

Structuring light sorter based on a cylindrically anisotropic spherulite prism

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Abstract. Structured light plays an important role in modern optical technologies, such as the high capacity communication and particle manipulation. In this paper, we design and experimentally demonstrate a patterned wedge-shaped liquid crystal prism, which is capable of sorting structured light of different vector polarizations and orbital angular momenta from a circularly polarized light. Mimicking the design of the metamaterials, the molecules inside the liquid crystal are intensively aligned azimuthally to form a spherulite with cylindrically anisotropic optical indices. Together with the wedged shape, a circularly polarized beam transmitting through the prism may experience a strong birefringence and is thus sorted into two optical vortex beams with radial and azimuthal polarizations. These results contribute to the advanced complex light manipulation, paving the way to realize the simultaneous control of light's polarization and orbital angular momentum in a compact and efficient way.

Keywords: Structured light / spherulite prism / cylindrical anisotropy

1 Introduction

The generation of the structured lights with complicated polarization states and phase distributions has attracted intense attention [1–13], for the promising applications in the next-generation optical communication [14,15] and optical manipulation [16,17]. Information can be encoded into the either the various polarization states or the topological charges of the orbital angular momentum (OAM), which can greatly enlarge the capacity and the security in the optical communication systems [18,19]. Therefore, the ability of demultiplexing the modes and thus decoding the information from the structured light is highly demanded [20]. Traditional ways of sorting vortex are always bulky and complex [21,22]. The emergence of metamaterials or metasurfaces with the artificially designed structures that can be used to achieve various phase or polarization modulation ability makes devices ultra-compact and highly integrated [23–25]. However, fabrication is always highly costed, especially in the visible range. Meanwhile, the approachable meta-atom size from the current nanofabrications is still the main reason of the

scattering loss [26–29]. The idea of structuring real atoms or molecules into certain orders can also bring metamaterials' properties to natural materials such as natural hyperbolic materials with indefinite dielectric tensor [30,31] and the spherulite crystals with cylindrical anisotropy [32–34]. Since these materials are homogenous at the atom/molecule level, fabrication challenges and scattering losses can be avoided. Here, by mimicking metamaterials, we designed and fabricated a spherulite prism with azimuthally patterned liquid crystals (LC) that can act as a vector vortices sorter. A cylindrical birefringence originated from the azimuthally arranged molecules separates the radially and azimuthally polarized vortex beams from the incident circularly polarized beam. The designed device of the wedge-like spherulite prism contributes to the advanced complex light manipulation techniques, paving the way to realize the simultaneous control of the polarizations and OAM of light in a compact and efficient way.

2 Design

Here, the spherulite with cylindrically anisotropic refraction indices is designed into a wedge-shaped prism by using the nematic LC (4'-pentyl[1,1'-biphenyl]-4-carbonitrile, 5CB). The 5CB molecule is intrinsically anisotropic with its refractive index (n_e) along the longer axis larger than that (n_o) along the short axis, as shown in Figure 1. Once

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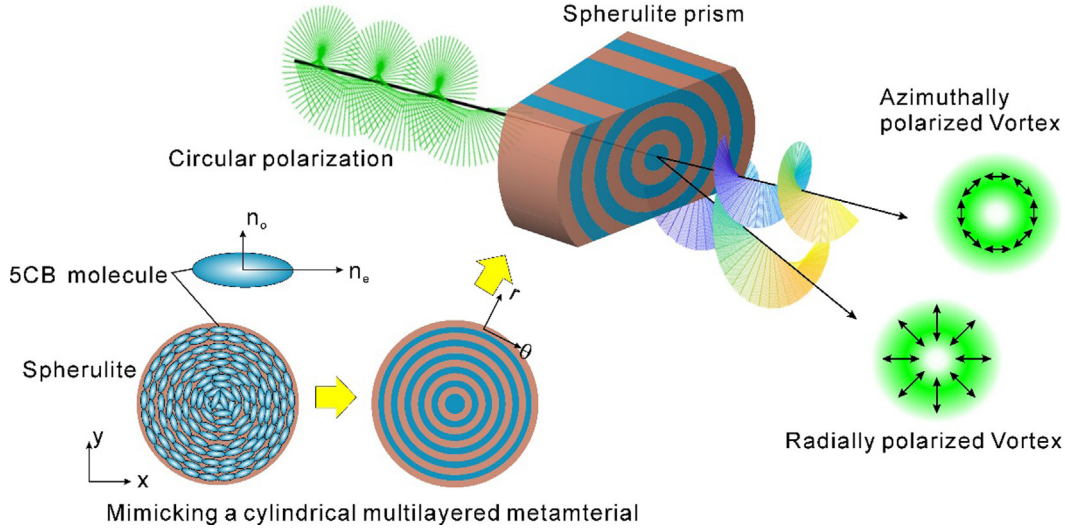


