Directional coupling of optical signals by odd dark beams with mixed phase dislocations

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Numerical simulations on the evolution of step-screw and edge-screw optical phase dislocations in bulk saturable self-defocusing nonlinear media are presented, with emphasis on their ability to induce steering waveguides for signal beams (pulses). Two schemes for directional coupling of such signals, both ensuring reasonable coupling-to-cross-talk efficiency ratio, are investigated. The parameters useful for performance optimization of the couplers are discussed.

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I. INTRODUCTION

Dark spatial solitons (DSSs) formed in bulk self-defocusing Kerr-type nonlinear media (NLM) are able to guide co-propagating probe beams/pulses 11,12. The physical mechanism underlying 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 4 are subject to effective induced-phase modulation and are trapped. In photorefractive NLM 3 the situation is even more spectacular 11. Because of the wavelength-dependent material response, dark spatial solitons generated at low powers but at a photosensitive wavelength are able to guide and steer much more powerful ‘signal’ beams at non-photosensitive wavelengths. This is confirmed for photovoltaic 11, biased 8 and quasi-steady-state 8 photorefractive solitons and seems to hold also for incoherent dark solitons 10.

Bright signal beams/pulses can be deflected by both electronically 11 and optically induced prisms 12. When they are guided by DSSs, the same can be done by manipulating the transverse dynamics of the dark beams. 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 3,13. Two practical ways to control the vortex rotation have their origin in the Guoy phase shift on both sides of the background beam waist 14,15 and in the interaction of ordered structures of OVSs 14 controlled by the topological charges. OVS steering is demonstrated by superposition of a weak incoherent background field 16. Operation of planar Y-junction splitters for signal beams is demonstrated in both Kerr-type 15 and photorefractive NLM 14 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 numerically in Ref. 20. Other branching and steering schemes can be realized by employing the inherent dynamics of ring dark solitary waves 21, eventual NLM saturation 22 and/or anisotropy 23.

In this work we present numerical results on how one input optical data channel can be linked to a selected output data channel by means of an optically-induced steering waveguide. A high steering speed of the induced waveguide can be obtained by using odd dark beams (ODBs) of finite lengths 24,25 with a suitable choice of the mixed phase dislocation. Special attention is paid to ensure high energy efficiency of the directional coupler and short length of the interaction zone. Reconfiguration of the coupler is proposed to be done by changing the type of the phase dislocation reproduced by a multiple, active, single-voltage controlled computer-generated hologram 26.

II. STEP-SCREW AND EDGE-SCREW MIXED PHASE DISLOCATIONS

The mixed phase dislocations considered consist of a one-dimensional phase step of limited length, which ends, by necessity, with pairs of phase semi-spirals with opposite helicities. In this work two possible cases are considered. The first phase dislocation of this type, which will be denoted step-screw (SS), is described by the phase distribution

\begin{equation}
\Phi_{\alpha,\beta}^{SS}(x,y) = \Delta \Phi \left\{ \frac{1 - \alpha}{2} \text{sgn}(y) - \frac{\beta}{\pi} \arctan \left( \frac{\alpha y}{x + b\beta} \right) \right\},
\end{equation}

where the parameters \(\alpha\) and \(\beta\) are defined as follows:

\begin{align}
\alpha &= \begin{cases} 
0 & \text{for } |x| \leq b, \\
1 & \text{for } x > b, \\
1 & \text{for } x \leq -b.
\end{cases}
\end{align}
The phase distribution
\[ \Phi^{ES}(x, y) = \frac{\Delta \Phi}{2\pi} \left( \arctan \left( \frac{y}{x + b} \right) - \arctan \left( \frac{y}{x - b} \right) \right) \],

(2.3)

will be referred to as edge-screw (ES). In Eqs. (2.3), the quantity \( \Delta \Phi \) stands for the magnitude of the step portion of the dislocation, \( 2b \) for its length, and \( x \) and \( y \) denote the transverse Cartesian coordinates parallel and perpendicular to the dislocation. Surface plots of the SS and ES phase dislocations are shown in Fig. 1a and 1b, respectively.

The formation of mixed phase dislocations was first identified by us in interferograms of decayed one-dimensional DSSs in the presence of moderate saturation of the nonlinearity [24]. From our present point of view the classification [24] of such formation generated as a result of an instability is not very reliable.

