APPLIED PHYSICS LETTERS **98**, 201101 (2011)

Radially polarized optical vortex converter created by femtosecond laser nanostructuring of glass

Martynas Beresna,[1,a] Mindaugas Gecevičius,[1] Peter G. Kazansky,[1] and Titas Gertus[2]
[1]*Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom*
[2]*Altechna Co. Ltd, Konstitucijos 23C, LT-08105 Vilnius, Lithuania*

(Received 11 January 2011; accepted 27 March 2011; published online 16 May 2011)

We demonstrate the generation of optical vortices with radial or azimuthal polarization using a space variant polarization converter, fabricated by femtosecond laser writing of self-assembled nanostructures in silica glass. Manipulation of the induced form birefringence is achieved by controlling writing parameters, in particular, the polarization azimuth of the writing beam. The fabricated converter allows switching from radial to azimuthal polarization by controlling the handedness of incident circular polarization. © *2011 American Institute of Physics*. [doi:10.1063/1.3590716]

Beams with radial or azimuthal polarization attract significant interest due to unique optical properties associated with their inherent symmetry. Such beams enable resolution below the diffraction limit[1] and interact without the undesirable anisotropy produced by linearly polarized light.[2] The large longitudinal electric field component of these beams is attractive for applications, such as particle acceleration.[3] Several methods have been proposed for the generation of space variant polarized beams, including birefringence manipulation with liquid crystals[4,5] and polarization selection inside a laser resonator.[6] However, the low damage threshold restricts the application of liquid crystal based beam converters. Alternatively, it has been demonstrated that the polarization can be manipulated by the form birefringence associated with the subwavelength gratings.[7] It has been also observed that the space variant phase produced by these converters can create a polarization vortex,[8] i.e., the beam with the orbital angular momentum, where its sign depends on the handedness of incident circular polarization.[9] Photolithography, which is usually used for fabrication of such structures has a limiting resolution that restricts the wavelength of operation to the far infrared. In this respect the femtosecond laser direct writing is an attractive alternative due to the possibility of energy deposition within the focal volume with a resolution of more than hundred nanometres.[10] Depending on the amount of deposited energy three distinctive types of modifications can be induced in the bulk of transparent materials. In particular, moderate fluencies result in the spontaneous formation of nanogratings,[11–13] which produce a form birefringence, referred as type 2 modification, with the slow and fast optical axes aligned, respectively, parallel and perpendicular to the grating corrugation.[14] The femtosecond laser self-assembly of nanostructures in fused silica offers a flexible and simple alternative for fabrication of polarization sensitive devices for the visible spectral range.[15–17] In this letter we demonstrate a polarization vortex converter, which produces radially or azimuthally polarized visible vortices from a circularly polarized beam, using femtosecond laser imprinting of space-variant self-assembled form birefringence in silica glass.

Polarization converters can be designed for incident beams with linear or circular polarization. For the incident linearly polarized beam, a half-wave plate with continuously varying slow axis direction has to be constructed, which rotates the incident linear polarization by the angle necessary to produce a radial distribution of the electric field. For the incident circular-polarized beam, the radial or azimuthal polarization can be formed with a space variant quarter-wave plate possessing a radial symmetry [Fig. 1(a)], which can be described using Jones calculus with the following matrix:

$$\begin{pmatrix} \cos^2\theta + i\sin^2\theta & (1-i)\cos\theta\sin\theta \\ (1-i)\cos\theta\sin\theta & i\cos^2\theta + \sin^2\theta \end{pmatrix},$$

where angle $\theta = \phi + \pi/4$ and ϕ is a polar angle. Multiplying a vector describing the left handed circular polarization by this matrix the following expression is derived:

$$\begin{pmatrix} \cos^2\theta + i\sin^2\theta & (1-i)\cos\theta\sin\theta \\ (1-i)\cos\theta\sin\theta & i\cos^2\theta + \sin^2\theta \end{pmatrix} \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ i \end{pmatrix} = \begin{pmatrix} -\sin\phi \\ \cos\phi \end{pmatrix} e^{i\phi} e^{i\pi/4}.$$

