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Interaction between one-dimensional dark spatial solitons and semi-infinite dark stripes

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ABSTRACT

In this work we numerically study the evolution and interaction of one-dimensional (1-D) dark spatial solitons and semi-infinite dark stripes (SIDSs) in a local self-defocusing Kerr nonlinear medium. The experimental results in the linear regime of propagation confirm that the SIDS bending and fusion with the infinite 1-D dark beam modeled for negative nonlinearity is due to the opposite phase semi-helicities of SID beam ends. Results for several interaction scenaria show that bending ends of the semi-infinite dark stripes splice to the 1-D dark beam to form structures resembling waveguide couplers/branchers. Well pronounced modulational stability of 1-D dark spatial solitons under strong symmetric background beam modulation from decaying SIDSs is predicted.

1. Introduction

Optical vortices (OVs) [1] and one-dimensional dark beams [2] with their characteristic helical and step-like phase profiles [3] are classical entities in the field of singular optics [4]. Due to the presence of a two-dimensional (2-D) point phase dislocation on the axis of the OVs and the presence of a one-dimensional (1-D) phase dislocation along a line for the 1-D dark beam, the phase of the optical field becomes indeterminate and the field amplitude vanishes at the dislocation point(s) [5]. It is known that the relative phases of interacting singular beams determine their coherent interaction in both the linear and the locally nonlinear propagation regime [6–8]. This also holds when singular beams are arranged to form optical lattices [9,10].

Propagation of optical beams in nonlinear media (NLM) has been a subject of continuing interest for more than four decades due to the possibility for creation of reconfigurable waveguides through the intensity-dependent refractive index change [11,12]. Such optically induced waveguides can guide weak signal beams and pulses [13,14], which motivate the investigation of novel techniques for the manipulation of the transverse beam dynamics and open possibilities for realization of waveguides with complex transient geometries. Besides their intriguing physical picture, particular interest in dark spatial solitons (DSSs) is motivated by their ability to induce gradient optical waveguides in bulk self-defocusing NLM [6,14–17]. The only known truly 2-D DSSs are the OV solitons [1] whereas in one transverse spatial dimension the DSSs manifest themselves as self-supporting dark stripes [2].

On the other hand, in the field of singular optics dark (or grey) waves are also known that slowly change their parameters even when they are generated from perfectly odd initial conditions. A classical example is the ring dark solitary wave [18–21]. In their pioneering analysis [22], Nye and Berry conjectured that phase dislocations with a combination of a step- and screw-like phase profile (fractional vortex dipoles, FVDs) cannot exist. Nonetheless, indications for their existence were found [23,24] for two interacting optical vortices of opposite topological charges. Moderate saturation of the medium's third-order nonlinearity enabled the suppression of the snake instability of crossed 1D dark solitons and the identification of 1-D fractional vortex dipoles (FVDs) of finite length [25,26]. Later on, such FVDs with step-screw phase dislocations were experimentally generated under controllable initial conditions by computer-generated holograms [27]. Although two different schemes for directional coupling of signal beams

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by steering FVD beams were proposed in Kerr media with negative nonlinearities [28], the first successful experiment was conducted years later in a biased photorefractive medium with a positive nonlinearity [29]. The evolution of ordered structures of semi-infinite FVDs was studied for the first time [30] in a self-defocusing Kerr nonlinear medium. The results showed that depending on their phase profiles, four parallel semi-infinite FVDs aligned to initially form two dark stripes can evolve into two different cross-connects able to partially redirect collinearly and perpendicularly propagating probe optical beams at different branching efficiencies.

Let us here clarify the terminology adopted in this paper: the semi-infinite dark stripes (SIDSs) are in essence fractional vortex dipoles (FVDs) with one screw-like dislocation nested on the background while the second one is located far outside the background.

In this work we numerically analyze the evolution and interaction of 1-D dark spatial solitons (DSSs) and semi-infinite dark stripes (SIDSs) in a local self-defocusing Kerr nonlinear medium (NLM). The presented experimental results in the linear regime of propagation confirm that the SIDS-beam bending and fusion with the 1-D DSS predicted numerically for the nonlinear regime is due to the (suitably chosen) opposite phase semi-helicities of SIDS beam ends. Results for several interaction scenaria are shown – single DSS interacting with one, two, and four parallel SIDSs. Within a certain propagation distance along the NLM, the inherently restless ends of the semi-infinite dark stripes splice to the 1-D DSS to form structures resembling waveguide couplers/branchers. The ability of such 2-to-1 and 3-to-1 couplers to guide and merge probe waves is numerically investigated. In some cases the interaction of 1-D DSS and SIDSs steering away from the DSS is investigated for comparison too. A well pronounced modulational stability of the 1-D DSSs under strong symmetric background beam perturbations from decaying SIDSs is observed.