Fig. 1. The schematic of spherulite prism working as a structured light sorter. The 5CB molecule is optically anisotropic with its refractive index n_e along the longer axis and n_o along the short axis. The spherulite is constructed by these molecules with the longitudinal axis along the azimuthal direction of the material, exhibiting the cylindrical anisotropy: $n_A = n_e$ and $n_R = n_o$, which is mimicking the metamaterials consisted of concentric multi-layered structure. Such a spherulite is cut into a prism and can be used to sort two optical vector vortices with radial and azimuthal polarizations from a circularly polarized beam.

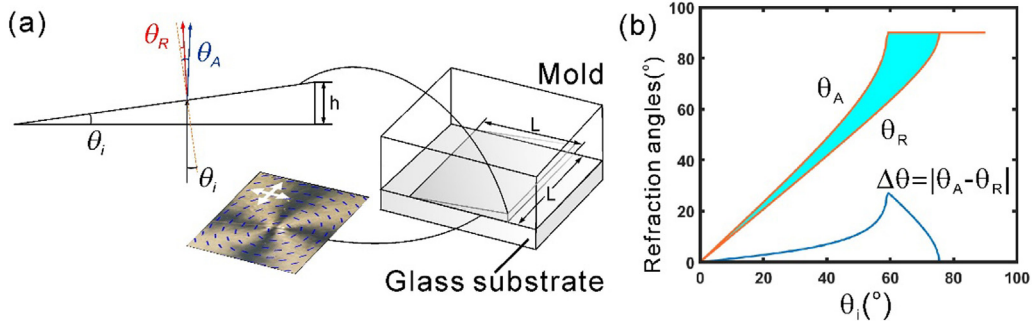


Fig. 2. Wedge-shape cell to form the spherulite prism. (a) The schematic diagram of the prism. The dimension of the wedge-shape is 20×20 mm side (L) by side (L) and with a height (h) of 1.75 mm, which forms an oblique surface of 5° . (b) The refraction angles of the two polarizations at different incident angles.

these molecules are constructed into a spherulite with the longitudinal axis along the azimuthal direction of the material, the formed spherulite may show cylindrically anisotropic indices with $n_A = n_e$ and $n_R = n_o$, which is mimicking the metamaterials consisted of concentric multi-layered structure. If such a spherulite is cut into a prism, cylindrical vector beams passing through the prism experience the cylindrical anisotropy and are thus refracted to two different directions. A left or right circularly polarized beam can be decomposed into radial and azimuthal components, i.e., $\mathbf{e}_r$ and $\mathbf{e}_\theta$ in equation (1) [35]:

$$\begin{aligned} E_L e^{il\theta} &= \frac{P(r)(e_r + ie_\theta)e^{i(l+1)\theta}}{\sqrt{2}}, \\ E_R e^{il\theta} &= \frac{P(r)(e_r - ie_\theta)e^{i(l-1)\theta}}{\sqrt{2}}, \end{aligned} \quad (1)$$

where $P(r)$ and θ are the amplitude profile and the azimuthal angle in the transverse plane of the incident

beam. The topological charge l is used to characterize beams' OAM. $\mathbf{e}_r$ and $\mathbf{e}_\theta$ are the unit-vectors at the radial and azimuthal directions. Consequently, once a circularly polarized beam is incident onto such a prism, two OAM beams of the radial and azimuthal polarizations can be obtained due to the different refraction angles, as shown in Figure 1. The acquired output beams contain topological charge of either $+1$ or -1 depending on the chirality of the input circular polarization.

