Light-induced waveguide by a finite self-trapped vortex beam in a photorefractive medium

Rémy Passier, Mathieu Chauvet, Bruno Wacogne and Fabrice Devaux

Département d’Optique P.M. Duffieux, Institut FEMTO-ST, UMR CNRS 6174, Université de Franche-Comté, 16 route de Gray, F-25030 Besançon Cedex, France

E-mail: remypassier@yahoo.fr

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Abstract

We report the formation of a 2D waveguide induced by a self-trapped vortex beam in a photorefractive–photovoltaic medium. Demonstrations are performed by monitoring the self-trapping dynamic of an annular vortex beam in a LiNbO$_3$:Fe crystal. Control of the experimental observations is consistent with the underlying physics revealed by a numerical model.

Keywords: electro-optical effects, photorefractive materials, photorefractive optics, self-focusing, optical waveguides

1. Introduction

During the last two decades, many techniques have been developed to achieve optically induced 3D light circuits, including micromachining [1] and optical masks [2, 3] as well as soliton-induced waveguides [4]. In particular, optical spatial solitons have been at the center of numerous studies to demonstrate fundamental properties [5] and to induce low loss reconfigurable waveguides [6]. The versatility of solitons has been shown using different optical nonlinearities such as the Kerr [7] or quadratic effect [8] and in different media like glasses [9], semi-conductors [10], or liquid crystals [11]. Solitons in photorefractive medium have been particularly studied since they can be formed at very low light power due to the high sensitivity of these materials. The first theoretical [12] and experimental [13] photorefractive solitons were produced using a static applied electric field. These photorefractive (PR) solitons are formed by the creation of an internal space charge field that modifies the refractive index by the Pockels effect. This effect can lead to the formation of bright [14] or dark PR solitons [15], depending on the sign of the applied electric field. The models [16–19] are now mature and experimental realization of (2 + 1)-D solitons has led to the study of more complex configurations such as the formation of junctions [20, 21]. Recently, Fazio et al [22] demonstrated beam self-focusing in a widely used photonic medium, LiNbO$_3$, by using a high applied voltage. To avoid the application of high electric field an alternative way consists of using the photovoltaic effect in a LiNbO$_3$:Fe crystal [30], creating the vortex beam by the help of a helicoidal phase.

Practically, vortex beams of small size such as small-ring intensity profile beams could be useful to induce multiple waveguides close to each other in a sequential manner with no overlap. Moreover, such vortex beams are easy to form. The behavior of small size vortex beams propagating in a nonlinear photorefractive medium consequently deserves a
This model allows calculation of the space charge field in 3D, propagating beam that would induce automatically a single-vortex to create self-trapped beams. (2 + 1)-D self-trapped beams in a defocusing photovoltaic media will be tackled both numerically and experimentally. Additionally, the potential to write waveguides inside bulk LiNbO₃ is assessed.

### 2. Numerical analysis

To determine the optimum conditions to obtain a soliton-like propagating beam that would induce automatically a single-mode waveguide, a numerical model has been developed [31]. This model allows calculation of the space charge field in 3D, based on a one carrier and one deep center model, and is derived from [12, 32]

\[
\frac{\partial N_D^+}{\partial t} = s(I + I_d)(N_D - N_D^+) - \gamma N_e N_D^+ \tag{1}
\]

\[
\nabla \cdot [\varepsilon \vec{E}] = \rho \tag{2}
\]

\[
\rho = \varepsilon (N_D^+ - N_A - N_e) \tag{3}
\]

\[
\vec{J} = \varepsilon\mu N_e \vec{E} + \mu_k T \nabla N_e + \beta_{ph}(N_D - N_D^+) I \vec{c} \tag{4}
\]

\[
\frac{\partial \rho}{\partial t} = -\nabla \cdot \vec{J} \tag{5}
\]

where \( I_d \) is the equivalent dark intensity, \( N_A, N_D, N_D^+ \) and \( N_e \) are respectively the densities of shallow acceptors, deep donors, deep ionized donors and free electrons. \( s \) is the photoexcitation coefficient, \( \gamma \) is the recombination constant, \( k_B \) is the Boltzmann constant, \( \mu \) is the electron mobility and \( T \) is the temperature. The photovoltaic current directed along the LiNbO₃ c-axis (i.e. the Z axis) is considered throughout \( \beta_{ph} \) which is a light polarization dependent component of the photogalvanic tensor. \( \beta_{13} \) is used for ordinary polarized beams.

\([\varepsilon] \) is the static dielectric tensor, \( \rho \) is the charge density and \( \vec{J} \) is the current density. In addition, the dynamic of the photorefractive effect is resolved and the intrinsic anisotropy of the photorefractive effect is taken into account [33]. The small size ring vortex beam is given by [34]

\[
\vec{U}_{env}(r) = \vec{A}(r_\perp, z) \exp(-i(\omega t - k_z z)) \exp(i m \theta) \tag{6}
\]

where \( r_\perp \) represents the coordinates in the transverse plane and \( z \) is the position along the propagation axis, \( m \) is the topological charge of the vortex, \( \theta \) is the azimuth angle and \( \vec{A} = A_0(r_\perp/\omega_0)^m \exp(-r_\perp^2/2\omega_0^2) \) is the optical field amplitude.

