlinearity leads to the transformation of the vortex and creation of two additional vortices with the charges opposite to the original charge and positioned inside the beam [see Fig. 3(c, bottom)]. Although we also notice that additional dislocations appear on the tails of a vortex beam outside its main four-lobe ring, we stress the fact that the direction of energy flow along this ring is determined by the algebraic sum of charges of the inner dislocations. Using this definition, we find that total topological charge of the beam is equal to -1 , which is opposite to the original vortex charge. We note that during this charge inversion the intensity distribution of the vortex remains largely intact [see Fig. 3(b,c top)].

Numerical simulations carried out in the framework of the photorefractive model [37] confirm our experimental observations [see Fig. 3(d)], in particular, the appearance of two additional vortices with the charges opposite to the central one. This is drastically different to the predictions made for model with isotropic nonlinearity [14, 15], namely the charge-flipping through unfolding, such as that observed in Fig. 1(c). Comparing our numerical results for both models, we conclude that anisotropy of the induced potential can be a key factor which leads to vortex nucleation even for the lowest order vortex beam. This dynamics is visualized in the movie FixedOFF.avi (6.2MB), where we also present the dynamics of the angular momentum of the vortex beam. We notice that the total charge of the beam in Figs. 3(c,d) is inverted with respect to its initial value; we observe the corresponding change of the sign of the angular momentum (direction of the energy flow) in numerical simulations.

While the experimental results can only give us an indication for the presence of the nonzero angular momentum of the beam by monitoring its total charge, the numerical simulation allows for examining the exact dynamics of the beam angular momentum. Note the white lines in the right panel of the movie (phase distribution), these are the contour plot on the low intensity level (in addition to the full contour plot of intensity on the left panel), and they help an eye to identify the dislocations positions inside the four-lobe ring.

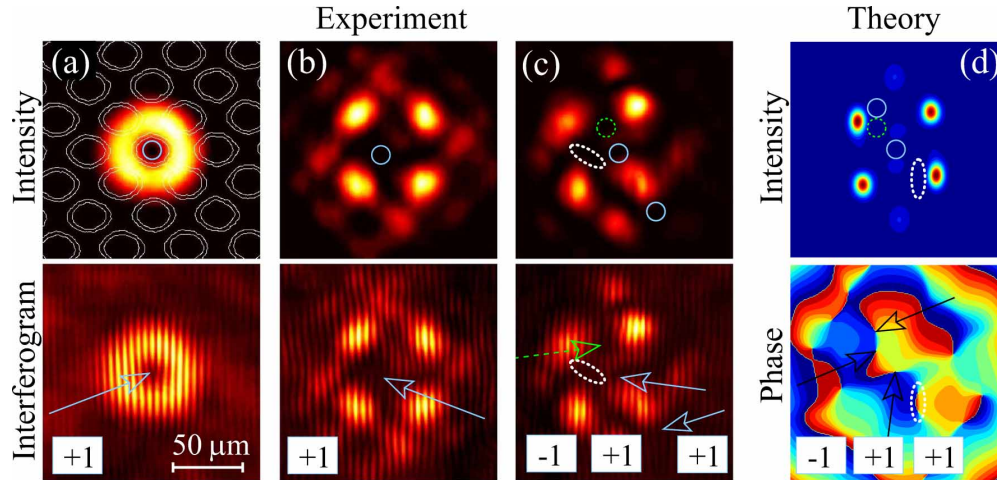


Fig. 4. Topological transformations of an on-site vortex in a mixed lattice with 3% nonlinear component. Upper row – intensity distribution; bottom row – phase interferograms. (a) Input vortex; (b) linear diffraction; (c) nonlinear output with a transformed phase structure; (d) corresponding numerical simulations [movie Mixed3ON.avi (2MB), see the description in the text]. Arrows and circles indicate the position of the vortex dislocations. Dotted oval indicates two closely positioned vortices with the opposite charges. The total beam charge in (c) is $+1$, i.e., it is preserved with respect to the initial charge $+1$.

