Influence of a Bulk Waveguide on the Propagation of Two-Component Vortices

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***Abstract*—Studying the propagation of 3D+1 pulses with dislocations in a quadratically nonlinear bulk waveguide we demonstrate that the waveguide geometry can make it possible to observe stable vortex light bullets for the extended range of parameters, in particualar, at normal dispersion. The reduction of waveguide geometry strength leads to the stretching of pulses either in spatial or temporal directions.**

Keywords—optical vortex, quadratic nonlinearity, waveguide

I. Introduction

Investigation of multidimensional solitons opens new classes of solitons which differ in their transversal shape and phase distribution [1,2]. In particular, there is a class characterized by the presence of phase singularity which results in existence of ring-shaped pulses and beams with zero intensity at the axis. These are called "vortex solitons". Typically, vortex solitons are denoted by topological charge of their phase distribution and non-vortex soliton is considered to have topological charge of zero and is usually the attractor on the scale of the topological charge.

Unlike one-dimensional case, these new classes exhibit low stability. It was demonstrated that self-focusing nonlinearity which causes the existence of soliton solutions also results in their collapse [3,4,5]. Vortex solitons are also subject to perturbations of their phase distribution which typically lead to their splitting into several non-vortex solitons. Note that analytically, the phase profiles of the multidimensional solitons are typically classified based on their topological charge with non-vortex case corresponding to zero charge and being the minimum of the energy.

Nowadays, researches are focused on obtaining stable solitons. One way is to incorporate several counteracting nonlinearities (quadratic-cubic [6], cubic-quintic [7] or other nonlinearities realizable in experiment [8]) to stop the collapse. Other direction is moving away from the homogeneous media and tailoring the medium properties to stabilize solitons propagating through it by composing nonlinear waveguides [9,10], by considering a light trapped in harmonic oscillator potential [11].

In this paper we apply the second approach and examine the optical bullets in waveguides. A similar approach is present in [12,13,14]. Xu et al. in [12] reports on stabilization of solitons in waveguides with Kerr-type (cubic) nonlinearity. Notably several solitons with higher topological charges are demonstrated to be more stable than those with lower ones. In our study we deal with quadratic nonlinearity instead of cubic one.

II. Results of Numerical Simulation and Discussion Selecting a Template

We describe the propagation of light in a waveguide with quadratic nonlinearity with the help of the quasi-optical approach. Dynamics of propagation of spatial-temporal dislocations of second-harmonic generation in a bulk waveguide is governed by the following system on nonlinear parametrically coupled dimensionless equations:

$$i\frac{\partial A_1}{\partial z}+D_{\tau 1}\frac{\partial^2 A_1}{\partial \tau^2}-\gamma_1 A_1^* A_2 = = D_{q1}\left(x^2+y^2\right)A_1+D_1\Delta_\perp A_1, \quad (1)$$

$$i\frac{\partial A_2}{\partial z}+D_{\tau 2}\frac{\partial^2 A_2}{\partial \tau^2}-\gamma_2 A_1^2 = = D_{q2}\left(x^2+y^2\right)A_2+D_2\Delta_\perp A_2, \quad (2)$$

where $A_{1,2}$ are the dimensionless complex amplitudes at the fundamental and double frequencies, x , y are the dimensionless transverse coordinates, τ is the dimensionless time, z is the dimensionless propagation coordinate, $\gamma_{1,2}$ are the nonlinear coefficients, $D_{\tau 1,2}$ are the dispersion coefficients, $D_{1,2}$ are the diffraction coefficients, and $D_{q1,2}$ are the coefficients of waveguide strength. All coefficients are dimensionless.

The relation between physical and dimensionless parameters in case of a planar waveguide is given in details in [15]. Here we add one more transversal dimension y and normalize it by an initial spatial pulse width in this direction.

The range of physical parameters have been chosen from the experiments where spatial-temporal solitons were self-trapped in the longitudinal and one of transversal directions, while the confinement along the other transversal coordinate was provided by a waveguiding structure [16,17].

