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Generation of multivortex ring beams by inhomogeneous effective diffusion

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ABSTRACT

By means of numerical simulations, we demonstrate generation of multivortex ring beams (MVRBs), i.e., circular chains built of small vortices, by launching necklace-shaped inputs, carrying angular momentum, into a dissipative optical medium modeled by the cubic-quintic complex Ginzburg–Landau equation with effective diffusion, which is periodically modulated in the longitudinal direction. The MVRB chains keep the original angular momentum. The number of external vortices is equal to the number of “beads” in the input necklace pattern. The individual small vortices are produced by the centrifugal force, which is originally induced by the angular momentum applied to the input necklace. Upon the propagation, the inner part of the MVRBs keeps initial counterclockwise direction of the rotation, while the outer part reverses to the clockwise direction (the present dissipative system does not conserve the angular momentum). Individual small vortices in the chain carry topological charge (“spin”) $+1$, whose sign agrees with the clockwise rotation. MVRB states do not exist in the usual model with constant diffusion. The results offer a method to produce new kinds of vortex beams, which may find applications in optics.

1. Introduction

Dynamics of spatial optical solitons in conservative and dissipative media is a vast research area [1–9], with a potential for applications to all-optical switching, pattern recognition, and parallel data processing [3]. Universal models for the light propagation in dissipative settings are provided by the complex Ginzburg–Landau (CGL) equations, with realizations in many areas, such as superconductivity and superfluidity, fluid dynamics, reaction-diffusion phenomena, nonlinear optics, Bose–Einstein condensates, quantum-field theories, and biology [10,11]. In particular, the CGL equations provide realistic dynamical models of laser cavities, which admit the formation of stable fundamental and vortex solitons, as well as solitons clusters [12–24].

Optical vortex solitons represent an important class of topologically organized stable propagation of beams in defocusing nonlinear media [25,26]. These beams carry a spiral structure with zero amplitude at the center [27]. In general, only vortex solitons with the unitary topological charge are stable, their propagation being limited by a finite size of the background beam, which severely limits applications of vortex solitons [28–33]. Basic applications of vortex solitons include the transfer of the optical angular momentum from light to matter [34], guiding light by light [35], and manipulation of nanoparticles in colloidal suspensions [36].

Inhomogeneity of the intensity and phase of the background field carrying vortex solitons may be used for steering their dynamics [37–41]. Ring-shaped vortex solitons have also been found in media with self-focusing or more complex self-defocusing nonlinearities [42,43], which can also be used to guide other waves [44]. Compression and stretching of ring-vortex solitons, which are novel self-similar solutions in $(2+1)$-dimensional diffraction-decreasing waveguides, were investigated too, analytically and numerically [45]. The modulation for the width, diffraction, and nonlinearity strongly affect the form and behavior of the self-similar vortices, and facilitate efficient compression of optical waves [45]. The existence and stability of vortex solitons with ring-shaped partially parity-time-symmetric configurations has been revealed too [46]. Similar to the studies in optics, in hydrodynamics the evolution of viscous elliptic vortex rings in an initially quiescent fluid or in the presence of linear shear flow was numerically simulated using the lattice Boltzmann method [47]. Further, the creation of robust vortex clusters embedded in two-dimensional beams and ring-shaped optical vortices in media described by the generic