The stability of discrete vortex solitons are significantly different for the vortices centered at the lattice site (on-site) or between neighboring sites (off-site) [11]. Nevertheless, we observe similar transformations of phase structure in both cases, see movie FixedON.avi (6.5MB) for the vortex beam initially positioned on-site. In this case, the charge transformation occurs at even longer propagation distances, since the four vortex spots are placed further apart and the energy flow between them is greatly reduced. Similar to the previous case of the off-site vortex beam, the angular momentum decays with the beam propagation. This scenario confirms well the previous theoretical predictions made for an isotropic saturable model [14], namely the initial stage of the vortex charge-flipping dynamics. We conclude that, despite the differences between on- and off-site vortices, their topological transformation is a generic effect.

3.3. Control of the vortex angular momentum

An important question related to the observed topological transformations and angular momentum inversion of vortices in periodic potentials is the possibility of controlling such process. A solution to this problem can open up new opportunities for controlled switching between soliton states with different values of the angular momentum. Here we demonstrate that the topological transformations of vortices, as well as their angular momentum dynamics, can be altered by controlling the so-called elasticity of the lattice. As we discussed above, by tilting the lattice polarization we generate a lattice composed of two orthogonally-polarized components (mixed lattice). By varying the angle of the linear polarization of the incident lattice field with respect to the c -axis of the crystal (inset in Fig. 2) we can change the relative amplitudes of the two components of the beam. Thus, we can control the degree of flexibility of the photonic lattice, i.e., the amplitude of the extraordinary polarized wave (a flexible component) with respect to the ordinary polarized wave (a fixed component). The principal difference with the previous case of a fixed lattice is that the flexible component propagates in nonlinear regime and inter-

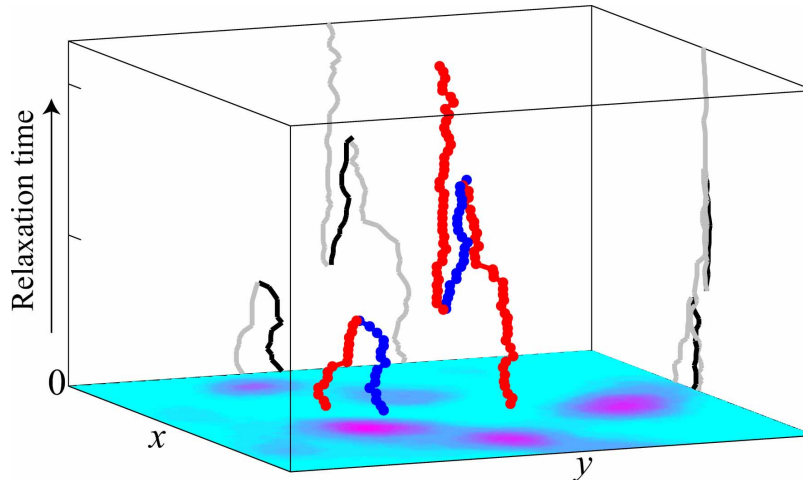


Fig. 5. Topological transformation of the off-site vortex on a square flexible lattice. Trajectories of vortices are shown vs. lattice depth (relaxation time t after blocking the lattice beam at $t = 0$). The red lines (gray projections) correspond to vortex dislocation of charge $+1$, while the blue lines (black projections) correspond to charge -1 .

acts via cross-phase modulation with the signal beam [34], vortex in our case. The incoherent coupling allows for an exchange of angular momenta between interacting components [38], i.e. between vortex beam and flexible part of the lattice. This is the basic physical mechanism we use to study a possibility for the controlled inversion of the angular momentum for both on-site and off-site vortex beams.

