Bright beam deflection by steering beams with mixed phase dislocations

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ABSTRACT

We study the ability of beams carrying mixed step-screw phase dislocations to guide and steer probe beams with non-zero transverse velocity. We report the first experimental demonstration of bright signal beam deflection by steering odd beams of finite length carrying such dislocation. The numerical simulations show that the beam deflection can be ruled by the geometry and orientation of the dislocation.

Keywords: Nonlinear optics, singular optics, photorefractive optics, self-focusing

1. INTRODUCTION

Spatial solitons formed in nonlinear media (NLM) attract considerable interest for more than four decades due to their ability to guide probe beams and pulses[1-4]. The underlying physical mechanism[5] is the intensity-dependent refractive index change in a plane perpendicular to the propagation direction. Weak signal beams passing along these optically induced gradient waveguides[6] are subject to effective induced-phase modulation and are trapped. This motivates the interest in investigating techniques for manipulating the transverse dynamics of laser beams.

Both bright and dark beams can be forced to steer in space by introducing a spatial chirp to their transverse phase profiles with spatial light modulators[7-9]. In this way, implementation of schemes for light steering based on dark spatial solitons (DSSs) appear specially attractive due to their intrinsic complex phase structure. Arrays of one-dimensional DSSs generated by two intersecting plane waves in the regime of adiabatic amplification (and the probe beams guided by them) can be steered by changing the relative intensities of the interfering waves[10]. The transverse velocity of an optical vortex soliton (OVS) has a radial and an angular component arising from the transverse phase and intensity gradients, respectively[11,12]. Two practical ways to control the vortex rotation have their origin in the Guoy phase shift on both sides of the background beam waist[12.13] and in the interaction of ordered structures of OVSs[14] controlled by the topological charges. Operation of planar Y-junction splitters for signal beams is demonstrated in both Kerr-type[15] and photorefractive NLM[16] with pairs of grey DSSs born from even initial conditions. The possibility to branch a single input probe beam into ordered structures of sub-beams by quasi-two-dimensional DSSs is demonstrated[17]. Other branching and steering schemes can be realized by employing the inherent dynamics of ring dark solitary waves[18], the eventual NLM saturation[19] and/or anisotropy[20]. In addition, dark beams containing mixed phase dislocation have shown important potential to steer beams in self-defocusing nonlinear medium[21-23].

However, the opportunities for implementation of beams with complex phase structure to steer beams in self-focusing nonlinear medium remain unexplored. In this work we demonstrate experimentally and describe theoretically, the ability of beams containing mixed phase dislocation to steer light beams in self-focusing photorefractive media.

2. RESULTS

2.1 Basic considerations

Odd dark beams of finite length are inherently restless on the bright background beam because of the mixed phase dislocations they are associated with. Loosely speaking, this type of dislocation consists of an one-dimensional phase

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step of a limited length, which ends, by necessity, with pairs of phase semi-spirals with opposite helicities[21,22]. The transverse steering of the dark beam is due to the phase gradients perpendicular to the one-dimensional phase step, i.e. due to the presence/interaction of the ending phase semi-spirals. To our best knowledge the only controllable way to produce odd dark beams of finite length is to use computer generated hologram (CGH). In this work we consider one of the possible mixed phase dislocations[23], the so-called step-screw (SS) dislocation, which phase profile is given by (see Fig. 1)

$$\Phi^{SS}_{\alpha,\beta}(x,y) = \Delta\Phi\left[-\frac{\beta}{\pi}arctg\left(\frac{\alpha y}{x+b\beta}\right)+\frac{1}{2}(1-\alpha)\,\mathrm{sgn}(y)\right]. \qquad (1)$$

The quantity $\Delta\Phi$ stands for the magnitude of the phase jump, $2b$ – for its length, x and y are the transverse coordinates. α=0 for $|x| \le b$; α =1 and β=-1 or 1, for x>b and x<-b, respectively. The linear optics of mixed SS phase dislocations shows that their transverse velocity $V_\perp$ depends on both the length b and the magnitude of the phase jump $\Delta\Phi$. After propagation lengths longer than 0.1 Rayleigh diffraction length $V_\perp$ remains nearly constant[23,24]. In the course of the dark beam propagation bright trailing peak is formed next to the mixed SS phase dislocation. In self-focusing nonlinear media this peak is able to initiate local self-focusing of the background. The transverse motion of this bright beam, however, is bounded to the dynamics of the mixed dislocation. In photorefractive nonlinear media the steering bright peak should be able to write curved all-optical waveguides which direction can be controlled by the orientation of the CGH. One can expect that ones written at a photosensitive wavelength, they will be able to guide and steer much more powerful "signal" beams at non-photosensitive wavelengths[25-27]. This was the motivation to model the beam evolution and to perform the reported experiments in a Strontium Barium Niobate photorefractive crystal (SBN:60; $Ba_{0.4}Sr_{0.6}Nb_2O_6$).

