# Self-Trapping of an Optical Vortex by Use of the Bulk Photovoltaic Effect

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We report the first observation of self-trapping of an optical vortex due to the bulk photovoltaic effect. A singly charged vortex nested on a broad cw laser beam is trapped in both transverse dimensions in a lithium niobate crystal. Although the optically induced photovoltaic current is inherently polar, the space charge field gives rise to two-dimensional self-defocusing effects. We observe both circular and elliptical self-trapped vortices, as well as beam deformation due to modulation instability. [S0031-9007(97)02947-5]

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Optical vortices [1] and vortex solitons [2–5] have become an active research topic because the topological charges (angular momenta) carried by the vortices enrich nonlinear dynamics with many new features, especially when several vortices are present and interact with each other. Vortex solitons form when self-defocusing balances diffraction, giving rise to a vortexlike phase structure which undergoes stationary propagation in a nonlinear medium. Such solitons also induce waveguides that can guide other beams [3,4], and are thus promising for manipulating light by light. This further motivates research on vortex motion and steering [5]. Some of these studies employed a Kerr-like nonlinearity [4] that is typically isotropic: a dark soliton stripe can occur in any direction in the transverse plane. This enables the generation of isotropic structures such as dark soliton crosses and grids [6] as well as circular vortex solitons [4]. Other studies of vortex solitons employed an isotropic saturable nonlinearity [5], leading to a similar behavior.

Recently, optical vortex solitons were observed in biased photorefractive (PR) nonlinear materials in quasi-steady state [7]. Such solitons differ from previously observed solitons in their physical origin: They employ the nonlocal nature of the PR effect assisted by an external bias field, balancing diffraction by nonlinear phase coupling [8]. Properties of quasi-steady state PR vortex solitons include, in contrast to vortex Kerr solitons, independence of absolute light intensity (for intensities much higher than the dark irradiance) and inherent anisotropy with respect to the transverse dimensions [7,8]. However, these solitons are transient: They exist during a "time window" but disappear in steady state. Steady state bright and dark PR solitons ("screening solitons") were predicted [9] and observed [10–12] in biased PR media. More recently, a steady-state bound vortex pair has been observed [13].

In this Letter we report on the first experimental observation of self-trapping of an optical vortex by use of the bulk photovoltaic (PV) effect [14,15]. Self-trapping of a 1D (bright and dark) optical beam in unbiased photovoltaic-photorefractive media was predicted in Ref. [16]. The optical nonlinearity responsible for photovoltaic solitons arises from transport of charges dominated by PV current. The index change results from the electro-optic effect driven by the space charge field. The PV nonlinearity is distinctly different from Kerr nonlinearity and from the nonlinearity in biased PR media. In particular, the PV induced current is inherently polar (i.e., charge carriers move in preferential crystalline directions). Accordingly, 1D dark PV solitons display anisotropic dependence on the direction of propagation, polarization of the optical beam, and orientation of the intensity gradient, with respect to the crystalline axes of the medium [17]. For example, for 1D solitons in $LiNbO_3$, self-trapping occurs when the narrow direction of the dark stripe (i.e., the direction along which the intensity varies) is parallel to the *c* axis and does not occur when it is parallel to the *a* axis [17]. This implies that crosses and grids cannot be trapped in PV $LiNbO_3$. A numerical study of 2D beam propagation in a PV crystal was presented in Ref. [18], and the inherent anisotropy of the induced change in the refractive index was also shown there (see Fig. 5 there). Based on these studies, it seems that 2D self-trapping based on the bulk PV effect, and, in particular, self-trapping of a beam of circular symmetry, should be impossible.

Here we show experimentally that, although a 1D photovoltaic dark soliton exists only in specific directions in the transverse plane, an optical vortex can self-trap in both transverse dimensions in a PV medium to either a circular or an elliptical solitonlike structure. Our observation poses an intriguing challenge to explain how a dark beam of a circular symmetry can self-trap in both dimensions in such highly anisotropic nonlinear media. Moreover, the self-trapped vortex can be rendered elliptical with its

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ellipticity controlled by the ratio between the optical intensity of the self-trapped beam and the dark irradiance, again, unexplained by existing theories. These studies are of fundamental interest to nonlinear dynamics of optical vortices and vortex solitons, as they add new features that are not present in isotropic media. For applications, such self-trapped vortices induce 2D waveguides in the volume of the bulk crystal that persist a long time in the dark because the dark conductivity is very small in all PV materials [15–17]. Finally, we note that optical nonlinearities that support 2D self-trapping of *bright* beams are very scarce: Thus far only PR solitons [11,19], quadratic solitons [20], and solitons in saturable nonlinear media [21] have been observed. Although the sign of the refractive index change in $LiNbO_3$ (negative) cannot support bright solitons [16], other PV materials in which the index change is positive (e.g., $BaTiO_3$, Ref. [15]) may be suitable for 2D self-trapping of *bright* optical beams.