This model is then used to resolve the usual following light wave equation, linking the optical field amplitude \( \vec{A} \) to the index modulation \( \Delta n \):

\[
\frac{\partial}{\partial z} \vec{A}(r_\perp, z) = i \left( \frac{1}{2k} \frac{\partial^2}{\partial r_\perp^2} + \frac{2\pi}{\lambda} \Delta n \right) \vec{A}(r_\perp, z) \tag{7}
\]

To describe the experimental configuration further we consider the propagation of a vortex beam at a wavelength of 473 nm focused to a 25 \( \mu \)m waist. This one-charged vortex \( (m = 1) \) is represented in figure 1. The beam waist is positioned before the crystal, at a distance equal to a beam Rayleigh distance of 6.8 mm. It has an external beam size diameter (or FWHM, full width at half maximum) of 120 \( \mu \)m and a dark core diameter of 36 \( \mu \)m at the crystal input (figures 1(b) and (e)). After 9 mm propagation in the linear regime in the iron doped LiNbO₃ the beam diffracts at the output to 162 \( \mu \)m for the external diameter and 48 \( \mu \)m for the dark core (figures 1(c) and (f)).

In a second set of numerical calculation we assume that the medium possesses photorefractive properties dictated by the photovoltaic effect. The self-trapping dynamic during the transient regime of the vortex beam is then monitored and
presented in figure 2. Propagation along the Y axis of the LiNbO$_3$:Fe crystal is chosen to avoid anisotropy playing an active role in the process [33]. Beam profiles are shown along X and Z. For a close fit with the values given in the literature and the physical experiment described further, the following parameters are set: $I_d = 1 \times 10^6$ W m$^{-2}$, $E_{ph} = -7, 7 \times 10^6$ V m$^{-1}$, $N_A = 5 \times 10^{23}$ m$^{-3}$ and $N_D/N_A = 1.1$. A peak power density of $I_{\text{max}} \approx 3 \times 10^6$ W m$^{-2}$ which gives a ratio $I_{\text{max}}/I_d \approx 263$ is used. Other parameters are taken from [35]. Since an unintentionally doped medium is used it is fair to consider a low concentration of deep donor around $10^{19}$ m$^{-3}$ [36].

Figures 2(a)–(c) show the temporal intensity distribution as the nonlinear effect is taking place. In addition, the corresponding refractive index distribution dynamic written in the material is represented (figures 2(f)–(j)). The last two figures (figures 2(e)–(j)) depict a strongly distorted beam. The beam intensity distribution is measured at the output of the crystal while the nonlinear effect takes place in the photovoltaic–photorefractive material. We observe that the nonlinear effect tends to elongate the beam more strongly along the Z axis which corresponds to the direction of the defocusing photovoltaic field ($\vec{c}$) (figure 2(b)). During this transient regime brighter areas appear on the left and right sides of the beam (figures 2(b)–(d)). Such a beam distortion is mainly due to the presence of low index areas on the bottom and top parts of the beam. Note that away from the illuminated areas, the refractive index change is due to the space charge field formed by the photovoltaic current loops present in this open-circuit configuration. For instance, an index increase is observed above and below the illuminated region while a slight index decrease is present on the right and left sides. Moreover symmetric low index lobes are present above and below the central core and form an elliptical high index area (figures 2(f)–(i)). This dynamic leads to the self-focusing of the dark core for which a stronger refractive index is present compared to the surrounding region, thus forming a potential 2D waveguide. These results confirm earlier published results [18, 33]. After $t = 1.35$ s, beam expansion and core focusing continue (figures 2(d) and (i)) and can lead to strong distortion (figures 2(e) and (j)) and even beam dislocation, showing that a steady-state spatial soliton cannot be reached. One way to produce proper waveguides is to stop the nonlinear phenomenon before appearance of this dislocation.

The detailed evolution of the vortex core and external diameters is analyzed to better visualize the dynamical behavior before beam distortion. Figure 3 represents both diameters along the X and Z axes. It clearly reveals the gradual increase of the external diameter while the internal core is shrinking. The anisotropy of the photorefractive effect has a strong influence on the evolution of the external beam diameter as shown by the appearance of a marked ellipticity (figure 3(b)). However the dark core looks circular (figure 3(a)) as the beam ellipticity is tilted by about 45°. After $t = 1.35$ s we observe that a similar core size of about 36 μm is present at the input and output faces of the crystal. If the induction process is stopped at that moment, before excessive focussing and any dislocation process occur, a homogeneous waveguide is expected to be memorized across the crystal, written by this finite size vortex beam.

In the following, the induced waveguides are analyzed with a probe beam at 473 nm with an ordinary polarization. The asymmetric photo-induced index transverse distribution is depicted in figure 4(a). The index profiles along X (figure 4(d)) and Z (figure 4(g)) are particularly explicit in highlighting the asymmetry. The modulation depth is more than two times as much along the polar axis $Z (\Delta n = 4 \times 10^{-6})$ as it is in the perpendicular direction $(\Delta n = 1.75 \times 10^{-6})$. The low index area surrounding the higher refractive index center forms a guiding structure. This guiding structure is first probed by a Gaussian beam which is larger than the central guiding region (FWHM of 130 μm). This provides a way to visualize the overall index distribution written in the medium as shown in figure 4(b).