2. Numerical model and calibration

The pure 1-D phase dislocation of the dark beam is given by (see Fig. 1a)

$$\Phi^{1D}(y) = \begin{cases} +\Delta\Phi/2 & \text{for } y \le 0 \\ -\Delta\Phi/2 & \text{for } y > 0. \end{cases} \tag{1}$$

The mixed (edge-screw, ES) phase dislocation of the FVD consists of a 1-D phase step of length $2b$, which ends with pairs of phase semi-spirals with opposite helicities. The phase profile of this mixed-type phase dislocation can be written in the form

$$\Phi^{FVD}(x,y) = \frac{\Delta\Phi}{2\pi}\left[\arctan\left(\frac{y}{x+b}\right) - \arctan\left(\frac{y}{x-b}\right)\right]. \tag{2}$$

In both equations $\Delta\Phi$ stands for the magnitude of the dislocation phase step and x and y denote the transverse Cartesian coordinates parallel and perpendicular to the dislocation respectively. In order to keep the dark beam contrast and the refractive index modulation as high as possible, all data in this work refer to $\Delta\Phi = \pi$. The semi-infinite dark stripes (SIDSs) analyzed in this work (FVDs much longer than the background beam diameter) are modeled by shifting the respective amplitude and phase distributions to place one of the FVD beam ends initially at the center of the background beam while the second one is far outside the background (and the computational window). A surface plot of the phase of the semi-infinite dark stripe beam is shown in Fig. 1b. The slowly varying electric field amplitude of each dark beam is assumed to be tanh-shaped of width a and, when centered on the background beam, of the form

$$E^J(x,y,z=0) = \sqrt{I_0}B(x,y)\tanh[r_{\alpha,\beta}(x,y)/a]\exp[i\Phi^J(x,y)], \tag{3}$$

where $J = 1D$ or $J = SIDS$. Here the effective coordinate $r_{\alpha,\beta}(x,y)$ is

$$r_{\alpha,\beta}(x,y) = [\alpha(x+\beta b)^2 + y^2]^{1/2}, \tag{4}$$

where for the 1-D dark beam $\alpha = 0$, while for the SIDS beam

$$\alpha = \begin{cases} 0 & \text{if } |x| \le b \\ 1 & \text{and } \beta = -1 \text{ for } x > b \\ 1 & \text{and } \beta = 1 \text{ for } x \le -b \end{cases} \tag{5}$$

The finite background beam carrying the singular beams is chosen to be of a super-Gaussian form

$$B(x,y) = \exp\{-[(x^2+y^2)/w^2]^8\}, \tag{6}$$

and its width w is chosen to exceed more than 20 times the initial dark beam width a. The numerical simulations of the dark beam propagation along the local Kerr NLM are carried out using the $(2+1)$-dimensional nonlinear Schrödinger equation

$$i\partial E/\partial(z/L_{Diff}) + (1/2)\Delta_T E - \gamma|E|^2E = 0, \tag{7}$$

which accounts for the evolution of the slowly varying optical beam envelope amplitude E under the combined action of nonlinearity and diffraction. Here Δ_T is the transverse part of the Laplace operator, $\gamma = L_{Diff}/L_{NL}$, and $L_{Diff} = ka^2$ and $L_{NL} = 1/(k|n_2|I)$ stand for the diffraction and nonlinear length of the dark beam respectively. The minus sign in Eq. (7) implies a self-defocusing nonlinearity, a necessary condition for dark spatial soliton ($\gamma = 1$) formation and for waveguiding by dark beams. In the above notations, k is the wave number inside the medium and I is the peak field intensity. The transverse spatial coordinates (x and y) are normalized to the odd dark beam width a. Eq. (7) was solved numerically by means of the split-step Fourier method with a computational window spanning over 1024×1024 grid points. As a standard test we modeled the formation of a fundamental 1-D dark spatial soliton up to $z = 5L_{NL}$ and compared it to the initial tanh-shaped 1-D dark beam profile. As shown in previous analyses of odd dark beams with mixed step-screw dislocations [27,28], the background-beam intensity has a weak influence on the FVD beam's dynamics. Negative nonlinearity however is important for keeping the optically induced refractive index modulation gradients (e.g. dark beam profile and refractive index profile) steep, which is

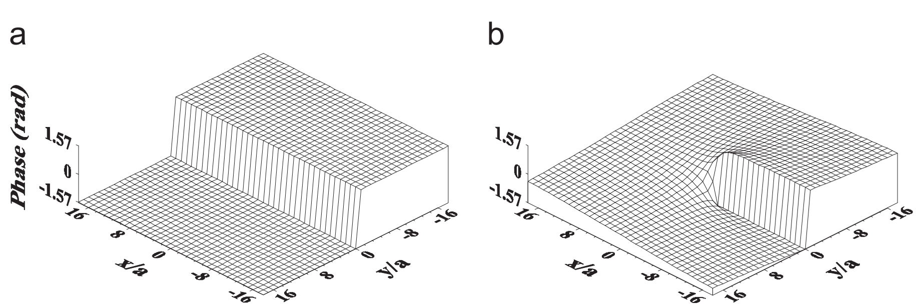

Fig. 1. One-dimensional step phase dislocation (a) and semi-infinite edge-screw mixed phase dislocation of a semi-infinite dark stripe (b) described by Eqs. (1) and (2), respectively.