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Citation: Applied Physics Letters **107**, 201101 (2015); doi: 10.1063/1.4935605
View online: http://dx.doi.org/10.1063/1.4935605
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Polar POLICRYPS diffractive structures generate cylindrical vector beams

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(Received 24 September 2015; accepted 28 October 2015; published online 16 November 2015)

Local shaping of the polarization state of a light beam is appealing for a number of applications. This can be achieved by employing devices containing birefringent materials. In this article, we present one such enables converting a uniformly circularly polarized beam into a cylindrical vector beam (CVB). This device has been fabricated by exploiting the POLICRYPS (POlymer-LIquid CRYstals-Polymer-Slices) photocuring technique. It is a liquid-crystal-based optical diffraction grating featuring polar symmetry of the director alignment. We have characterized the resulting CVB profile and polarization for the cases of left and right circularly polarized incoming beams.
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The spatial modulation of the optical axis orientation of a birefringent material can be employed to build devices capable of locally modifying the state of polarization (SOP) of a light beam. For example, a light beam entering such a device with uniform polarization can exit with a tunable SOP that is spatially variable over the beam area. This holds the promise of exploiting effects and phenomena that can expand the functionalities and enhance the capabilities of optical systems. In fact, this is the core of Tabiryan's idea for optics of the 4th generation,[1] following optics based on simple shape (1st generation), refractive index (2nd generation), and effective birefringence (3rd generation). As these kinds of devices shape the SOP of a beam, we will call them *polarization shapers* or *polshapes*. In this article, we report on the design and realization of a specific polshape that is able to convert a circularly polarized beam into a cylindrical vector beam (CVB).

CVBs are vector solutions of Maxwell's equations that obey axial symmetry in amplitude, phase, and polarization.[2,3] As shown in Fig. 1, the simplest 1st-order CVBs can be expressed as the superposition of two orthogonally polarized 1st-order Hermite-Gaussian (HG) beams.[3] A radially polarized CVB is obtained as (Fig. 1(a))

$$\mathbf{E}_r^{CV}(x,y,z) = \mathrm{HG}_{10}(x,y,z)\hat{x} + \mathrm{HG}_{01}(x,y,z)\hat{y}, \qquad (1)$$

and an azimuthally polarized CVB as (Fig. 1(b))

$$\mathbf{E}_a^{CV}(x,y,z) = \mathrm{HG}_{10}(x,y,z)\hat{x} - \mathrm{HG}_{01}(x,y,z)\hat{y}. \qquad (2)$$

Also, other 1st-order CVB exists, e.g., a superposition of the radial and azimuthal CVBs leads to the hybrid CVB shown in Fig. 1(c). The interest in CVBs arose mainly because of their unique focusing properties due to their polarization symmetry.[4,5] A radially polarized CVB can be focussed into a tighter spot[6,7] when compared to a Gaussian beam, while the focus of an azimuthally polarized CVB has a donut shape. This has been exploited, e.g., in optical trapping,[8] where radial CVBs have been used to trap metallic particles[9,10] and azimuthal CVBs to trap particles with dielectric constant lower than that of the surrounding medium.[5] Switching between radial, azimuthal and hybrid polarization can be done using two half-wave plates.[11,12] Various alternative methods have been proposed to produce CVBs including: a double-interferometer configuration to convert a linearly polarized laser beam into a radially polarized one;[13] a radial analyzer consisting of a birefringent lens;[11] a surface-emitting semiconductor laser;[14] a space-varying liquid crystal cell;[15] the summation inside a laser resonator of two orthogonally polarized TEM_{01} modes;[16] the excitation of a few-modes optical fiber with an offset linearly polarized Gaussian beam;[17] a space-variant dielectric subwavelength grating;[18] a few-modes fiber excited by a Laguerre-Gaussian beam;[12] a conical Brewster prism;[19] and a Sagnac interferometer.[20]