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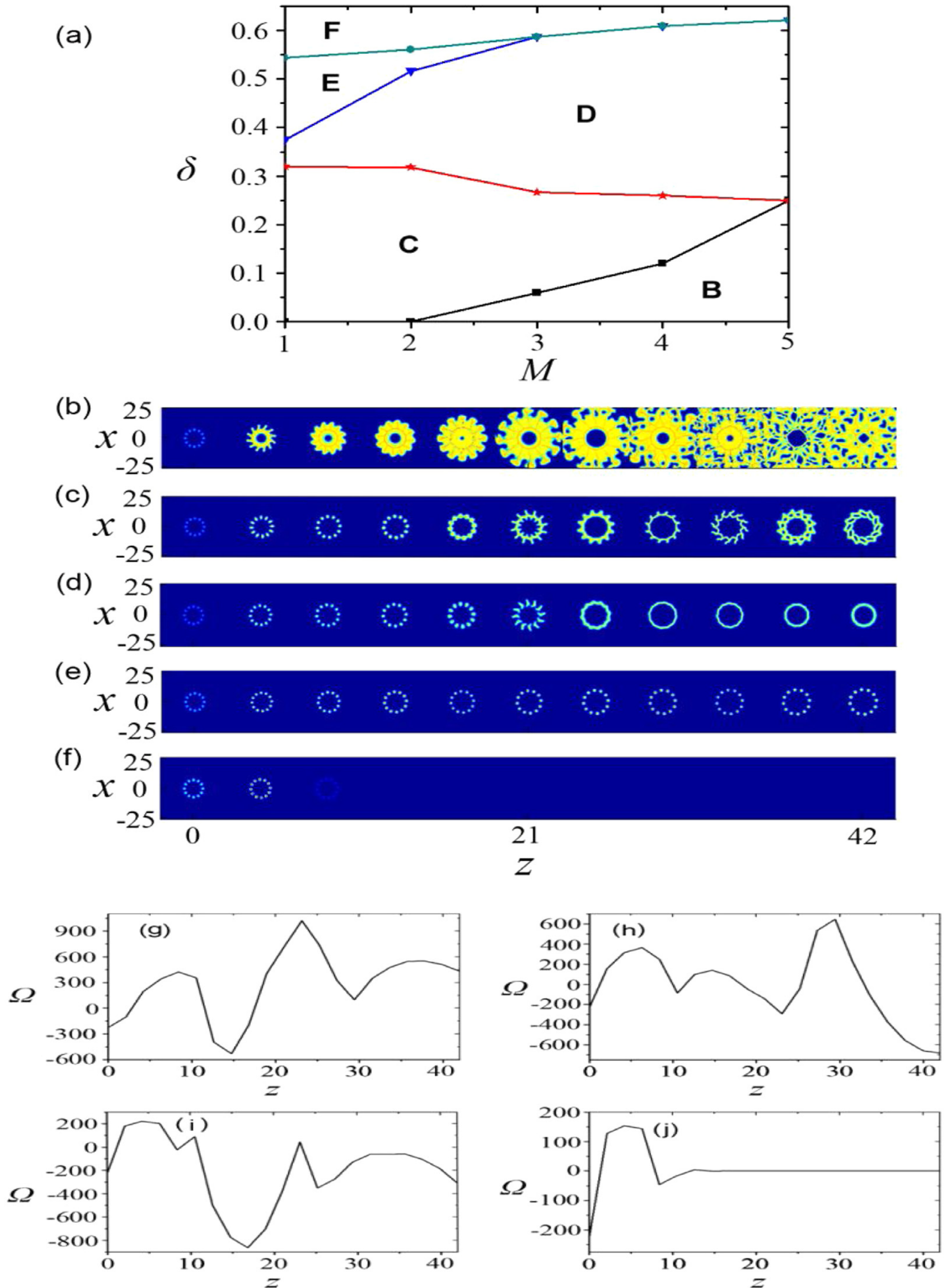

Fig. 1. (a) Domains of different propagation scenarios of the input necklace pattern (4) in the plane of vorticity and linear-loss parameter, (δ, M) with the diffusion-modulation parameters in Eq. (3) $T = 5$ and $A = 0.4$. Region B: spatial blowup of the input in the underdamped setting; C: formation of stable MVRBs, D: generation of the axially uniform vortex soliton; E: stable propagation of the original necklace pattern; F: decay of the input in the overdamped setting. (b) An example of the blowup for $M = 4$ and $\delta = 0.1$, corresponding to region B in panel (a). (c) The generation of MVRBs for $M = 1$ and $\delta = 0.3$ (corresponding to region C). (d) The formation of the smooth vortex soliton for $M = 1$ and $\delta = 0.35$ (corresponding to region D). (e) Stable propagation of the necklace pattern for $M = 1$ and $\delta = 0.5$ in region D. (f) The decay of the input for $M = 1$ and $\delta = 0.6$, in region F. In all panels, $N = 6$ is fixed. (g)–(j) The evolution of the total angular momentum, defined as per Eq. (5), in the cases corresponding to the dynamical regimes displayed in panels (c)–(f), respectively.

cubic-quintic (CQ) CGL equation with an inhomogeneous effective diffusion term was studied recently [48,49].

In this work, we report the generation of gear-shaped multivortex ring beams (MVRBs) by launching a two-dimensional necklace-ring beam, carrying angular momentum, into the CQ CGL medium with inhomogeneous effective diffusion, subject to periodic modulation along the propagation distance. The results are produced by means of systematic numerical simulations. In particular, the number of multiple vortices arranged along the MVRB is equal to the number of “beads” in the input necklace. We identify parameter regions in which robust MVRBs are generated by the model under consideration. It is relevant to stress the difference of these results from those reported for a similar model in [49], where the input was taken as an azimuthally uniform ring with angular momentum imprinted onto it, rather than a necklace pattern: it generated stable patterns in the form of vortex rings, deformed square- and