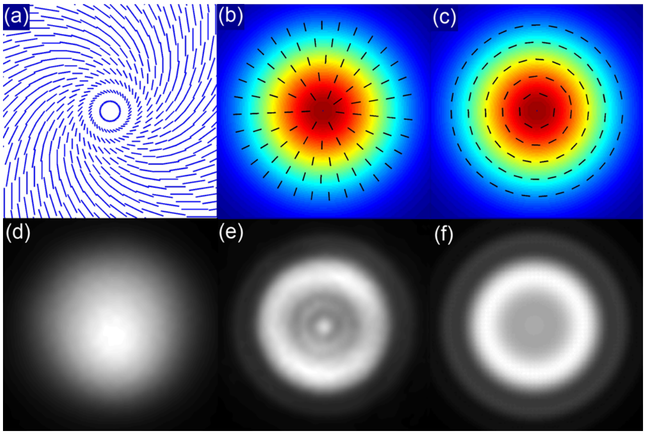

FIG. 1. (Color online) (a) Schematic drawing of nanograting distribution in polarization converter. [(b) and (c)] Distribution of the electric field for left-hand and right-hand circularly (see white circles) polarized beam after passing through the polarization converter. [(d) and e)] Measured beam profiles of argon ion cw laser before and after beam converter. (f) Modeled beam profile after beam converter.

---

[a] Electronic mail: mxb@orc.soton.ac.uk.

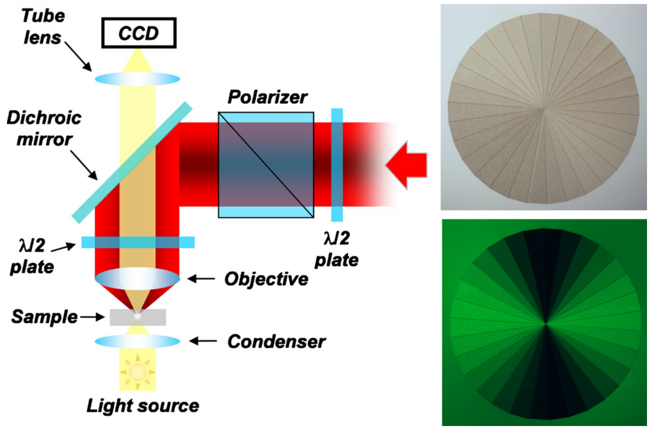

FIG. 2. (Color online) (Left) The setup for femtosecond laser direct writing. (Right) Microscope images of the polarization converter in the bright field and crossed polarizers. The diameter of the circle is 1.2 mm. The radial lines emerging from the center of the structure are due to finite step size in the writing process, which results in the visible segmentation of the structure.

Neglecting constant phase shift $\pi/4$ we see that the resultant electric field possess the azimuthal orientation and the orbital angular momentum $l=1$, as is indicated by the exponent with the complex argument. If the vector of the right handed circular polarization is treated by this Jones matrix, then one would obtain the radial polarization with the orbital angular momentum $l=-1$. Thus the space variant phase of the converter produces a polarization vortex beam with the orbital angular momentum, where its sign is controlled with the handedness of the incident circular polarization. Furthermore, depending on the handedness of the incident circular polarization, the radial or azimuthal polarization can be obtained with the same birefringent element [Figs. 1(b) and 1(c)].

The advantage of the quarter-wave plate based converter over the half-wave plate one is a considerably smaller retardance value, $R=\Delta n d$ for a given induced birefringence Δn and length of structure d, which is needed for the polarization conversion, e. g. $R \approx 130$ nm for 532 nm wavelength.

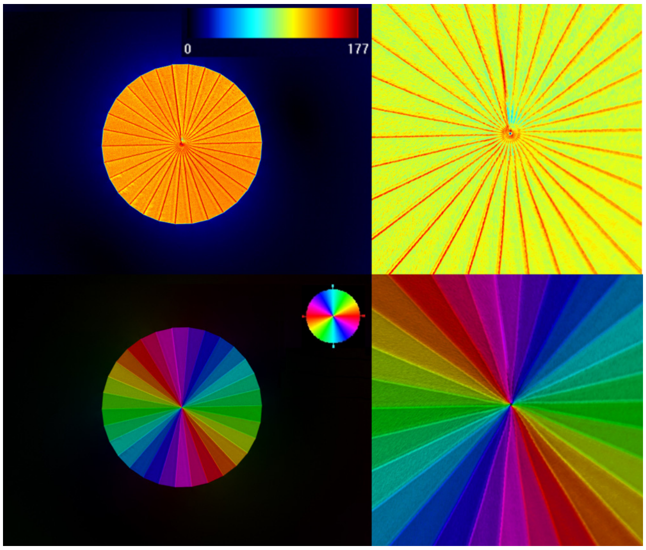

FIG. 3. (Color online) Birefringence characterization of the structure performed with the Abrio system. The top images represent retardance value distribution with 5× (left) and 20× (right) magnification of the structure. The bottom images represent the color-coded distribution of slow axis.