3 Experiment

The spherulite prism is formed by injecting the 5CB LC into a wedged shape cell, as shown in Figure 2. The top part is a glass mold of 20×20 mm side by side and an oblique surface of 5° , and is then put on a glass substrate. Both the top and below surfaces are spin-coated with a 30 nm

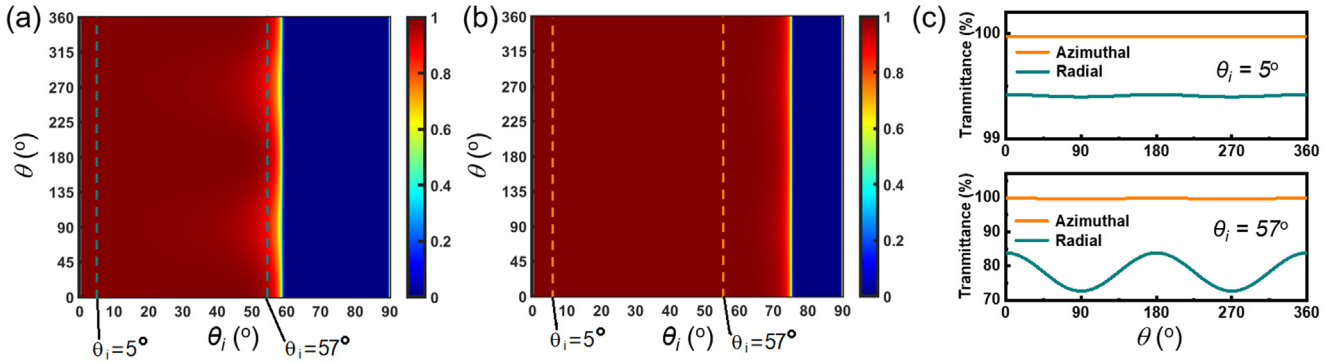


Fig. 3. Intensity distortion due to the refraction. (a) The dependence of the azimuthally polarized output beam intensity distribution along the azimuthal direction θ with respect to different incidence angle θ_i . (b) The dependence of the radially polarized output beam intensity distribution along the azimuthal direction θ with respect to different incidence angle θ_i . (c) Intensity variations of output beams at incident angles of 5° (the upper panel) extracted from the (a) and (b) along the left dashed lines and the intensity variations of output beams at incident angles of 57° , which is a little below the critical angle (the lower panel) extracted along the right dashed lines in (a) and (b).

thick layer of photoalignment agent (sulfonic azo dye, sodium 4,4'-bis (4-hydroxy-3-carboxy-phenylazo) benzidine-2,2'-disulphonate, SD1) for the molecular arrangement. Subsequently, the light irradiation on the SD1 layer is carried out by using a radially polarized vortex laser at 405 nm for 15 min to supply the photo-alignment, which is used in turn to align the molecules azimuthally. Under the polarized optical microscope, the illuminating white light is linearly polarized. After the sample, we put a linear polarizer with its transmittance direction perpendicular to the linear polarization of the incidence. Then we can see the Maltese dark cross, which is the signature of the cylindrical anisotropy [36,37].

A circularly polarized beam at 532 nm is incident on to the prism from the substrate side normally, which means the incident angle θ_i at the top oblique surface is 5° . The anisotropic refractive indices of the 5CB LC are $n_o = 1.55$ and $n_e = 1.75$ along the short and long-axis of the molecule [38], respectively. In our case, the n_o and n_e are corresponding to indices along the radial and azimuthal directions of the spherulite. Based on Snell's law, we calculate the refraction angle of the beams at radial (θ_R) and azimuthal polarization (θ_A) as below:

$$\sin \theta_R = \frac{n_0 \sin \theta_i}{n_g}, \sin \theta_A = \frac{n_e \sin \theta_i}{n_g}, \quad (2)$$

where $n_g = 1.5$ is the refractive index of the glass.

The theoretical calculation results are shown in Figure 2b. The separation of the two beams in angle $\Delta\theta = |\theta_A - \theta_R|$ reaches to the maximum at 58° in Figure 3c. The horizontal line at $\theta = 90^\circ$ indicates the occurring of the total refraction of the two beams. In principle, a large separation means a high efficiency of the sorter. However, the refraction angle of θ_R and θ_A are also very large, which may bring in a serious deviation of the intensity distribution around the azimuthal angle θ and thus greatly affect the purity of the vortex beams. In the experiment, the incident angle θ_i is just 5° and the distortion to the intensity is almost negligible, as shown in Figure 3. It should be noted that the value of $\Delta\theta$ at the magnitude

of 1° is large enough to spatially split the two output beams of the orthogonal polarizations at the far field.