We now proceed to experiments with an optical vortex. An optical vortex is a phase singularity in an optical beam at which the field amplitude goes to zero and the phase gradient on any loop around the vortex equals $2m\pi$ ($m$ being the topological charge) [1,2]. Various techniques have been used earlier to generate an optical vortex, including phase retardation platelets inserted in parts of the beam [4], adjusting the intracavity laser aperture to launch a donutlike Gauss-Laguerre mode [7], superposing a $TEM_{01}$ beam and a $TEM_{10}$ beam with a mutual phase separation of $\pi/2$ [7] (giving a Gauss-Laguerre beam), and using a computer-generated holographic mask [5,13,22]. These techniques produce a phase singularity borne on a finite beam. For our experiments with PV media, we wish to isolate the vortex dynamics from possible 2D currents and fields which would be present around the margins of a finite "ring" beam. Therefore, a vortex with a small core (a few $\mu$m in diameter) on a uniform background beam which is as broad as possible ($\sim$1 cm in diameter here) is desirable. We generate this vortex by a helicoidal phase mask fabricated using *e*-beam microlithography [23]. The phase material, PMMA, was spun onto a $SiO_2$ substrate, exposed with a patterned *e*-beam dose, and developed to yield a 1-cm-diameter specimen whose thickness increased azimuthally by $\lambda/2$. This generated a helical $2\pi$ phase upon reflection from the mask. Figure 1 shows photographs of the vortex beam. The single-start spiral in Fig. 1(c) indicates that the vortex is of $m = 1$ topological charge [2].

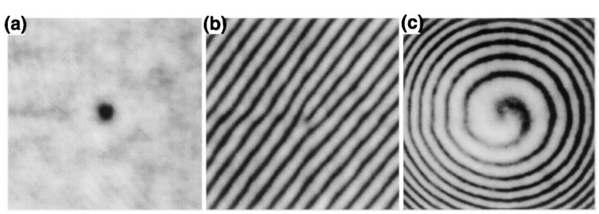


FIG. 1. (a) Intensity profile of a singly charged optical vortex-nesting beam. Interference of the vortex beam with (b) a plane wave and (c) a spherical wave.

We use a cw 488 nm argon-ion laser. The vortex reflected from the phase mask is imaged onto the input face of a Fe-doped $LiNbO_3$ crystal (1 $cm^3$), whose crystalline $c$ axis is oriented in parallel with the beam polarization (i.e., the beam is extraordinarily polarized, thus the change in the refractive index is dominated by the electro-optic coefficient $r_{33}$, and the optically induced PV current flows only in the direction of the $c$ axis [15–17]). Another coherent beam split from the same laser is provided to interfere with the vortex beam to monitor the phase fronts of the input-output beam, when necessary. When we focus the reference beam so that the center of the "spherical wave" coincides with the vortex core, the interference generates spiral fringes [Fig. 1(c)]. With a collimated reference beam the interference results in linear fringes that exhibit a single defect at the phase singularity [Fig. 1(b)]. Since the strength of the space charge field (and thus of the refractive index change) depends on the ratio between the optical intensity and the dark irradiance, it is desirable to control this ratio and fine tune the nonlinearity. In previous experiments with PV media this has been done by temperature tuning [17]. Here we add "artificial dark irradiance" by using white light illuminating the entire crystal, providing a bias density of charge carriers in the conduction band (as commonly done for screening solitons [10–12]). The beam profiles at the input-output faces of the crystal are monitored by a CCD camera.

