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CRYSTALLINE SANDWICH STRUCTURE FOR CONTROL OF MULTIPLE VORTEX BEAM. FOUR-CRYSTALS STRUCTURE

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Abstract. In this work, we experimentally and theoretically analyzed the conoscopic patterns produced by a sandwich crystalline system comprising four uniaxial lithium niobate (LN, $LiNbO_3$) crystals, two of which (external) are aligned along their optic axes (*Z*-cuts), with two *X*-cut LN crystals placed between them. Our results show that the conoscopic patterns calculated for linearly polarized incident light agree well with experimental observations. It has been found that conoscopic patterns consist of eight dark (or bright in the case of parallel polarizers) spots located around the center. As shown by polarimetric experiments, these dark spots correspond to eight pairs of polarization singularities with opposite signs and half-integer strength, which lead to the appearance of C-points in the outgoing optical field. These C-points can generate the single-charged OVs. In general, the maps of ellipticity angle and azimuth of polarization contain eight chains of such C-points that form an eight-armed "cross". If only one *Z*-oriented sample is left, the conoscopic pattern is represented by the four spots that are located between isogyres. At these spots, the four pairs of C-points are revealed experimentally. These pairs are topologically the same as in a four-crystal sandwich structure. However, in the case of one sample, the "cross" of the chains of polarization singularities has only four arms. It has been proved that the number of polarization singularities depends on the number and orientation of samples in the sandwich structure. Therefore, by changing the number of samples, one can control the number of optical vortices in the composite vortex beam.

Keywords: crystalline sandwich structure, optical vortex, optical vector beam, composite vortex beams, structured light, orbital angular momentum, anisotropic crystals, topological defect
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1. Introduction

Optical vortices (OVs), which represent physical objects in the optical field carrying orbital angular momentum (OAM), have been an intriguing area of study over the last few decades [1]. Interest in optical fields with phase-front singularities is driven by the application of OVs in new branches of technology, particularly high-capacity optical communications [2,3]. Using OAM encoding, it is possible to increase the information transmission rate to the hundred Gbit/s range [2]. The potential to encode and transmit information with multiple vortex beams has driven research in singular telecommunications [3,4]. Methods for generating multiple vortex beams and composite vortex beams (CVBs) have been developed and require advanced, costly technologies [5,6]. Therefore, we have aimed to consider a relatively simple technique for generating such beams using a subsequent set of solid crystals. In our recent work [7], we have shown that the propagation of the conical beam through a sandwich structure consisting of three $LiNbO_3$ (LN) crystals (1st and 3rd oriented along the optic axis, while the 2nd – along the *X* axis) leads to the appearance of a set of topological defects (TDs) of the so-called effective optical indicatrix orientation and

polarization singularities that have to generate a set of OVs. At the relatively small angular aperture, one can observe four pairs of such singularities. As the aperture increases, the number of such TDs increases with each additional interference conoscopic fringe. Notably, the appearance of four pairs of such polarization singularities has been demonstrated in Ref. [8] using only one crystalline sample and oblique propagation of the incident optical beam relative to the optic axis. Therefore, one can suppose that the number of crystals in the sandwich structure likely does not affect the number of polarization singularities in the outgoing optical field. In the present work, we will check this using a four-crystal sandwich structure. Moreover, the preliminary results of conoscopic patterns created by such a sandwich structure are known and were obtained by Prof. Orest G.Vlokh in 1962 [9] and published on the cover page of Ukr. J. Phys. Opt. (No. 1, 2000) (Fig. 1a).