The output beams are characterized by a Mach–Zehnder interference setup, as shown in Figure 4. A linearly polarized laser beam at 532 nm is transformed into circular polarization by a quarter waveplate and then imported into the Mach–Zehnder interference setup by a beam splitter (BS). The spherulite prism sample is put in one arm of the Mach–Zehnder interference setup while the beam in the other arm is transformed into left or right circular polarization by using a linear polarizer (LP) and a quarter wave plate ($\lambda/4$ WP). After the sample, the circularly polarized incidence is split into two beams with radial and azimuthal polarizations. We extract either one of the two output beams which is realigned by the two mirrors (M1 and M2) and then interfered with the reference beam after the second BS. According to equation (1), we can obtain the expressions of the radial and azimuthal polarizations as:

$$\begin{aligned} e_r e^{il\theta} &= \frac{E_L e^{i(l-1)\theta} + E_R e^{i(l+1)\theta}}{P(r)\sqrt{2}}, \\ e_\theta e^{il\theta} &= \frac{E_L e^{i(l-1)\theta} - E_R e^{i(l+1)\theta}}{P(r)\sqrt{2}}, \end{aligned} \quad (3)$$

which imply that a radially or azimuthally polarized vortex beam with topological charge l is a superposition of right and left circularly polarized vortex beams with $l \pm 1$. Therefore, by rotating the quarter wave plate, we can use the reference beam with two opposite circular polarizations to detect the left or the right circular polarized components in the output structured light beams through the inference pattern and the results are shown in Figure 5.

4 Results and discussion

Figure 5a shows the output beam with a large refraction angle, whose intensity profile is in a doughnut shape with a dark center. After a linear polarizer, the doughnut is split

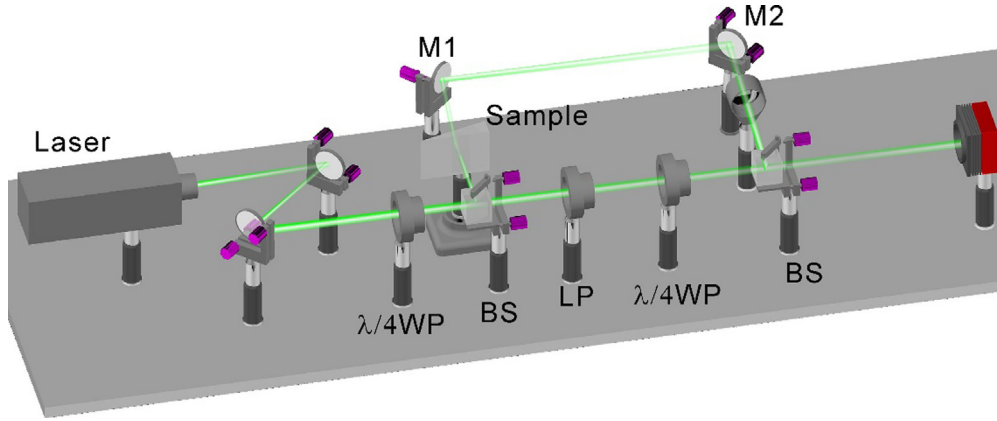


Fig. 4. The Mach–Zehnder interference setup used to characterize the output structured light beams.