We have realized the CVB polshape employed in this work by using the one-step POLICRYPS photocuring technique described in detail in Refs. 21–23. The fabricated sample is a polar diffractive device that contains a polymeric support structure and a birefringent material, i.e., liquid crystals (LCs), whose optical axis is radially oriented. This radial symmetry matches the cylindrical symmetry of CVBs (see Fig. 1) and, thus, led us to expect that such a polshape could generate a CVB. The sample has been assembled by putting two glass substrates at a controlled distance (10 μm), to form a cell that is, later on, filled in by capillarity with a photosensitive syrup; this is made of the pre-polymer system NOA61 (72% wt., by Norland) and the nematic liquid crystal E7 (28% wt., by Merck). The exact fabrication procedure is reported in Ref. 24. In brief, we have followed the ensuing steps:

(1) A curing laser-light pattern with the shape of concentric rings induces phase separation between the polymer and LC molecules. The resulting formation of polymeric rings replicates the light pattern and drives the diffusion of LC molecules in the regions comprised between rings.
(2) The photocuring process takes place at high temperature (e.g., above the nematic-isotropic transition temperature of the LCs) as in a typical POLICRYPS fabrication

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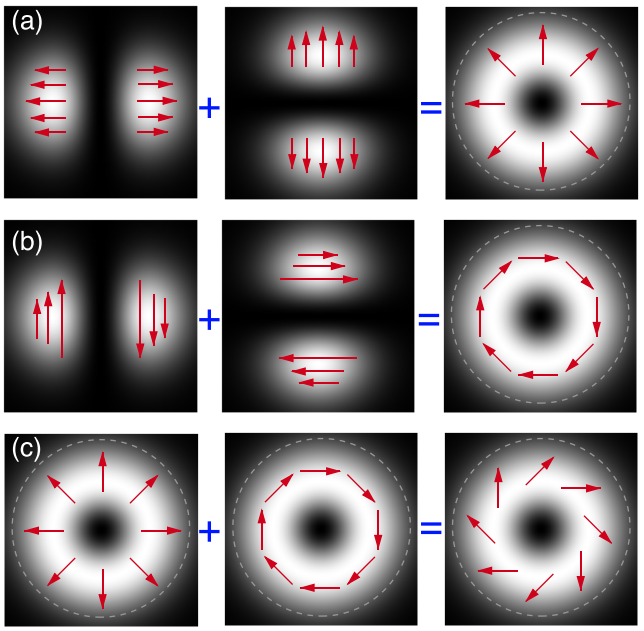


FIG. 1. Cylindrical vector beams (CVBs). (a) Radially and (b) azimuthally polarized 1st-order cylindrical vector beams can be considered as the linear superposition of orthogonally polarized 1st-order Hermite-Gaussiam beams. (c) A hybrid CVB can be obtained as the superposition of a radial CVB and an azimuthal CVB. The arrows represent the local direction of the polarization vector.