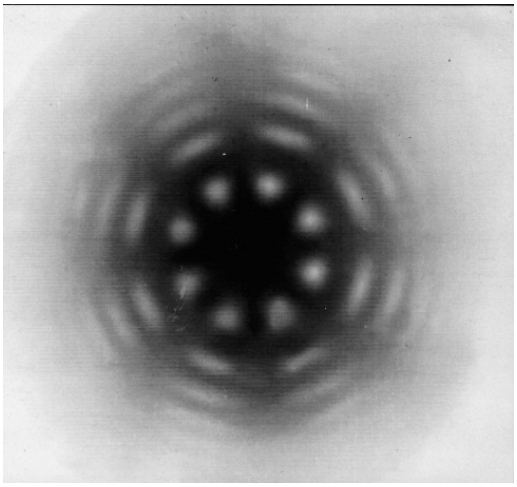


Fig. 1. Experimentally obtained conoscopic patterns in the crossed linear polarizers of sandwich structures of four-sequence-set crystals: Ammonium dihydrogen phosphate (ADP, $NH_4H_2PO_4$), light along *Z* axis (optic axis), L-Rhamnose monohydrate (LRM, $C_6H_{12}O_5{\cdot}H_2O$) – light along one principal crystallographic axis, LRM – light along another principal crystallographic axis, and ADP, light along *Z* axis [9].

2. Experimental method and simulation

A standard polarimetric setup was used to observe and record the conoscopic patterns. The light source was a 632.8 nm He-Ne laser. Glan-Thompson prisms served as linear polarizers, and quarter-wave plates combined with linear polarizers produced circularly polarized light. In both the simulation and experiment, we used four LN crystals: samples 1 and 4 were cut

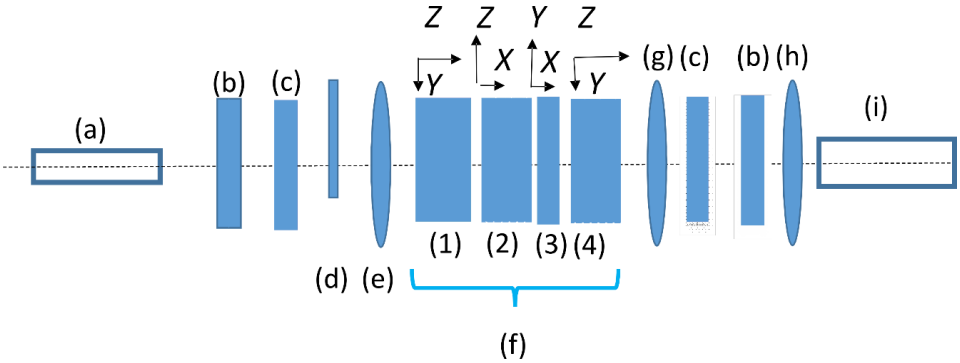


Fig. 2. The experimental scheme for conoscopic pattern registration. (a) – laser, (b) – polarizers, (c) quarter-wave plates, (d) – coherence scrambler, (e) - focusing lens, (f) - sandwich structure of four crystals, (g) –collimating lens, (h) –objective lens, and (i) - CCD camera.

perpendicular to the optic (Z) axis, while samples 2 and 3 were cut perpendicular to the X crystallographic axis (Fig. 2). Along the direction of beam propagation, the X-cut samples were placed between the Z-cut samples and were rotated by 90° relative to one another around the optical axis of the beam. All four samples were placed inside a specially designed holder. The four-crystal sandwich was located between crossed (or parallel) linear or circular polarizers. At λ = 632.8 nm, the refractive indices are n_0 = 2.28647 and n_e = 2.20240 [10]. The sample thicknesses were $d_1 = d_4 = 5.32$ mm, $d_2 = 5.11$ mm, and $d_3 = 3.04$ mm, where d_1, d_2, d_3, and d_4 denote the thicknesses of the first, second, third, and fourth samples, respectively. In the simulation and in experiment, the incident optical beam had an angular aperture of 10°. The X and Y crystallographic axes of the first and fourth samples were parallel, while the Z axes of the second and third samples were mutually perpendicular. The incident optical wave was linearly polarized.

The method for computing conoscopic patterns is described in our recent paper [7]. The maps of azimuth and ellipticity angle have been studied with the imaging polarimeter described earlier in our work (see, e.g., [11]). In these experiments, the incident light was linearly polarized.