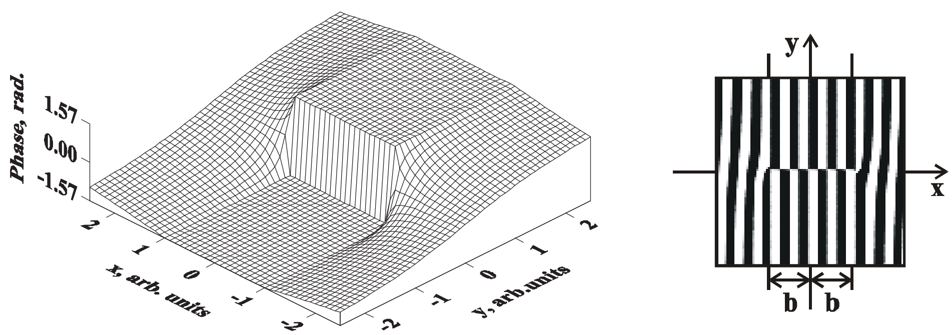

Fig. 1. Phase profile of the step-screw mixed phase dislocation (left) and structure of the corresponding computer-generated hologram (right).

2.2 Numerical procedure

The propagation of the two (pump and probe) optical beams along the z axis of the crystal, with an external dc electric field E_0 applied along the x axis (being parallel to the crystalline c-axis) we modeled by the equations[28,29]

$$i\frac{\partial A_j}{\partial z}+\frac{1}{2}\left(\frac{\partial^2 A_j}{\partial x^2}+\frac{\partial^2 A_j}{\partial y^2}\right)-\gamma\left(E_{spc}+E_0\right)A_j=0\ , \qquad (2)$$

in which A_j is the j-th component of the slowly varying optical field amplitude, E_{spc} is the space-charge field related to the electrostatic potential ϕ ($E_{spc}=-\partial\phi/\partial x$), $\gamma=(1/2)(2\pi/\lambda)^2 x_0^2 n_0^4 r_{eff}$ is a material nonlinear parameter accounting for the corresponding term r_{eff} of the electrooptic tensor ($r_{eff}=r_{33}$ for SBN). γ>0 accounts for a self-focusing nonlinear response of the crystal. All transverse coordinates are expressed in units of the beam width x_0, whereas the propagation coordinate z is expressed in units of the Rayleigh diffraction length $L_{Diff}=(2\pi/\lambda)n_0x_0^2$. The electrostatic potential ϕ is modeled by the equation[28,29]

$$\nabla^2\phi+\nabla\phi.\nabla\ln(1+I)=E_0\frac{\partial}{\partial x}\ln(1+I)\ , \qquad (3)$$

where $I = |A_1|^2 + |A_2|^2$ is the total light intensity, supposing that the incident beams are polarized along the *x*-axis (i.e. parallel to the crystal *c*-axis), and the last term accounts for the drift of the charge carriers. In the above notations the refractive index of the medium is modulated via the Pockels effect according to the relation $n^2 = n_0^2 + n_0^4 r_{33} \partial\phi / \partial x$. All material parameters taken in the numerical simulations correspond to the typical values encountered in SBN crystals ($r_{eff} = 180.10^{-12}$ m/V and $n_0 = 2.3$ for $\lambda = 500$ nm).

2.3 Experimental results and comparative numerical simulations

In the experiment we used a continuous wave frequency-doubled Nd:YAG laser at a wavelength of 532nm. The desired odd dark beams of finite length and the SS phase dislocations are generated by reproduced binary CGH (see Fig. 1) fabricated photolithographically with a grating period of 30µm. The first-order diffracted beam carrying the dislocation was focused on the front face of a 20mm long SBN photorefractive crystal. The 110µm long SS dislocation encoded in the CGH was demagnified down to 35µm at the crystal entrance with a dislocation length-to-width ratio 2*b*/*a*=2.4. The polarization of the beam was orientated parallel to the crystalline *c*-axis, thus the beam experienced a strong photorefractive nonlinearity. The crystal was biased by an externally applied electric field (~500V). Either the front face or the back face of the crystal was imaged with a lens onto a CCD-camera. Special attention was paid to the alignment of the CGH in order to maintain unchanged position of the central part of the encoded SS-dislocation with respect to the illuminating background beam when the hologram is rotated stepwise by 90^o. Thanks to the relatively long (tens of seconds) response time of the self-focusing photorefractive nonlinearity we used the same laser beam as a "probe" beam. For this purpose the CGH was fast controllable shifted horizontally in order to illuminate a side-lying portion of the binary structure consisting of parallel stripes only. Without any other change in the alignment the distribution of the ("probe") beam guided by the already written curved gradient waveguide was recorded no later than 2s after the crystal exposure. During twice longer period the sensing ("probe") Gaussian beam was not able to affect noticeably the written structure and the recorded power density distribution was stationary.