When the vortex beam is launched into the crystal, we observe the self-trapping evolving progressively in both transverse dimensions as the PV space charge field builds up in time. Typical experimental results are presented in Fig. 2, showing photographs of the optical beam at the output face of crystal 2(a) after 1 second of exposure (long before the PV space charge field has built up), corresponding to normal diffraction of the vortex, and 2(b) after 4

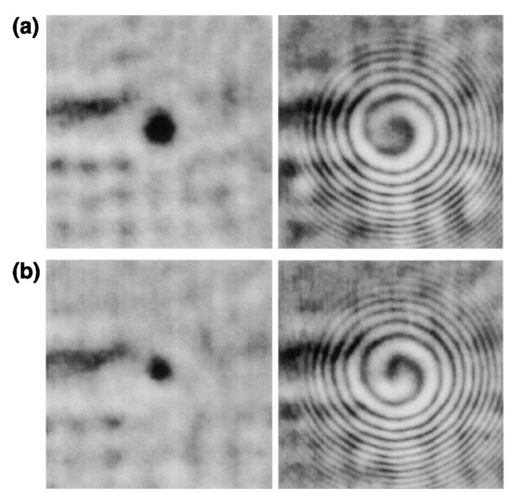


FIG. 2. Self-trapping of a circular vortex. Photographs taken at output face of crystal when the vortex normally diffracts (a) and when it is self-trapped (b).

hours, showing the self-trapped vortex. Figure 2 (right) also shows that the vortex beam continues to be of a helical phase pattern after the vortex has propagated through the crystal and self-trapped. The average intensity of the vortex beam is roughly 75 $\mu W/cm^2$, and it illuminates nearly the entire crystal. The vortex is 12 $\mu$m (FWHM) at the input, diffracting to 23 $\mu$m after 10 mm of propagation through the crystal, or self-trapping to its initial size when the space charge field has reached steady state. Since the vortex has self-trapped to its initial size while exhibiting a vortex phase structure, we interpret it as a *vortex soliton.* The intensity of the white light used for dark illumination is roughly 500 $\mu W/cm^2$ (spread over wavelengths from 400 to 900 nm). Because of the low optical intensities and the small electron mobility in $LiNbO_3$ [15], the nonlinearity evolves very slowly in time.

Increasing the optical power of the vortex beam speeds up the self-trapping effect, but at the same time, it increases the nonlinearity so that it overcompensates diffraction. This gives rise to modulation instability, resulting in distortion of the vortex along with the entire beam that bears it. (Similar modulation instabilities have been observed for screening solitons [11,12].) Thus, the incoherent white light serves to fine-tune the nonlinearity to the level that it balances the diffraction of the vortex but does not overcompensate it. Figure 3(a) shows an example of a distorted vortex beam obtained after 4-hour exposure when the intensity of the vortex beam is increased to about 240 $\mu W/cm^2$ and the intensity of the white light is kept unchanged. The effect of the modulation instability is even more pronounced when no incoherent background illumination is provided (the nonlinearity is larger). To see this, we launch a uniform beam (with no vortex nesting on it) with an average intensity of 375 $\mu W/cm^2$ into the crystal and monitor the temporal evolution of the beam pattern with no white light illumination. Figure 3(b) shows the beam taken after 3 hours of exposure. Adding an appropriate intensity of incoherent illumination reduces the modulation instability as shown in Fig. 3(c), taken after 3-hour exposure using the same uniform beam of the same intensity but with a white light beam of much higher intensity (10 $mW/cm^2$). This shows how the incoherent white light is used to fine-tune the strength of the nonlinearity. However, if the white light is too intense, the light-induced index modulation eventually diminishes. In fact, this is how we "clean" up the crystal before each subsequent experiment.

As we established that the ratio between the intensities of the vortex and the incoherent beams is directly related to the PV refractive index change, we also find that self-trapping of a vortex depends on its initial shape and size. If the vortex is initially slightly elliptical (adjusted by a small off-axis displacement of the imagining lens), we cannot obtain a circular self-trapped vortex. Furthermore, even if the input vortex is circular, one can still end up with an elliptical self-trapped vortex if the experimental parameters are not adjusted properly, e.g., the intensity of the vortex beam is too high or the initial size of the vortex is too small. Figure 4 shows an example of an elliptical self-trapped vortex after 4-hour exposure when the intensity of the vortex beam is 125 $\mu W/cm^2$. To characterize that, we perform a series of experiments using different intensities while keeping all other experimental conditions unchanged. In most cases, the vortex is self-trapped into an elliptical shape, and circular self-trapped vortices are observed only at particular sets of parameters. This behavior is similar to self-trapping of circular bright beams in biased PR media, where *elliptical* 2D self-trapping was observed when the strength of the applied field was not appropriate [11] (too large or too small). It seems that, similar to 2D bright screening solitons, circular PV vortex solitons require a specific relation between the nonlinearity (determined by the intensity ratio and the electro-optic and PV coefficients) and the width of the self-trapped beam, which is manifested in an "existence curve." As with 2D screening solitons, a small deviation from this curve renders the solitons elliptical. It is possible, however, that the elliptical vortex rotates its ellipticity during propagation.