3. Results and discussion

As shown in Fig. 1, the conoscopic patterns experimentally obtained from a sequence of uniaxial crystals (ADP) and a biaxial crystal (LRM) are characterized by eight bright spots, positioned between isogyres, surrounded by a dark region [9]. We obtained the similar patterns using LN crystals with crossed (Fig. 3a) and parallel (Fig. 3b) linear polarizers. In general, we see eight spots, as shown in Fig. 1. The difference between the early conoscopic patterns (Fig. 1) and those obtained in the present work is that, in our case, the patterns on the lower-left and upper-right sides of the figure are distorted, probably due to inhomogeneity in the LN crystals (note that the conoscopic patterns presented in Fig. 1 were obtained using crystals grown from an aqueous solution that were therefore less strained than lithium niobate).

Let us consider simulated conoscopic patterns for the sandwich structure based on four LN crystals (Fig. 4). It is seen that the conoscopic patterns presented in Fig. 1, Fig. 3a, and Fig. 4a are similar. Analyzing these interference patterns requires considering maps of ellipticity and the azimuth of polarization of the emergent light. These experimentally obtained maps are presented in Fig. 5.

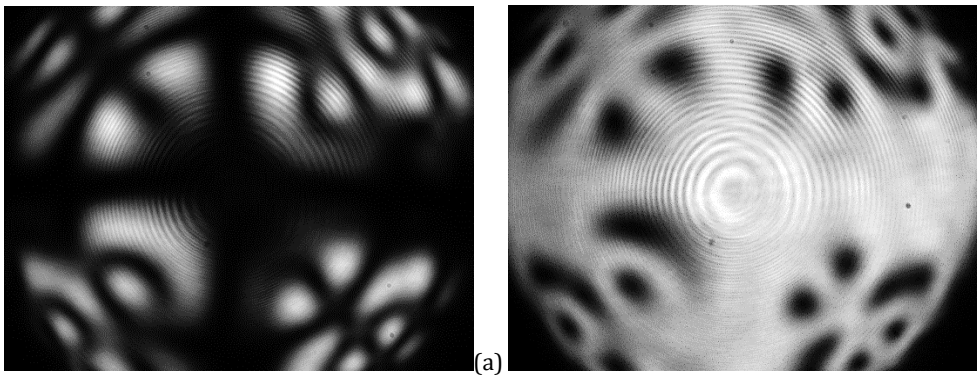

(a) (b)

Fig. 3. Experimentally obtained conoscopic patterns of a sandwich structure consisting of four sequentially arranged LN crystals, placed between crossed (a) and parallel (b) linear polarizers.

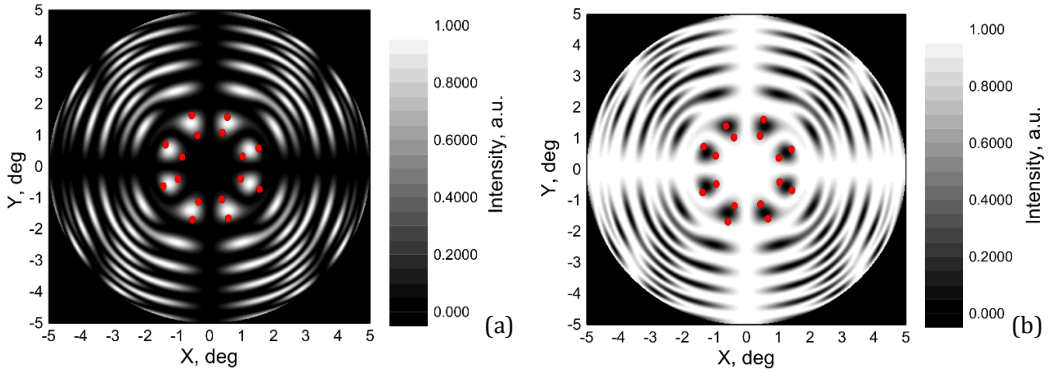


Fig. 4. Simulated conoscopic patterns of a sandwich structure consisting of four sequentially arranged LN crystals, placed between crossed (a) and parallel (b) linear polarizers (the cores of polarization singularities are indicated with the red points).