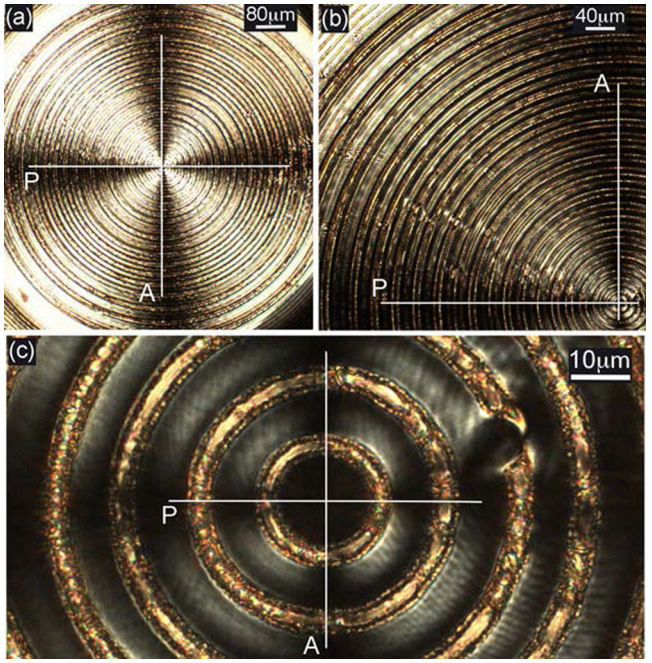


FIG. 2. Micrographs of a POLICRYPS polshape with radial symmetry. All the images are acquired with a polarized optical microscope between crossed polarizers and represent the same sample but at different magnifications. The yellow/light grey rings are the polymeric circles and the dark grey rings are the aligned LC regions.

procedure.[25] This ensures that the LC molecules do not separate in droplets but remain homogeneous between the polymeric rings and their directors orient perpendicularly to the rings in a radially symmetric configuration.

Some micrographs of the obtained structure are reported in Fig. 2. All images represent the same sample, but at different magnifications, as observed at the polarized optical microscope between crossed polarizers. The Maltese cross confirms the expected radial alignment of the LC director between the polymeric rings of the polshape.[26,27] Interestingly, the high magnification detail of the center (Fig. 2(c)) reveals the contrast between the polymeric circles (yellow/light grey rings) and the aligned (dark grey) LC regions.

The setup used to generate CVBs using our POLICRYPS polshape is shown in Fig. 3. The light source is a He-Ne laser (633 nm). The laser beam passes first through a plane polarizer (P) whose axis is parallel to the vertical *y*-axis and a quarter wave plate (QWP) whose optical axis is kept at ±45° with the vertical axis; depending on the sign of this angle, the resulting light beam is either left circularly polarized (LCP) or right circularly polarized (RCP). Afterwards, the beam undergoes diffraction passing through the characteristic ring structure of the POLICRYPS. Both the diffracted and transmitted beams are then focused onto a CCD camera by a lens. We remark that the part of the beam passing through the polymer rings does not undergo a change of polarization and propagates as a standard TEM_{00} Gaussian beam because the polymer rings are not birefringent (in fact, while some LC molecules can remain trapped in the polymer, they are not aligned); thus, the beam emerging from the POLICRYPS is a superposition of a pure CVB generated by the LC fringes and the unperturbed (Gaussian) beam coming through the polymer rings. This is a drawback in terms of both the quality of the generated CVB and the efficiency of the device. In more detail, the unperturbed beam coming through the polymer affects the light/dark contrast between the outer part of the donut shaped CVB and its center. Nevertheless, the polymeric rings in the structure represent a real valuable advantage since they confine, align, and stabilize the LC material, thus preserving the radial alignment even when the device is used with high-power lasers.[26]

We illuminated the polshape with a LCP polarized Gaussian beam obtained by adjusting the QWP at −45° with the vertical axis. This generated a diverging CVB, which we could image on a camera by using a lens. By placing the camera at the focal plane of the lens, we recorded the beam profile shown in Fig. 4(a). We then proceeded to measure the components of the beam along various linear polarizations by placing the analyzer before the camera at different angles, i.e., 0°, 45°, 90°, and 135° (Figs. 4(b)–4(e), the analyzer axis direction is shown by the white arrow in each panel). We

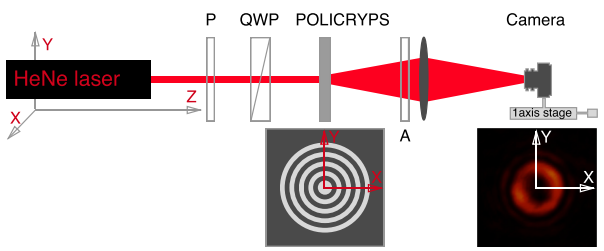


FIG. 3. Setup employed to generate CVBs using the POLICRYPS polshape. It includes a He-Ne laser source (633 nm), a linear polarizer (P), a quarter-wave plate (QWP), a POLICRYPS polshape, a lens, another (removable) polarizer (A), and a camera mounted on a *z*-axis translation stage.