A representative example of this process is shown in Fig. 4, where an on-site vortex interacts with a mixed lattice with only 3% of nonlinear (extraordinary polarized) component, i.e., the polarization direction is tilted by $\sim 10^\circ$ with respect to the crystal c -axis. The crystal is biased with a DC electric field of 2.8 kV/cm. As follows from Fig. 4(c), the resulting structure contains three (or more) single-charge vortices similar to the case discussed above. However, the total topological charge at the output in Fig. 4(c) is $+1$ and, thus, in contrast to the case of the vortex propagating in a fixed lattice, the topological transformation is not accompanied by the vortex charge flipping. The performed numerical simulations confirm qualitatively the observed dynamics of the vortex, as shown in Fig. 4(d). An important finding [see Fig. 4(d), and the movie *Mixed3ON.avi* (2MB)] is that in this case the angular momentum of the vortex beam decays at a different rate than that in the previous case of a fixed lattice. The frames of the movie now contain the intensities of the flexible part of the lattice (left) and vortex (middle) waves, the phase portrait of a vortex (right), and the dynamics of angular momenta of two components (bottom), as well as their total angular momentum (black dashed line). The straightforward conclusion from this example is that even a small nonlinear component of the lattice can result in a dramatic change in the dynamics of the phase front of the vortex beam, thus providing an effective tool for a control of its angular momentum.

The suppression of the angular momentum decay becomes stronger for the lattices with larger flexible component, and the example for the off-site vortex beam is demonstrated in the movie *Mixed50OFF.avi* (4.9MB), where the ratio of the intensities of fixed and flexible parts of the lattice is unity. Indeed, our experimental studies showed that if we gradually change the angle of the input polarization of a mixed lattice, we also gradually modify the dynamics of the transformation.

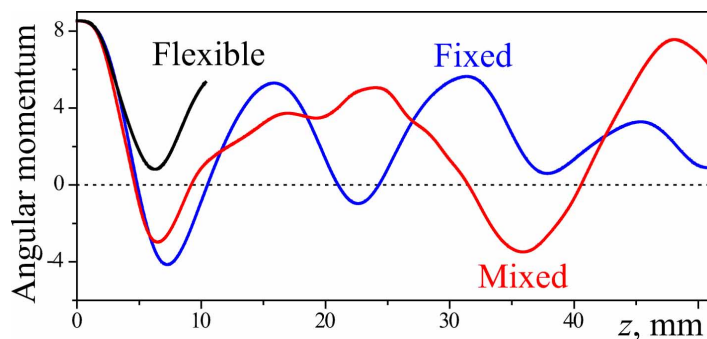


Fig. 6. Dynamics of the angular momentum for an off-site vortex interacting with a flexible lattice (black), fixed lattice (blue), and mixed (50/50%) photonic lattice (red). The black line is terminated when the flexible lattice loses its symmetry during interaction.

To get a deeper insight into the dynamics of the topological vortex transformations in flexible lattices, we study experimentally the limiting case of “fully elastic” (e-polarized) lattice. In this case the angular momentum can be transferred between the probe vortex beam and the lattice more efficiently, however, the deformation of the lattice is also much more pronounced. We monitor the phase structure of an off-site vortex as it changes with the decrease of the lattice depth. Experimentally, this is realized by simply blocking the lattice and monitoring the output transverse phase structure in time. Due to a slow nonlinear response of the photorefractive crystal, the process of an adiabatic decrease of the lattice depth takes several seconds, and thus facilitates the experimental observations. In this experiment the crystal is biased with an electric field of 2.4 kV/cm and the maximum intensity of the vortex is 20% of the lattice intensity.

From the obtained output phase interferogram, we measure the vortex trajectories in the transverse output plane vs. the lattice depth (relaxation time) [see Fig. 5]. Such measurements are somewhat analogous to the monitoring of the backward propagation dynamics inside the crystal, since the nonlinear coefficient (depth of the lattice) can be used to scale the propagation coordinate [32]. From Fig. 5 one can see that the dynamics includes two successive births of vortex pairs and one vortex annihilation. As a result, the output structure carries a positive unit total topological charge, similar to the input beam. Similar results have been obtained in numerical simulations [movie FlexibleOFF.avi (4.9MB)], where the angular momentum returns to its initial positive value at the output. The interaction of the on-site vortex beam with a flexible lattice [shown in the movie FlexibleON.avi (10MB)], is much slower because the four vortex sites are separated far apart. Nevertheless, the value of the beam angular momentum remains positive at the output. We conclude that the flexibility of the lattice can influence significantly the vortex dynamics and even suppress the vortex charge flipping, and thus it provides a mechanism of an active control over the evolution of vortex beams in periodic photonic lattices.