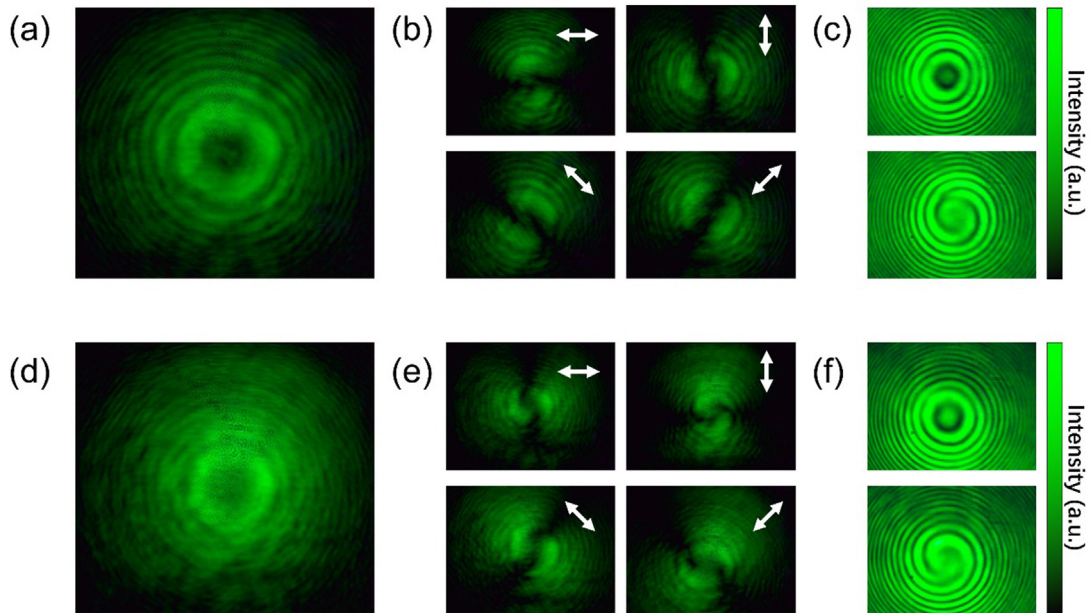


Fig. 5. Polarization characterizations and the OAM determination of the two output beams. (a) The doughnut-shaped intensity profile of the output beam with a large refraction angle. (b) Intensity profiles of the output beam after a rotating linear polarizer. (c) The interference pattern of the output beam and the reference of left/right circular polarization. (d) The doughnut-shaped intensity profile of the output beam with the small refraction angle. (e) Intensity profiles of the output beam after a rotating linear polarizer. (f) The interference pattern of the output beam and the reference of left/right circular polarization.

into two bright lobes. The central dark line is always along the polarizer when it is rotated, which proves the beam to be at the azimuthal polarization, as shown in Figure 5b. Figure 5c illustrates the interference patterns obtained by using left and right circularly polarized beams. The upper one shows no fork while the lower one shows a spiral fork with two times, which demonstrates the topological charge to be 1. Figure 5d shows the output beam with the small refraction angle, which is also in a doughnut shape. After a linear polarizer, the doughnut is split into two bright lobes while the central dark line is always normal to the polarizer when it is rotated, as shown in Figure 5e. Therefore, the polarization state of this beam is radial. In Figure 5f, the interference patterns of the radially polarized beam with the left and right circularly polarized beams show non fork

and a spiral fork of two times, which also demonstrates the topological charge of the radial polarization to be 1.

To further demonstrate the sorting performance, we used a right circularly polarized vortex beam with a topological charge $l=1$ as the incident beam. According to equation (1), the output beams are two non-OAM ($l-1=0$) beams at radial and azimuthal polarizations after the spherulite prism. Meanwhile, each non-OAM radial or azimuthal polarization contains left and right circular polarization components with ± 1 charge OAM. Therefore, the interference with left and right circularly polarized beams in each case show opposite one fold spiral patterns for both the two output beams, as shown in Figure 6. Accordingly, incident left or right circularly polarized beam with any l OAM can be separated into