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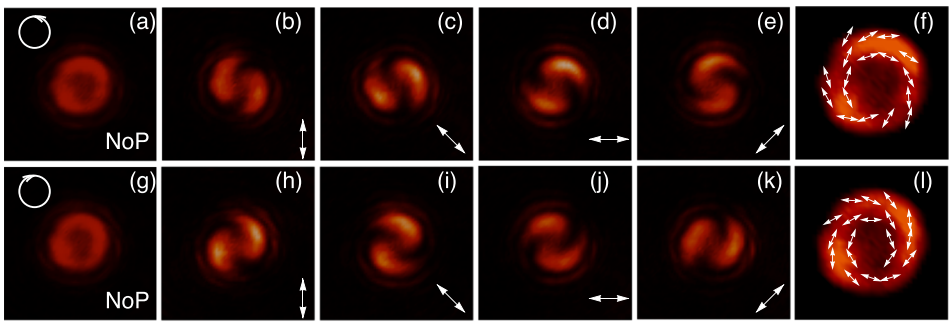


FIG. 4. CVBs generated using a POLICRYPS polshape illuminated with (a)–(f) a LCP Gaussian beam and (g)–(l) a RCP Gaussian beam. (a) and (g) The resulting beams emerging from the polshape, focused by the lens and imaged by the camera (see setup in Fig. 3). (b)–(e) and (h)–(k) The beams after an analyzer (i.e., a linear polarizer) oriented along the direction of the arrow. (f) and (l) The polarization states measured using Stokes parameters.

finally used this information to infer the local (i.e., as a function of the coordinates over the beam profile) Stokes parameters[28,29] I, Q, U, and V, which completely describe the polarization state of a harmonic electromagnetic field. In fact, the polarization ellipse which characterizes a generic harmonic electric field can be written as

$$I^2 = Q^2 + U^2 + V^2, \tag{3}$$

where the Stokes parameters can be expressed in terms of the field components as

$$\begin{cases} I = E_{0x}^2 + E_{0y}^2 \\ Q = E_{0x}^2 - E_{0y}^2 \\ U = 2E_{0x}E_{0y}\cos(\delta) \\ V = 2E_{0x}E_{0y}\sin(\delta) \end{cases}$$

where E_{0x} and E_{0y} are the amplitudes of the x- and y-components of the field, and δ is their phase difference. These parameters can be represented as a linear combination of the intensity values measured with the analyzer set at orthogonal polarizations, i.e.,

$$\begin{cases} I = I_0 + I_{90} \\ Q = I_0 - I_{90} \\ U = I_{45} - I_{135} \\ V = I_{\mathrm{RCP}} - I_{\mathrm{LCP}}, \end{cases}$$

where I_0, I_{45}, I_{90}, and I_{135} represent the measured intensity at each point for linear polarization of the analyzer at 0°, 45°, 90°, and 135°, respectively (Figs. 4(b)–4(e)), and I_{RCP} and I_{LCP} the intensity measured by using a QWP instead of the analyzer set at −45° and +45°, respectively. The polarization angle of the beam is finally given by $\frac{1}{2}\arctan(U/Q)$ and shown in Fig. 4(f). The resulting intensity and polarization show a cylindrical symmetry permitting us to identify this beam as a hybrid CVB (Fig. 1(c)). This hybrid CVB is the result of the superposition of the radially polarized CVB diffracted by the POLICRYPS polshape with the undiffracted illuminating Gaussian beam transmitted through the