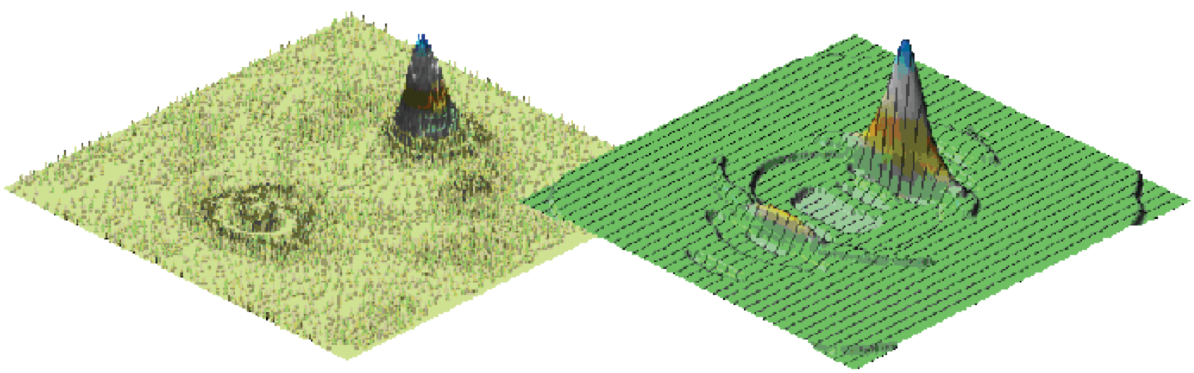

Fig. 2. Experimental (left) and numerically simulated pump beam profiles (right) at the exit of the SBN crystal.

Fig. 2 presents experimental (left) and numerically simulated profiles (right) of the pump beam at the exit of the SBN crystal. In the simulation some 16% of the total computational area is shown. One can clearly recognize that the deflection of the dark beam with mixed SS phase dislocations causes formation of a steering bright peak which becomes self-focused in the course of his nonlinear evolution. As a result, curved optically-induced waveguides are written in the crystal. In Fig. 3 we show the recorded power density distributions of the deflected signal beams at different orientations of the CGH. For better visibility they are converted to three-dimensional surface plots. As seen, the output channels can be clearly distinguished. Except in the upper left frame, in which the carrier drift and the associated refractive index change coincide with the deflection direction and, therefore, contribute positively to the guiding efficiency, in the remaining three frames there is always a cross-talk signal guided along the crystalline *c*-axis. In Fig. 4 we present composed image showing all four deflected beams. Four virtual output channels are marked with L (left), R (right), U (up) and (D) down. According to this notation we summarize in Table 1 the estimated guiding efficiencies in each channel. The results show reasonable contrast between the signal in the intentionally addressed output channel and the remaining channels. The highest guiding efficiency (49%) was estimated when the probe beam deflection is along the crystalline c-axis, whereas the deflection in the opposite direction has the lowest efficiency of 30%. The particular data have not to be taken to literally, since the transverse velocity of the dark beams $V_{\perp}$ forcing the trailing and self-focusing bright beams to self-focus can be changed by both the dislocation length-to-width ratio $2b/a$ and the magnitude of the phase jump $\Delta\Phi$ and the deflection depends on the length of the particular crystal used.