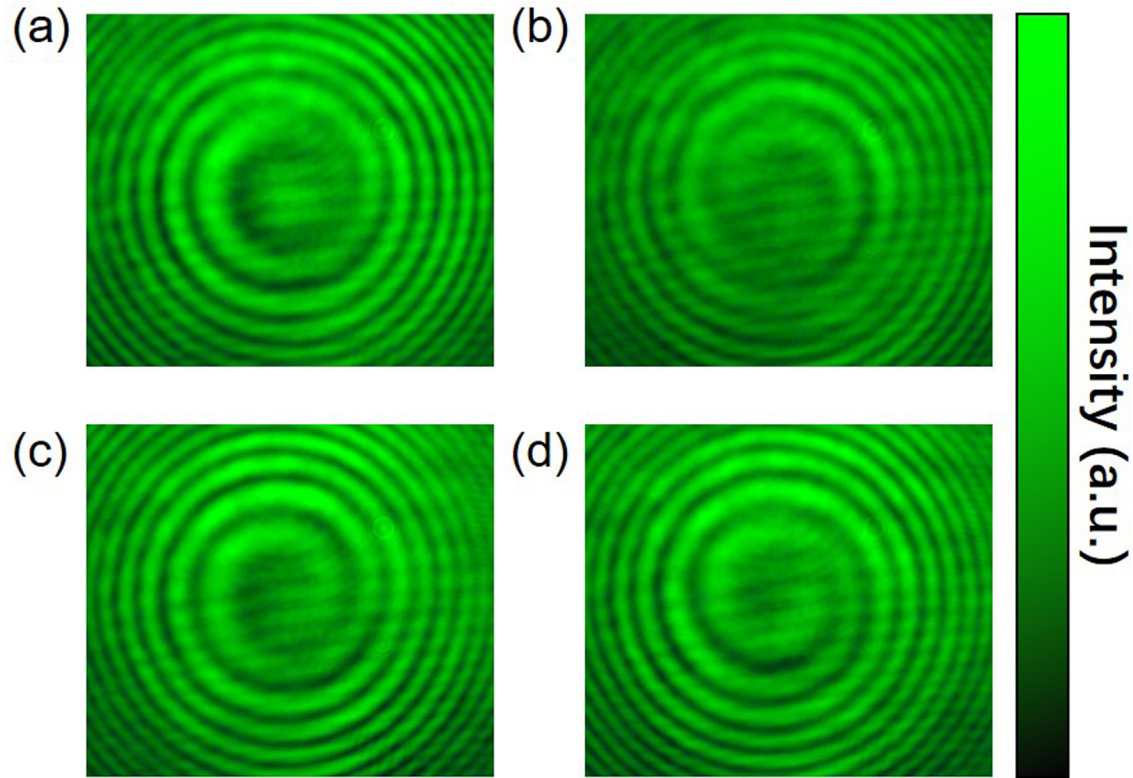


Fig. 6. The interference patterns of the output beams from a charge 1 circularly polarized beam interfered with the referenced beams of left/right circular polarizations. (a) The interference pattern of the output radial polarization and the reference of left circular polarization. (b) The interference pattern of the output radial polarization and the reference of right circular polarization. (c) The interference pattern of the output azimuthal polarization and the reference of left circular polarization. (d) The interference pattern of the output azimuthal polarization and the reference of right circular polarization.

two beams according to the cylindrical polarization states while with OAM $l+1$ and $l-1$. In addition to birefringence, the anisotropy also causes the spin-orbital angular momentum conversion, which provides the modulation ability to the topological charge.

5 Conclusion

In summary, we design and experimentally demonstrate a structured light sorter by using a spherulite prism consisted of 5CB molecules, which are azimuthally aligned to produce the cylindrical birefringence. In the experiment, a circularly polarized beam with or without OAM can be separated into two beams with radial and azimuthal polarization states at 532 nm. Since the optical vortex beams with helical wave fronts carry an orbital angular momentum with unlimited range of the topological charge, it provides an unbounded state space, and hence a large potential information capacity. Also, orbital angular momentum modes are the candidate for free-space quantum key distribution systems, where the ability to efficiently sort single photons based on their OAM mode number is very important. Therefore, the proposed device may find applications of the future high-capacity optical communications and quantum communications [39–45].

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Conflicts of Interest

The authors have no conflict of interest to disclose.

Data availability statement

This article has no associated data generated and/or analyzed / Data associated with this article cannot be disclosed due to legal/ethical/other reason.

Author contribution statement

Conceptualization, J.S.; Methodology, Y.L and L. Z.; Validation, Y.S., J.Z. and J.S.; Formal Analysis, Y.L.; Investigation, Y.L.; Resources, Y.L.; Data Curation, Y.L.; Writing – Original Draft Preparation, J.S. and Y.L.; Writing – Review & Editing, J.Z.; Visualization, Y.W.; Supervision, Y.S., J.Z. and J.S.; Funding Acquisition, J.S.

Supplementary material

Fig. S1. Comparison of the interferences with incident circularly polarized beam of non-OAM .

Fig. S2. Comparison of the interferences with incident circularly polarized vortex beam of charge 1.

The Supplementary Material is available at <https://epjam.edp-open.org/10.1051/epjam/2024004/olm>.

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