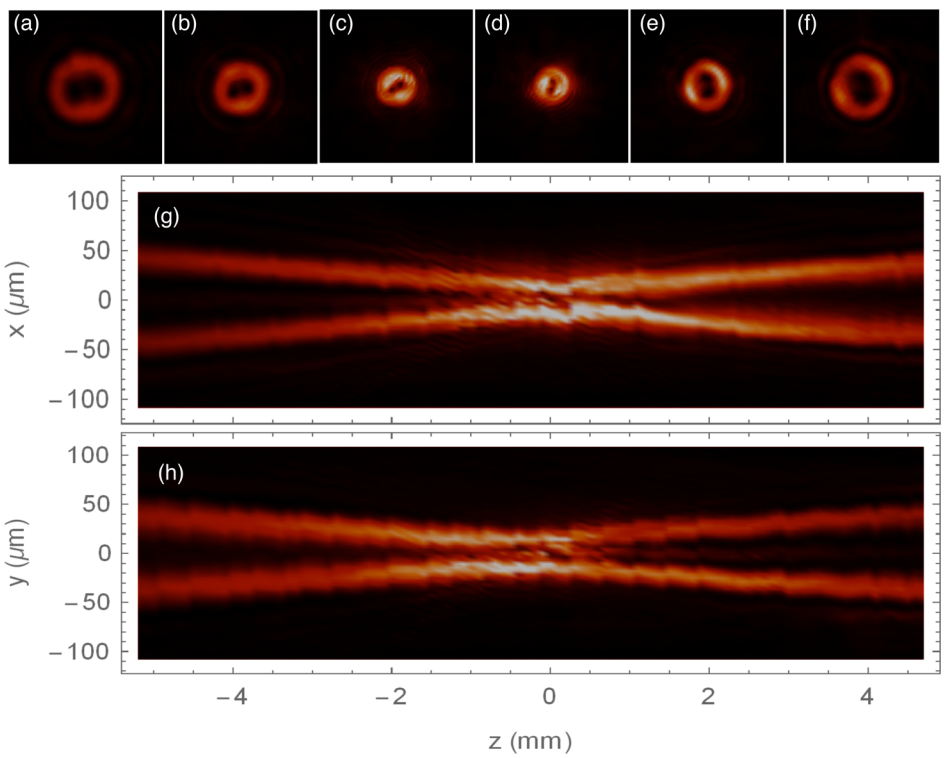


FIG. 5. Propagation of the CVB generated by the POLICRYPS polshape. (a)–(f) Transverse beam profiles in the xy-plane at $z = -25$, -15, -5, 5, 15, and 25 μm from the focal plane of the lens (see reference system in Fig. 3). (g) and (h) beam profiles in the xz ($y = 0$) and yz ($x = 0$) planes.

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polshape. Similarly, when we illuminated the POLICRYPS polshape with a RCP Gaussian beam (obtained by adjusting the QWP at +45° with the vertical axis), we generated another hybrid CVB with the same intensity profile, but different polarization (Figs. 4(g)–4(l)).

Fig. 5 shows that the transversal intensity profile of the CVB generated by the POLICRYPS polshape is donut-shaped for a quite long path, i.e., at least for ±10 mm around the focal plane of the lens. This measurement was performed by translating the camera (fixed on a single-axis translation stage) along the *z*-direction and acquiring transversal images of the beam profile at 10 μm steps.

In conclusion, a cost-effective device has been realized that can locally modify the state of polarization of an incoming beam. This has been achieved by fabricating a birefringent (LC) plate with a specific (radial) orientation of the optical axis. This device allows the conversion of a (left or right) circularly polarized beam into a hybrid CVB. This beam can be further transformed into a pure radial or azimuthal CVB using two half-wave plates.[11,12] The generated CVB has been experimentally studied by characterizing its polarization and intensity profiles. We remark that the realized sample represents only one of the possible examples of active devices that can locally influence the state of polarization of a light beam. Moreover, considering that the birefringency of the LC material is electrically tunable, application of an external electric field to the device can turn the POLICRYPS polshape into an active device: the polarization shaping ability of the device can be easily controlled by a knob, up to the point of being modified in real-time or completely switched off at will. Experiments of these kinds are at present ongoing, and the results of the possibilities we are actually exploring will be soon available.