$LiIO_3$ may be chosen because it has a large value of second order nonlinearity. Sufficiently large group velocity dispersion

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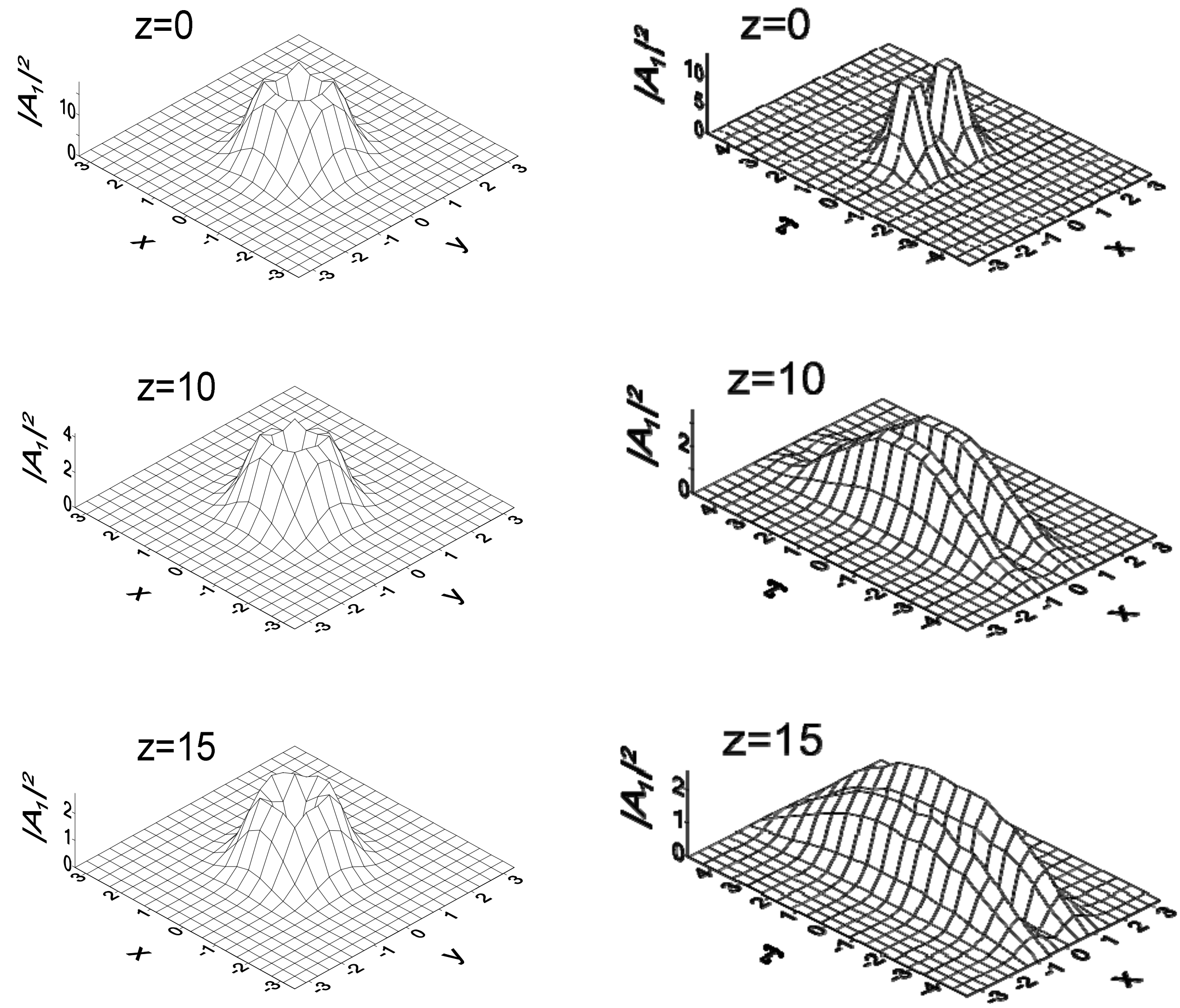

Fig. 1. Dynamics of the intensity space (time-space) distribution of the wave at the fundamental frequency. Parameters: $E_1 = 10$, $D_1 = 1$, $D_2 = 0.5$, $D_{\tau 1} = -0.05$, $D_{\tau 2} = -0.1$, $\gamma_1 = 1$, $\gamma_2 = 0.5$, $D_{q1} = D_{q2} = -10$. The initial pulse is of the form (3).