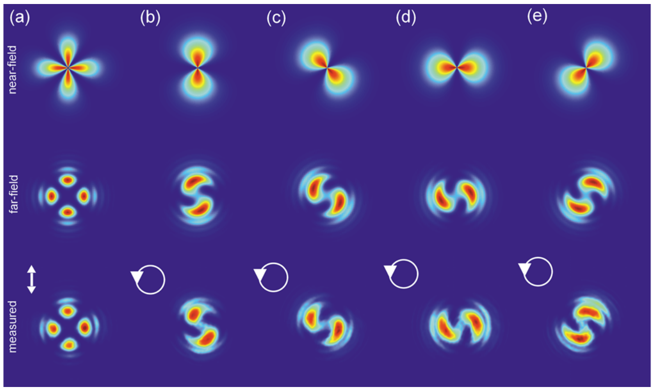

FIG. 4. (Color online) Modeled near and far-field (top and middle) and measured (bottom) intensity distributions after the polarization converter for incident linear polarization (a) and for left handed circular polarization (i.e., azimuthal polarization with the orbital angular momentum $l=1$ is generated) at different angles of polarizer 0° (b), 45° (c), 90° (d), 135° (e). White arrows indicate incident polarization state.

The experiments were performed using a mode-locked regenerative amplified Yb:KGW (Yb-doped potassium gadolinium tungstate) based femtosecond laser system PHAROS (Light Conversion Ltd.), operated at a wavelength of 1030 nm with a pulse duration of 270 fs and repetition rates up to 500 kHz (Fig. 2). A relatively low numerical aperture (NA) objective (Nachet, 20×, NA=0.35) was chosen for the fabrication, since the retardance value increases with the structure length, which is longer for lower NA objectives yielding a longer Rayleigh length. In the experiments we achieved the retardance as high as $R=260$ nm, which was sufficient for the fabrication of polarization converters working in the visible and near infrared. The optimum values for the pulse energy, repetition rate, and writing speed required to achieve the desired quarter-wave retardance at 532 nm wavelength, were found to be 0.5 μJ, 200 kHz, and 1 mm/s, respectively. The laser beam was focused 200 μm below the surface of a 2 mm thick fused silica sample, which was mounted onto XYZ linear air-bearing translation stage system (Aerotech Ltd.). The stages were computer controlled via SCA software (Altechna Ltd.) to move in a spiral trajectory with steps of 1 μm, enabling in a complete scan to cover uniformly a circular area of 1.2 mm diameter in about 1.5 h (Fig. 2). The laser beam polarization azimuth was manipulated by an achromatic half-wave plate mounted on a motorized rotation stage. By controlling the angle of the half-wave plate and XY stage position we could fabricate a space-variant quarter wave plate with the desired geometry of anisotropic modification distribution (Fig. 2).

The fabricated birefringent element was analyzed with a quantitative birefringence measurement system (CRi Abrio imaging system) and Olympus BX51 optical microscope. To verify the presence of radial polarization, the converter was illuminated with a circularly polarized green beam and imaged under a microscope with linear polarizer (analyzer) inserted at the output. The propeller shape typical for the radial or azimuthal polarization was clearly observed, confirming the successful implementation of the polarization converter (Fig. 2). The birefringence measurements confirmed that the constant value of retardance with a continuously varying direction of the slow axis was achieved (Fig. 3).

The polarization converter was also tested with 532 nm second harmonic from a continuous-wave (cw) Nd:YAG la-

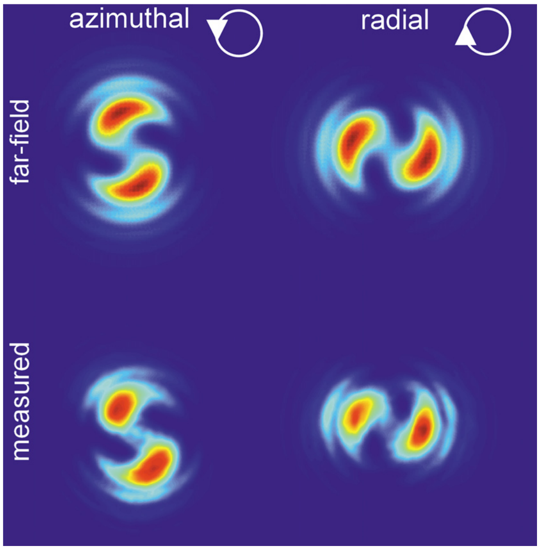

FIG. 5. (Color online) Modeled and measured far-field patterns of optical vortices with azimuthal and radial polarization at 532 nm and the same (horizontal) orientation of linear analyzer. White arrows indicate incident polarization state.