This work has been possible thanks to two short term scientific missions supported by COST Action IC1208. S.P. was supported by Tübitak Grant No. 113Z556. G.V. acknowledges funding from Marie Curie Career Integration Grant (MC-CIG) PCIG11GA-2012-321726 and a Distinguished Young Scientist award of the Turkish Academy of Sciences (TÜBA).

[1]N. Tabirian, in *11th Workshop, Novel Optical Materials and Applications* (Cetraro, Italy, 2013).
[2]D. G. Hall, Opt. Lett. **21**, 9 (1996).
[3]Q. Zhan, Adv. Opt. Photonics **1**, 1 (2009).
[4]Q. Zhan and J. Leger, Opt. Express **10**, 324 (2002).
[5]Q. Zhan, J. Opt. A: Pure Appl. Opt. **5**, 229 (2003).
[6]S. Quabis, R. Dorn, M. Eberler, O. Gackl, and G. Leuchs, Opt. Commun. **179**, 1 (2000).
[7]R. Dorn, S. Quabis, and G. Leuchs, Phys. Rev. Lett. **91**, 233901 (2003).
[8]P. H. Jones, O. M. Maragó, and G. Volpe, *Optical Tweezers: Principles and Applications* (Cambridge University Press, 2015).
[9]Q. Zhan, Opt. Express **12**, 3377 (2004).
[10]Q. Zhan, Proc. SPIE **5514**, 275 (2004).
[11]Q. Zhan and J. R. Leger, Appl. Opt. **41**, 4630 (2002).
[12]G. Volpe and D. Petrov, Opt. Commun. **237**, 89 (2004).
[13]S. C. Tidwell, D. H. Ford, and W. D. Kimura, Appl. Opt. **29**, 2234 (1990).
[14]T. Erdogan, O. King, G. W. Wicks, D. G. Hall, E. H. Anderson, and M. J. Rooks, Appl. Phys. Lett. **60**, 1921 (1992).
[15]M. Stalder and M. Schadt, Opt. Lett. **21**, 1948 (1996).
[16]R. Oron, S. Blit, N. Davidson, A. A. Friesem, Z. Bomzon, and E. Hasman, Appl. Phys. Lett. **77**, 3322 (2000).
[17]T. Grosjean, D. Courjon, and M. Spajer, Opt. Commun. **203**, 1 (2002).
[18]Z. Bomzon, G. Biener, V. Kleiner, and E. Hasman, Opt. Lett. **27**, 285 (2002).
[19]Y. Kozawa and S. Sato, Opt. Lett. **30**, 3063 (2005).
[20]V. G. Niziev, R. S. Chang, and A. V. Nesterov, Appl. Opt. **45**, 8393 (2006).
[21]R. Caputo, L. De Sio, A. Veltri, C. Umeton, and A. V. Sukhov, Opt. Lett. **29**, 1261 (2004).
[22]M. Infusino, A. Ferraro, A. De Luca, R. Caputo, and C. Umeton, J. Opt. Soc. Am. B **29**, 3170 (2012).
[23]L. De Sio, A. Veltri, R. Caputo, A. De Luca, G. Strangi, R. Bartolino, and C. P. Umeton, Liq. Cryst. Rev. **1**, 2 (2013).
[24]D. Alj, R. Caputo, and C. Umeton, Opt. Lett. **39**, 6201 (2014).
[25]A. Marino, F. Vita, V. Tkachenko, R. Caputo, C. Umeton, A. Veltri, and G. Abbate, Eur. Phys. J. E **15**, 47 (2004).
[26]L. D. Sio, N. Tabiryan, R. Caputo, A. Veltri, and C. Umeton, Opt. Express **16**, 7619 (2008).
[27]R. Caputo, I. Trebisacce, L. De Sio, and C. Umeton, Opt. Express **18**, 5776 (2010).
[28]G. G. Stokes, Trans. Cambridge Philos. Soc. **9**, 399 (1852).
[29]M. Born and E. Wolf, *Principles of Optics* (Cambridge University Press, 1988).

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