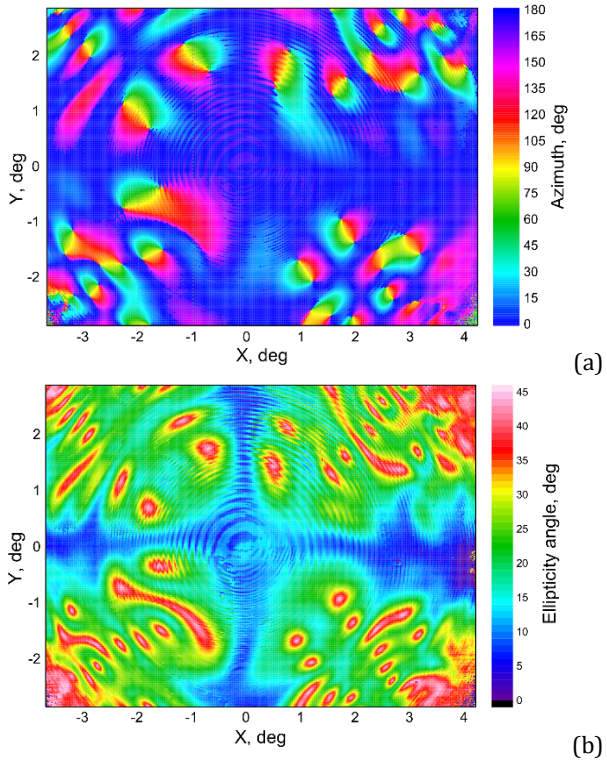


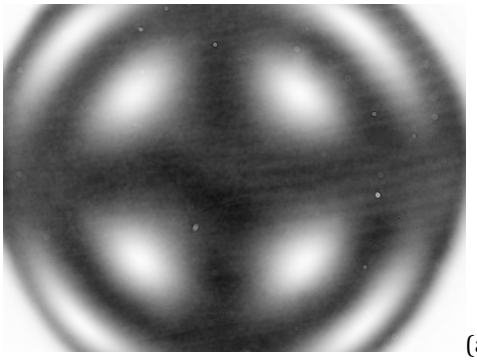
Fig. 5. The maps of the azimuth (a) and ellipticity angle (b) of polarization of the light emerging from a sandwich structure containing four LN crystals.

At an angular radius of ~2° in Fig. 5, one can see sixteen polarization singularities where the ellipticity angle of light equals 45° (the emergent light is circularly polarized). These polarization singularities represent typical C-points with opposite topological strength in pairs, i.e., ±1/2 (when moving full circle around C-point, the polarization azimuth changes by ±180°). These pairs of polarization singularities correspond to dark (or bright) spots in conoscopic patterns (Figs. 1, 3a,b and 4a,b) and can generate pairs of the OVs (Fig. 6). We detected one such OV in the pair using an interferometric experiment with a Mach-Zehnder interferometer (Fig. 6). The interference rings in the upper part of the photo (Fig. 6) may relate to the shadowed counterpart OV in the pair.

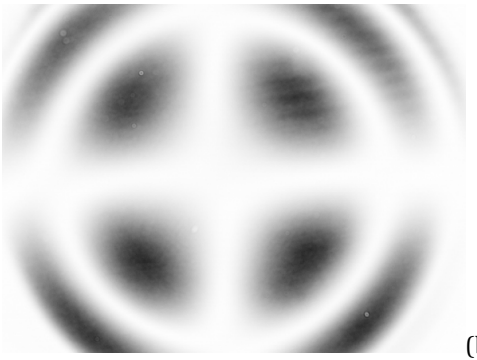


Fig. 6. Spiral interferometric pattern corresponding to the OV. The spiral interference patterns are located in the lower part of the photo. The interference rings in the upper part of the photo may relate to the shadowed counterpart OV in the pair.

To determine whether the number of crystals in the sandwich structure affects the number of polarization singularities in the outgoing optical field, we performed a conoscopic and polarimetric study of a single *Z*-cut LN sample. The corresponding conoscopic patterns are shown in Fig. 7. These patterns are characteristic of optically uniaxial crystals. The maps of azimuth and ellipticity angle of polarization are presented in Fig. 8. Four pairs of polarization singularities appear in this case. These pairs are located between isogyres (Fig. 8a). The ellipticity angle in the cores of the polarization singularities is 45° (Fig. 8b), corresponding to the formation of eight C-points. Our observations for a single *Z*-oriented uniaxial crystal agree well with the description presented in [8]. The topological strength of the polarization singularities in the pairs has opposite signs and equals ±1/2. As in a four-sample sandwich structure, increasing the angular radius reveals chains of polarization singularities in mutually perpendicular directions. Recall that, in a four-sample sandwich structure, this chain "cross" has eight arms.