In our experiments, we have an undesired stripe superposed on the input vortex beam. It arises from a small imperfection in the mask: The azimuthal round-trip phase shift is not exactly $2\pi$. This dark stripe propagates along with the vortex throughout the crystal (Fig. 2). With an appropriate strength of the optical nonlinearity, this dark stripe can be self-trapped into a 1D soliton. We use this stripe as a perfect example to show the anisotropy of the PV nonlinearity that strongly depends on the orientation of the dark stripe. Specifically, when the narrow direction of the dark stripe is oriented parallel to the crys-

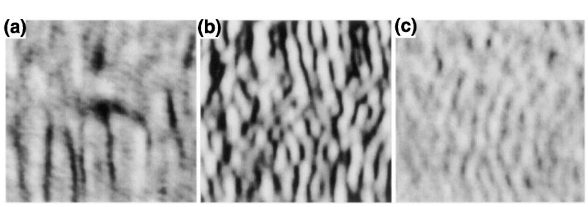


FIG. 3. Deformation of a beam due to modulation instability. (a) A vortex-nesting beam distorted when the beam intensity is too high. (b) and (c) A uniform beam distorted when the incoherent beam is (b) "off" and (c) "on."

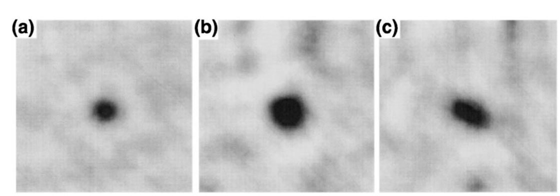


FIG. 4. Self-trapping of an elliptical vortex. Photographs taken at (a) the input and (b) and (c) the output faces of crystal, showing normal diffraction (b) and self-trapping (c) of the vortex.

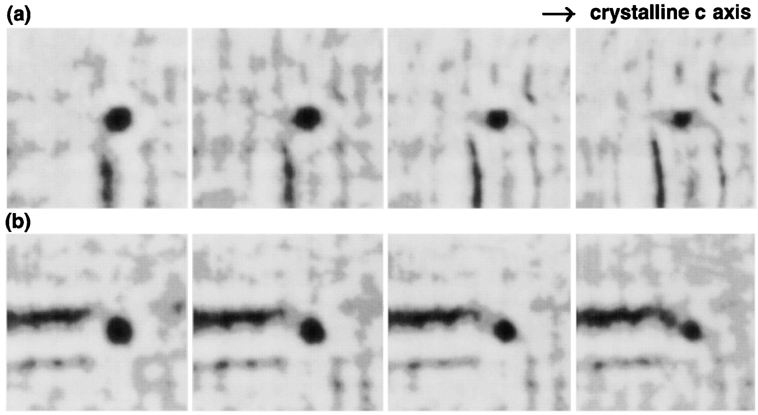


FIG. 5. Temporal evolution of a vortex beam at the output face of crystal. The dark stripe is oriented (a) normal and (b) parallel to the *c* axis.

talline *c* axis, the dark stripe self-focuses progressively in time (along with the vortex), leading to a 1D dark solitonlike structure that coexists alongside the vortex soliton [Fig. 5(a)]. However, when the narrow direction of the dark stripe is oriented perpendicular to the *c* axis (by rotating the phase mask 90° and keeping the beam extraordinarily polarized), the output dark stripe remains broad and almost does not change in its shape, whereas the vortex self-traps and is almost unaffected by the rotation [Fig. 5(b)]. (The self-trapped vortex has a small difference between the two cases only in the region of close proximity with the dark stripe.) The behavior of the dark stripe is in full agreement with previous observations of the orientational behavior of 1D dark PV solitons [17].

In summary, we observed self-trapping of an optical vortex in a bulk photovoltaic-photorefractie medium. Despite the inherently polar properties of the bulk photovoltaic effect, as manifested in the orientational behavior of one-dimensional photovoltaic dark solitons, the vortex can be self-trapped into a solitonlike structure of a circular or an elliptical shape.

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