To evaluate the guiding properties of the central area, the probe beam is then focused at the entrance face to a spot similar in size to the vortex core. The guided beam reveals an elliptical beam profile at the crystal output as shown in figure 4(c). The mode of this single-mode waveguide is 61 μm along the X axis and 36 μm along the Z axis (figures 4(f) and (i)), with a deeper...
Figure 3. Temporal evolution of the core (a) and external (b) beam diameters (FMHM) for the numerical experiment corresponding to figure 2 from $t = 0$ to $t = 2.25$ s, along the $X$ (dashed line) and $Z$ axes. The horizontal dashed line indicates the core diameter at the input face of the photorefractive medium.

Figure 4. The index modulation distribution induced by a one-charge vortex beam after $t = 1.35$ s induction time (a), and the corresponding profiles along the $X$ (d) and $Z$ (g) axes. The intensity distribution at the exit face of a 9 mm long guiding structure when probed with a large beam ((b), (e), (h)) and when probed with a focused beam ((c), (f), (i)). The dashed curves show the beam profile without the guiding structure.

index modulation along the $Z$ axis (figures 4(g)–(i)) than along the $X$ axis (figures 4(d)–(f)).

3. Experimental study

To verify these numerical predictions, experimental studies are performed. A single topological charge vortex ($m = 1$) is imprinted on a 473 nm CW laser using a reflective hologram fabricated by photolithography on a silicon wafer. Experiments are realized with a typical power of 100 $\mu$W and the vortex beam is focused before the crystal with a 200 mm focal length to form an external diameter beam of about 120 $\mu$m at the crystal input. The sample is cut from a LiNbO$_3$ wafer doped with 0.01% of iron to increase the photorefractive effect. The beam is polarized along the ordinary axis of the crystal and propagates along a 9 mm long distance perpendicular to the crystal $c$-axis.
Figure 5. Experimental images at the LiNbO$_3$:Fe crystal input (a) and output (b) and corresponding profiles along the $X$ ((c), (d)) and $Z$ ((e), (f)) axes.

Figure 6. Experimental intensity distribution evolution at the exit face ((a)–(d)) for different induction times and corresponding profiles along the $X$ ((e)–(g)) and $Z$ ((h)–(k)) axes.
time of the photorefractive effect, such as the active iron concentration, have been set to arbitrary values. Adjustment of parameters to obtain similar response times between the model and the experiments was not pursued.

In figure 7, experimental points showing the temporal evolution of the vortex characteristic dimensions are presented. In figure 7(a) we observe that the core is efficiently self-trapped along both transverse axes as expected from numerical simulation. In addition the initial beam core ellipticity vanishes and tends to become more circular. Finally, the vortex core maintains an almost constant size of about 30 μm over propagation. Note also that the external beam diameter (figure 7(b)) enlarges more rapidly along the X axis than along the Z axis in accordance with the predictions from figure 3(b).

We, however, observe that the beam diameter along the polar axis Z is unexpectedly unaffected; this may be due to the initial elliptical vortex core. Note that in these experiments focusing dynamics up to the quasi-steady-state regime are considered. As a consequence the refractive index change does not reach saturation. In figure 7(a) we observe that the core width tends to reach a minimum value which is the sign of the approaching quasi-steady-state regime; a longer experiment gives beam dislocation.

The holographic storage time in LiNbO3 can extend up to several months. As a consequence, the index structure written by the vortex beam can be subsequently probed to check its properties. In the present work, the probe beam is a strongly attenuated 473 nm beam unable to alter the memorized structure. To check the overall index modulation, the crystal is first illuminated by a large weakly diffracted beam. The wave propagation is perturbed by the written index modulation present along the crystal. At the exit face the beam distribution gives a qualitative shape (figure 8(a)) very similar to the calculated index modulation Δn (figure 4(a)) where brighter areas correspond to higher index changes. In a second step a 25 μm diameter low power Gaussian beam is injected in the central part of the induced structure. At the output, a confined spot is observed witnessing the presence of a 2D waveguide (figure 8(b)). Mode FWHM 36 μm along the Z axis (figure 8(d)) and 41 μm along the X axis (figure 8(f)) is confirmed by the numerical results (figure 4).

4. Conclusion

We showed that finite size vortex beams in a defocusing photovoltaic medium such as LiNbO3 tend to dislocate due to
the anisotropy of the nonlinear effect. However, vortex self-trapping in the transient regime can inscribe 2D waveguides in the medium in place of the vortex dark core. Formation of the guiding structures is analyzed experimentally and with the help of a numerical model to reveal a complex refractive index distribution. Finite size vortices are shown to be viable tools to photo-induce waveguides. Sequential writing with annular vortex beams can authorize the formation of multiple guiding structures inside bulk LiNbO$_3$.

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