In order to maintain the correspondence to the conditions in our previous experimental work [23, 24], where NLM with saturation was used, we adopted the refractive-index correction
\[ \Delta n = n_2 |E_D|^2 / (1 + s |E_D|^2)^\gamma, \]

(3.2)

with \( s = 0.3 \) and \( \gamma = 3 \). In a weak-signal approximation we took into account the bright-signal beam diffraction and the refractive-index changes it sees as induced by the ODB. In the NLM its evolution is described by
\[ i \frac{\partial E_B}{\partial \zeta} + \frac{1}{2} \frac{\lambda_B}{\lambda_D} \Delta \Phi E_B - \sigma L_{Diff} |E_D|^2 E_B L_{NL} (1 + s |E_D|^2)^\gamma = 0. \]

(3.3)

The coupling coefficient \( \sigma \) depends on the nature of the physical process of the optical nonlinearity (e.g. molecular orientation, electronic response of bound electrons, etc.) and on the experimental conditions (e.g. the polarizations of the waves). The numerical simulations presented in this work refer to the wavelength ratio \( \lambda_B / \lambda_D \approx 1 \) and \( \sigma = 2 \). The slowly-varying electric-field amplitudes of the ODBs were assumed to be \( \text{tanh} \)-shaped and of the form
\[ E_D(x, y, z = 0) = \sqrt{I_0 B(r_{1,0}(x, y))} \text{tanh} \left[ \frac{r_{\alpha,\beta}(x, y)}{a} \right] \exp^{i \Phi(x, y)}, \]

(3.4)

where \( \Phi(x, y) = \Phi^{SS}_{\alpha,\beta}(x, y) \) for an SS, \( \Phi(x, y) = \Phi^{ES}(x, y) \) for an ES phase dislocation, and \( r_{\alpha,\beta}(x, y) = \sqrt{\alpha(x + \beta b)^2 + y^2} \) is the effective radial coordinate. In order to avoid any influence of the finite background beam of super-Gaussian form \( B(r_{1,0}) = \exp\{-\left(\sqrt{x^2 + y^2}/w_0^2\right)^{14}\} \), its width was chosen to exceed the maximal ODB deflection at \( \zeta = 10 \) more than \( 10 \) times. The signal beam is assumed to be \( \text{sech} \)-shaped and equal in width to the ODB width \( a \). Its intensity is chosen hundred times weaker than \( I_0^{1D} \) of the NLM, and the background beam intensity at its entrance is normalized to that needed to form an 1D DSS of width \( a \) \((I_0 = I_0^{1DSS})\).
ratio, the phase step $\Delta \Phi$ and the background beam intensity. As it is seen in Fig. 2, changing the ODB length-to-width ratio gives an effective way to manipulate the ODB velocity. It is higher for the short and slower for the long dislocations. The long ones however could experience a transverse instability. More strongly pronounced is the increase of the velocity with decreasing the magnitude of the step portion of the phase dislocation $\Delta \Phi$, but we refrained from exploiting this. The reason is that during the steering process both types of ODBs inevitably become grey (and asymptotically disappear), which tends to destroy the coupler modeled. The numerical calculations performed showed similar but slightly weaker coupling efficiencies when the transverse deflection is controlled by $\Delta \Phi$ than by $b/a$. All data in this work refer to $\Delta \Phi(\zeta = 0) = \pi$. Characteristic of the evolution of the ES phase dislocation is that it disturbs the background beam more weakly than the SS dislocation. In order to emphasize this, the number of gray-scale levels in the frames shown in Fig. 3 are intentionally reduced in the same way. The data refer to $\zeta = z/L_{NL} = 4$ and $b/a = 1$. The background beam intensity in this simulation is chosen to correspond to that of a 1D DSS ($I_{DSS}$). The dashed line is intended to underline that the ES ODB is stronger deflected than the SS ODB.

The background beam intensity could be additionally used to control the dynamics of the ODBs, even their deflection does not strongly depend on it $\Delta \Phi$. The background beam intensity, however, influences substantially the transverse beam profile and the guiding properties of the induced waveguide. Better spatial confinement could be expected at higher intensities. Numerical simulations were made to confirm this statement. Depending on the type of the dislocation (ES or SS) the highest coupling efficiencies were achieved for levels $(1.25 \div 1.75)I_{DSS}$. Higher intensities tend to destroy the induced waveguide due to the strong deformation of the dark beam profile under saturation of the nonlinearity.