ser [Fig. 1(d)]. The linear polarization of the laser beam was converted into circular with a quarter wave plate, then focused onto the polarization converter with 50 mm focal length plano-convex lens [Fig. 1(e)], and finally projected through the linear polarizer onto a charge coupled device camera. For comparison the optical test system was modeled using the algorithm based on Jones matrix formalism described above and Fourier propagation. In both cases the propeller shape typical for the circular polarization can be clearly observed (Fig. 4). In the far-field the diffraction distorts this shape producing a typical "*s*" shape pattern, although it can be restored in the near-field by focusing the beam again. The appearance of a *s* shape pattern, which is typical for double charged optical vortices, can be explained as follows. An azimuthally (radially) polarized vortex with the orbital angular momentum $l=1$ ($l=-1$) can be considered as a superposition of two circularly polarized beams, one possessing the orbital angular momentum $l=2$ ($l=-2$), and the other with a plane front.[8] The interference of these two beams after the polarizer (analyzer) produces a characteristic *s* shape pattern, which was observed in our experiment (Fig. 4). The observed pattern indicates also the presence of a phase discontinuity as it was confirmed by the modeling. Moreover, the theoretical prediction of the dependence of orbital momentum sign on the sense of incident circular polarization was also experimentally confirmed by comparing the far-field images of radially and azimuthally polarized beams produced by incident left and right circular polarizations (Fig. 5). The sense and the orientation of the *s* shape were changing with the handedness of circular polarization. The transmission of the element at 532 nm wavelength was estimated about 70%. The losses are attributed to the microscopic inhomogeneities and induced defect absorption, which could be reduced by optimizing the writing parameters.

In summary, by exploiting the ability of femtosecond lasers to create subwavelength anisotropic modifications inside silica glass, a polarization vortex converter, operating in the visible is demonstrated. A significant advantage of the technique is the possibility of achieving radial or azimuthal polarizations with a single optical element, simply by controlling the handedness of the incident circular polarization.

The work was supported by the Engineering and Physical Sciences Research Council (EPSRC Project No. EP/E034802/1) and the project FEMTOPRINT, financed by the European Commission Factories of the Future program (FP7/NMP/Project No 260103), http://www.femtoprint.eu/.

[1] R. Dorn, S. Quabis, and G. Leuchs, Phys. Rev. Lett. **91**, 233901 (2003).
[2] V. G. Niziev and A. V. Nesterov, J. Phys. D **32**, 1455 (1999).
[3] Y. Liu, D. Cline, and P. He, Nucl. Instrum. Methods Phys. Res. A **424**, 296 (1999).
[4] J. A. Davis, D. E. McNamara, D. M. Cottrell, and T. Sonehara, Appl. Opt. **39**, 1549 (2000).
[5] R. Yamaguchi, T. Nose, and S. Sato, Jpn. J. Appl. Phys., Part 1 **28**, 1730 (1989).
[6] D. Pohl, Appl. Phys. Lett. **20**, 266 (1972).
[7] F. Xu, R. C. Tyan, P. C. Sun, Y. Fainman, C. C. Cheng, and A. Scherer, Opt. Lett. **20**, 2457 (1995).
[8] Z. Bomzon, V. Kleiner, and E. Hasman, Appl. Phys. Lett. **79**, 1587 (2001).
[9] M. Beresna, P. G. Kazansky, Y. Svirko, M. Barkauskas, and R. Danielius, Appl. Phys. Lett. **95**, 121502 (2009).
[10] R. R. Gattass and E. Mazur, Nat. Photonics **2**, 219 (2008).
[11] Y. Shimotsuma, P. G. Kazansky, J. R. Qiu, and K. Hirao, Phys. Rev. Lett. **91**, 247405 (2003).
[12] V. R. Bhardwaj, E. Simova, P. P. Rajeev, C. Hnatovsky, R. S. Taylor, D. M. Rayner, and P. B. Corkum, Phys. Rev. Lett. **96**, 057404 (2006).
[13] Y. Bellouard, E. Barthel, A. Said, M. Dugan, and P. Bado, Opt. Express **16**, 19520 (2008).
[14] E. Bricchi, B. G. Klappauf, and P. G. Kazansky, Opt. Lett. **29**, 119 (2004).
[15] E. Bricchi, J. D. Mills, P. G. Kazansky, B. G. Klappauf, and J. J. Baumberg, Opt. Lett. **27**, 2200 (2002).
[16] W. J. Cai, A. R. Libertun, and R. Piestun, Opt. Express **14**, 3785 (2006).
[17] M. Beresna and P. G. Kazansky, Opt. Lett. **35**, 1662 (2010).