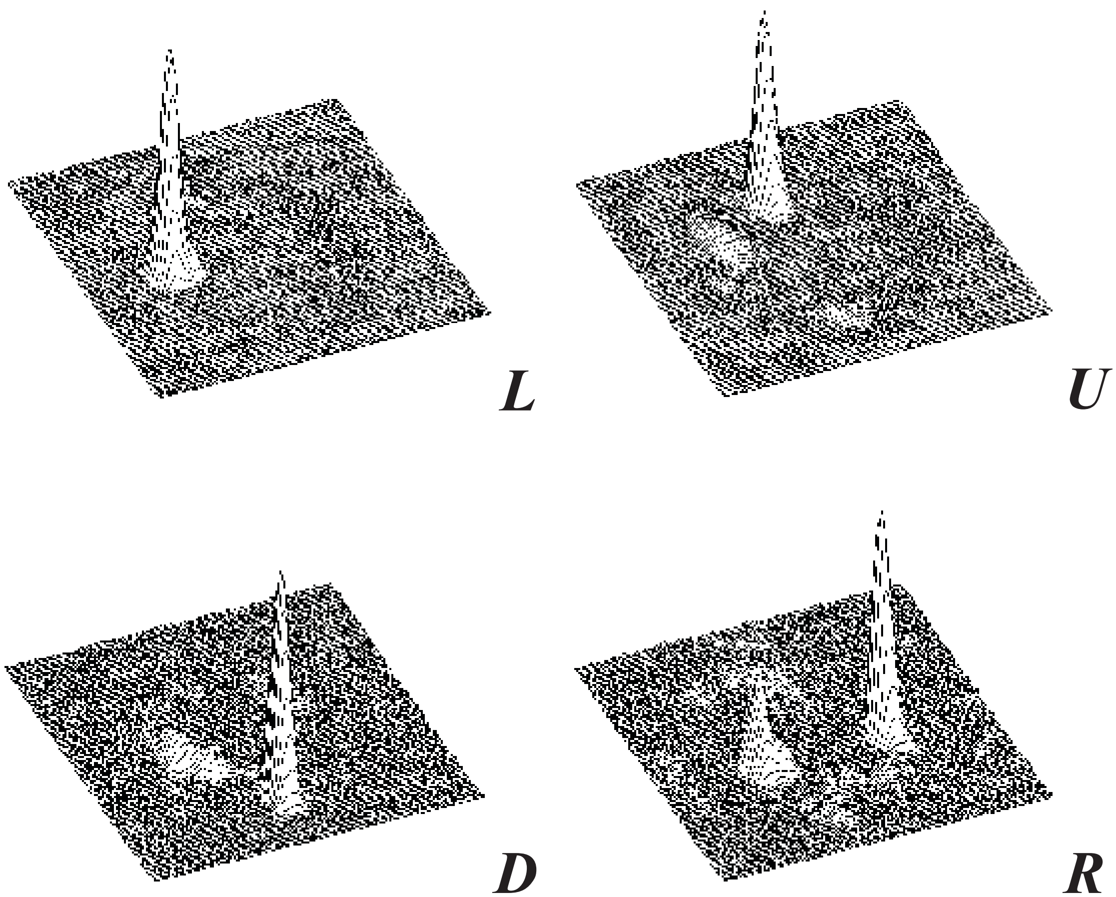

Fig. 3. Experimental results: Surface plots of the deflected probe beams at the exit of the SBN crystal for four different orientations of the CGH. The crystalline c-axis is oriented horizontally (along a line connecting the peaks in case R).

Table 1. Guiding efficiencies for the four virtual output channels marked in Fig. 4 for the different orientations of the CGH.

Addressed channel	Guiding efficiency in channel			
	U	***L***	***D***	***R***
U	**47%**	7%	5%	2%
L	9%	**49%**	3%	6%
D	3%	12%	**38%**	4%
R	7%	18%	4%	**30%**

Typical numerical results obtained by solving equations (2) and (3) are shown in Fig. 5. The relatively long CGH-to-NLM distance needed in the experiment to separate well the diffracted order beams and to filter out the first order

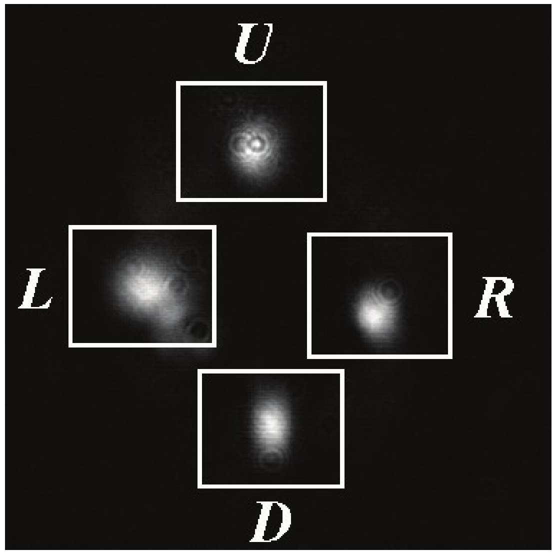

Fig. 4. Composed image of all four deflected beams. The virtual output channels (100x80 pix.) are marked with L (left), R (right), U (up) and (D) down.