The main task of the numerical simulations presented below is to find the proper parameter range for $b/a$ and beam intensity in order to reach maximal coupling efficiency in the analyzed schemes for directional coupling.

**IV. ONE-DIRECTIONAL COUPLER**

As a first step in this work we modeled the coupling of an input signal beam (pulse) to a desired output channel by optically induced waveguides. Figure 3 shows the positions and the forms of the weak signal beams guided by the corresponding dark one after a nonlinear propagation path length $\zeta = 10$. Channel 0 is assumed to be supported by an OVS with background intensity $1.5I_{DSS}$, channels 1 and $\pm 1$ by ODBs with SS phase dislocations of $b/a = 1.5$ at $I = 1.5I_{DSS}$, whereas channels 2 and $\pm 2$ are considered to be induced by ODBs with ES phase dislocations with $b/a = 2.5$ at $I = 1.25I_{DSS}$. The change of the ODB steering direction in the NLM (i.e. the switching between channels with positive and negative numbers) is controlled by reversing the gradients of the screw portions of the dislocations. First, real implementation of this directional switching is feasible if there are reliable means to change the phase distributions of the ODBs. The electrically-controllable, multiply-active, computer-generated holograms developed [26] are well suited for doing that. Because of the time needed to reconfigure the hologram, the relatively rare redirection of the data streams addressed to a desired channel will be preferable. Second, the energy efficiency of the guiding and switching should be as high as possible at the lowest possible cross-talk between the channels. The imaginary information channels considered to be coupled to the exit of the NLM are assumed to be rectangle-shaped with a width (height) 1.5 (3.0) times the input signal-beam FWHM. In Fig. 3 the respective positions along the steering direction (the arrow in Fig. 3) are sketched as rectangles.

The results for the directional coupling and cross-talk efficiencies obtained as ratios of the transmitted energy in a particular channel to the total one are summarized in Table I. The ODB with an SS phase profile is assumed to couple the input channel to channel No. 1, whereas this with an ES dislocation redirects the input to channel $\pm 2$. The maximal efficiencies for channels $0, \pm 1,$ and $\pm 2$ to be expected are 74.7%, 70.7%, and 52.2%, respectively. In most channels the cross-talk signal should remain well below 14%. The ODB steering is accompanied by the creation of a leading dark wave and a trailing bright peak on the background beam (see Fig. 3 in Ref. [24]) which are more strongly pronounced in the SS case. The bright trailing peak pushes the signal beam stronger. This qualitatively explains the relatively high efficiency of the coupling to channels $+1$ and $-1$. Because of the additional self-defocusing of this peak it appears more effective to address channels $+2$ and $-2$ by ES ODBs. If the outlying channels are 2.25 times larger than the input signal beam width $a$, in the ES case the efficiency in coupling the signal to them can be increased by 3.6% to 55.9%. Due to the numerical discretization the overall accuracy in estimating the energies is within 0.02% and the coupling efficiencies in the respective channels are correct to within $\pm 0.04\%$.

We should note here that because of the saturation of the nonlinearity the width of the induced waveguide is larger than in the case of pure Kerr nonlinearity. If a Kerr medium is considered (i.e. $s = 0$) the coupling efficiencies increase by 10%, whereas the cross-talk coefficients become slightly weaker.