4. Discussions

To describe quantitatively the process of the angular momentum control in periodic potentials, we compare the dynamics of the angular momentum for the three different cases of the fixed, flexible, and mixed photonic lattice. Figure 6 shows the evolution of the vortex angular momentum vs. the propagation distance inside the crystal. As is seen in Fig. 6, the angular momentum changes its sign in a fixed lattice. For flexible lattices, the vortex angular momentum remains always positive, as the lattice deforms due to the interaction with the vortex [35]. In this case, the vortex propagation distance is shorter due to an instability of the periodic lattice at larger propagation distances. With a mixed lattice, the angular momentum can change between two

limiting cases. In particular, the switching points between positive and negative values of angular momentum can be easily moved even with a very small component of the flexible lattice. This is exactly the case in our experiments since the angular momentum flipping occurs at approximately 10mm of the total propagation distance inside the crystal. In experiment, a small portion of the flexible lattice can change the total charge from negative to positive. Near the inversion point, the beam angular momentum is strongly reduced and, therefore, it should be expected that the vortices will be situated further away from the beam center, similar to our experiments. If no noise or anisotropy is present in the system, the point of the spin-flip would correspond to the vortex unfolding into a line dislocation [14].

A simple physics of these processes [see Fig. 6] can be qualitatively understood by drawing a mechanical analogue of the problem. The vortex is trying to twist its intensity distribution inside the periodic potential due to its circular energy flow. In the potential induced by the lattice, this process will result in multiple reflections of the energy flow from the potential, causing the vortex to wobble from the left to the right and back and thus changing the sign of its angular momentum. If the lattice, however, possesses elasticity, it will deform following the twist induced by the vortex, and thus it may balance the vortex rotational force. In this process some internal vibrations can be excited, however, the angular momentum of the vortex will remain positive.

5. Concluding remarks

We have demonstrated, for the first time to our knowledge, topological transformations of vortex beams in nonlinear periodic photonic lattices. Alongside with nonlinear self-action effects, we have identified three major physical processes which govern the vortex topological transformations. *The first process* is a reshaping of the vortex intensity into four sites, experiencing twist, which is more pronounced for flexible lattices [35]. *The second process* is a topological transformation of the vortex phase front, such as the charge flipping in isotropic lattices or splitting of an initial phase dislocation into several vortices demonstrated above for anisotropic photorefractive media. In the latter case, the net phase twist around the vortex ring is determined by the total topological charge. *The third process* is the evolution of the beam angular momentum, in particular, a strong exchange of partial momenta between the vortex beam and a flexible photonic lattice. These three processes are in mutual relation, e.g. a change of the total vortex charge leads to a reverse energy flow along the vortex ring and thus to a change of the vortex angular momentum. From the other hand, the exchange of the angular momentum between the vortex and a flexible lattice, as well as the twist deformations, both influence the vortex topological transformation.

In addition, we have suggested a novel way to control the energy flow in the vortex beam by controlling its interaction with a flexible periodic photonic lattice, and thus providing an effective tool for the angular momentum control. Such a control can be established by a relatively simple technique by changing the polarization direction of the lattice wave relative to the symmetry axis of a photorefractive crystal. The concept of mixed photonic lattices can be thus applied to a more general class of physical problems for controlling the light propagation in nonlinear photonic structures.

Acknowledgment

This work was partially supported by the Australian Research Council and the Australian National University. The work of Zhigang Chen is supported by NSF, AFOSR, PRF, and NSFC. Dragomir Neshev thanks SFSU for a hospitality during his research visit and acknowledges support from the Australian Academy of Science. Anton Desyatnikov thanks Albert Ferrando for useful discussions.