(GVD) gives possibility to observe soliton formation in a reasonably short propagation length. In the [16,17] pulses of duration 110 fs and energy up to 1 mJ at a wavelength of 795 nm were produced by a Ti:sapphire regenerative amplifier.

Incident beam at the fundamental and double frequencies is as follows:

$$A_{01} = E_1(x + iy)\exp(-(x^2 + y^2 + \tau^2)), \qquad (3)$$

$$A_{20} = 0.$$

$$A_{01} = E_1(x + iy)\exp(-(x^2 + y^2 + \tau^2)), \qquad (4)$$

$$A_{20} = E_2\left|x + iy\right|\exp(2\varphi(x + iy))\exp(-x^2 - y^2 - \tau^2)$$

Typical results are given in Fig. 1. Propagating in the waveguide the pulse-beam preserves its vortex structure in x and y coordinates. At that, we distinguish profile distortions but due to waveguide influence the pulse-beam is at the same position with respect to the transversal coordinates. The less is waveguide influence, the greater is pulse spreading. Due to waveguide geometry on the periphery of the xy plane, there is no threshold value of the waveguide coefficients at which the pulse-beam infinitely spreads. Each value of waveguide coefficient determines a finite radius of pulse spreading. It is worth noticing a quite visible pulse spreading in time. This results in the intensity decrease at the cross-section $t = 0$. If the incident pulse intensity increases, up to $E_1 = 100$, the pulse contracts at one or several points on the xy plane. Several vortex solitons are forming in the process of pulse propagation.

In contrast to the work [11] we do not impose any bond between the coefficients of diffraction and dispersion and we investigate not only the case of anomalous dispersion but normal dispersion as well. Typical results for normal dispersion are presented in Fig. 2. We can see a rather robust propagation

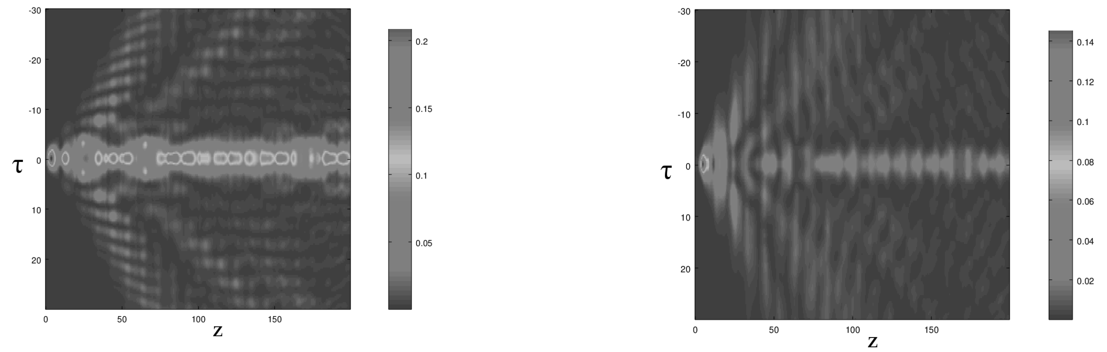

Fig. 2. Amplitude dependence on the local time τ and the propagation length z. Parameters: $E_1 = 1$, $D_1 = 0.1$, $D_2 = 0.05$, $D_{\tau 1} = 0.02$, $D_{\tau 2} = 0.04$, $\gamma_1 = 1$, $\gamma_2 = 0.5$, $D_{q1} = D_{q2} = -10$ The initial pulse is of the form (4).

of a two-color vortical soliton. In fact, our simulations were performed for a range of problem parameters $0.02 < D_{\tau 1} < 0.8$, $0.1 < D_1 < 1$, $-2 < D_{q1} < 0$.

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