**V. TWO-DIRECTIONAL COUPLER**

For addressing a desired channel from an imaginary array of information channels ($3 \times 3$ in this work) we
used the squared-shaped channel configuration shown in Fig. 5. The data presented below refer to \( \zeta = 10 \) and channel width and height 1.5 times the input signal beam FWHM. Best spatial confinement of the signal beams is achieved at 1.5 times higher background beam intensity than that needed to form a 1D DSS of width \( a \). Besides being controlled by the type of the phase dislocation (screw, ES, SS), the ODB transverse velocity and deflection at the exit of the NLM are adjusted by the initial ODB length-to-width ratio \( 2b/a \) (\( b/a = 1.5 \) in the SS case; and \( b/a = 3.4 \) in the ES case; both at \( \Delta \Phi = \pi \)). Let us denote the channels as \( C_{IJ} \), where \( I \) and \( J \) are the respective row and column indices. The central output channel \( C_{22} \), which is on axis with respect to the input one, is addressed by an OVS (screw, ES, SS), the ODB transverse velocity and alignment of the signal beams as located on the imaginary array of information channels considered. Coupling to each of the diagonal channels \( C_{11}, C_{12}, C_{13}, C_{31}, C_{33} \) is performed by ODBs with ES phase dislocations rotated ±45°. The calculated coupling efficiencies are summarized in Table 2. The maximal efficiencies for the direct channel \( C_{22} \), the neighboring channel \( C_{23} \), and the diagonal channel \( C_{11} \) to be expected are 61.6%, 49.6%, and 47.1% respectively, at cross-talk signals remaining well below 12%. In Fig. 6 we composed grey-scale frames of the signal beams as located on the imaginary array of information channels considered. Coupling the input channel to information channel \( C_{11} \) (by an ES ODB) should result in undesired but equal cross-signals in channels \( C_{11}, C_{12} \) and \( C_{13} \) (\( I \neq J \)). If the input signal is coupled to channel \( C_{23} \) the same should hold for channels \( C_{11}, C_{21} \). The data obtained indicate that the discretization in our simulations leads to a maximal inaccuracy in estimating the coupling efficiencies that is within ±0.04%. If pure Kerr nonlinearity is considered the coupling efficiencies are 1% to 8% higher.

VI. CONCLUSION

The numerical data on the nonlinear evolution of mixed step-screw and edge-screw phase dislocations under equivalent conditions shows an amazing difference between the transverse steering dynamics of SS and ES ODBs. Such odd dark beams are able to induce steering conduits for weak information beams (pulses) in bulk nonlinear media. Due to this two different schemes for directional coupling are proposed. The relatively high coupling and moderate cross-talk efficiencies in both of them provide a reasonable basis for further optimization and may open the way to constructing parallel reconfigurable all-optical logical elements.

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FIG. 1. (a) step-screw and (b) edge-screw mixed phase dislocations described by Eqs. (2.1) and (2.3), respectively.

FIG. 2. Relative deflection of ODBs with edge-screw (ES) and step-screw (SS) phase dislocations vs. nonlinear propagation path length $\zeta = z/L_{NL}$ for $b/a = 1.0$ (solid), 2.0 (dashed), and 3.0 (dotted) at $\Delta \Phi = \pi$.

FIG. 3. Grey-scale plots of ES and SS ODBs with initial length-to-width ratio $b/a = 1$ after nonlinear propagation path length $\zeta = 4$. Some 3% of the total computational area is shown. See text for details.

FIG. 4. Transverse profiles (along the steering direction $y$) of the signal beams coupled to one of the five output channels considered. The intensities are normalized to that of the signal in the direct channel No. 0.

FIG. 5. Composition of grey-scale images of the signal beams at the exit of the two-directional coupler. Each channel is addressed separately and the coupler length is $\zeta = 10$. 
TABLE I. One-directional coupler: Efficiencies (in %) in addressing channels 0, 1, and −2 by an OVS, SS ODB, and ES ODB, respectively, and cross-talk efficiencies.

| Channel guiding by | -2 | -1 | 0  | 1  | 2  | Energy losses |
|-------------------|----|----|----|----|----|---------------|
| OVS               | 0.3| 9.5| 74.7| 9.5| 0.3| < 9.5         |
| SS ODB            | 0.5| 0.2| 9.6| 70.7| 5.6| < 13.4        |
| ES ODB            | 52.2| 14.1| 1.4| 1.6| 0.8| < 29.9       |

| Channel guiding by | C_{11} | C_{12} | C_{13} | C_{21} | C_{22} | C_{23} | C_{31} | C_{32} | C_{33} | Energy losses |
|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|---------------|
| OVS               | 1.3    | 7.3    | 1.3    | 7.3    | 61.6   | 7.3    | 1.3    | 1.3    | 1.3    | < 4.0         |
| SS ODB            | 0.2    | 2.4    | 12.6   | 0.1    | 6.1    | 49.6   | 0.2    | 2.4    | 12.6   | < 13.7        |
| ES ODB            | 47.1   | 5.5    | 0.7    | 5.5    | 0.3    | 0.5    | 0.7    | 0.5    | 0.5    | < 38.6        |