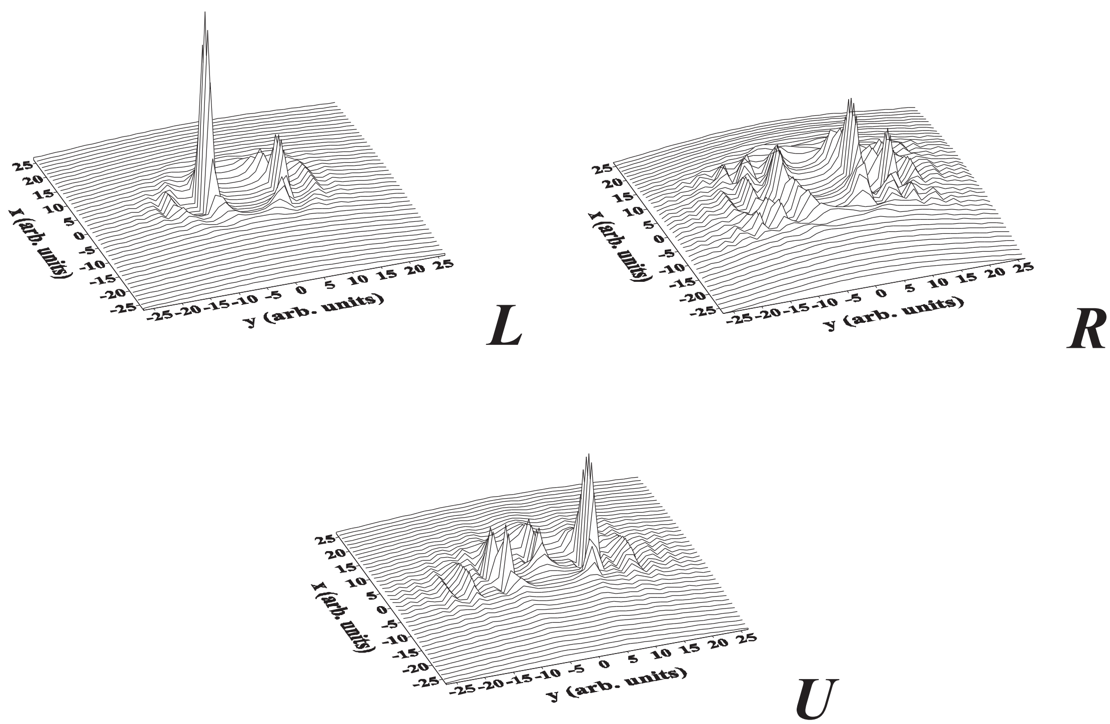

Fig. 5. Numerical results: Surface plots of the deflected probe beams at the exit of the NLM for $2b/a$=1.2. Some 16% of the total computational area is shown. For better visibility, plot L is scaled by a factor of 2. See the text for details.

diffracted beam is modeled by linear beam propagation over $z = 7.5L_{Diff}$. The nonlinear beam propagation length inside the SBN:60 crystal spanned over $2.5L_{Diff}$. We varied the dislocation length-to-width ratio $2b/a$ in the range from 1.2 to 4 keeping the magnitude of the initial phase jump $\Delta\Phi$ equal to π. The numerical results agree qualitatively with the experimental ones. Quantitatively, the photorefractive NLM anisotropy and the bright beam modulational instability are gradually stronger pronounced in the numerical results as compared to the experimental data. Qualitatively similar to the experiment, the most clear deflection with the highest contrast between the channels was obtained in the case when the dark/bright beam steering direction coincides with the direction of the carrier drift along with the crystalline-axis. Nevertheless, second peak self-focusing at a smaller growth-rate is clearly visible. When the direction of the bright/dark beam steering is reversed, the signal guided to the opposite right channel still dominates, but appears split and with a weaker growth rate in the simulations. This is only in a qualitative agreement with the experimental observation shown in Fig. 3(R). Steering the waveguide perpendicular to the crystalline *c*-axis the background in the experimental frames (Fig. 3, U) is somewhat disturbed along the *c*-axis and opposite to the deflection direction. This is much stronger expressed in the numerical results in which the dominating peaks are actually along the *c*-axis. In agreement with earlier results obtained in Kerr NLM[22,24] the numerical data confirmed that the transverse velocity $V_\perp$ of the odd dark beams with mixed SS phase dislocations and $V_\perp$ of the self-focusing bright peaks depend inversely proportional to the dislocation length-to-width ratio $2b/a$, whereas the modulational instability increases with $2b/a$.

3. CONCLUSION

We reported here the first experimental demonstration of bright signal beam deflection by steering odd dark beams of finite length carrying such dislocation. The reasonably high contrast between the signal guided to the desired output channel and the remaining channels seems promising for future optimization of all-optical deflectors based on beams with mixed phase dislocations.

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