(a)



(b)

Fig. 7. Conoscopic patterns for one LN crystal of *Z*-cut placed between crossed (a) and parallel (b) linear polarizers.

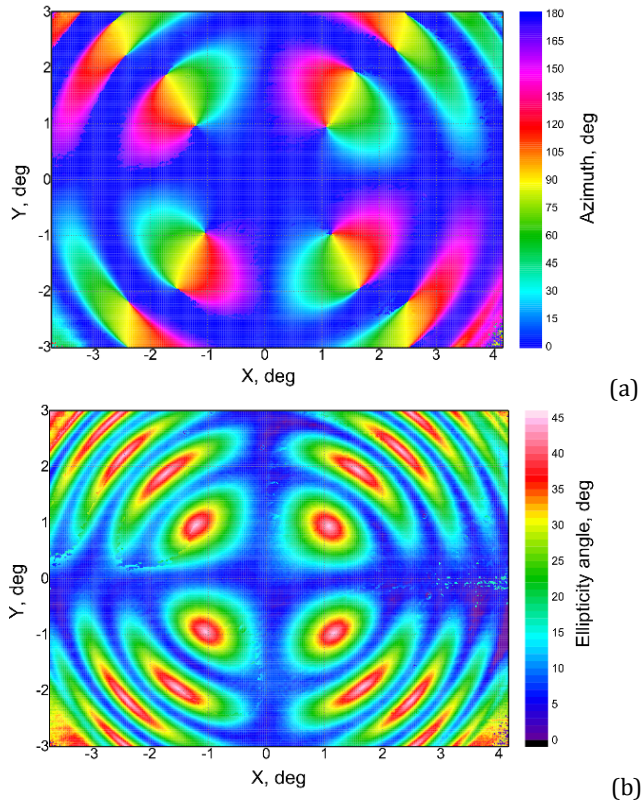


Fig. 8. Maps of azimuth (a) and ellipticity angle (b) of polarization obtained for a single $LiNbO_3$ crystal.

Therefore, the number of polarization singularities in the outgoing optical field depends on the number and orientation of the crystalline samples within the sandwich structure.

4. Conclusions

In conclusion, we experimentally and theoretically studied the conoscopic patterns arising from a sandwich crystalline structure comprising two outermost uniaxial LN crystals aligned along their optic axes (*Z*-cuts), with two internal *X*-cut LN crystals placed between them. It has been found that conoscopic patterns consist of eight dark (or bright in the case of parallel polarizers) spots located around the center at an angular radius of ~2°. As shown by polarimetric experiments, these dark spots correspond to eight pairs of polarization singularities with opposite signs and half-integer strength, which lead to the appearance of C-points in the outgoing optical field. These C-points can generate the single-charged OVs. In general, the maps of ellipticity angle and azimuth of polarization contain eight chains of such C-points that form an eight-armed "cross". If the first three samples in the sandwich structure are removed and only the last *Z*-oriented sample is left, the conoscopic pattern is represented by the four spots that are located between isogyres. At these spots, the four pairs of C-points are revealed experimentally. These pairs are the same from a topological point of view as in the case of a four-crystal sandwich structure. However, in the case of one sample, the "cross" of the chains of polarization singularities has only four arms. This means that the number of polarization singularities depends on the number and orientation of samples in the sandwich structure. Therefore, by changing the number of samples, one can control the number of OVs in the multiple vortex beam.

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Conflict of interest. The authors declare no conflict of interest.

Authors contribution. Conceptualization and methodology, [Vlokh R.]; validation and formal analysis, [Skab I.]; computer simulation, [Vasylkiv Yu.]; experimental investigation, [Krupych O., Say A.]; writing – original draft preparation, [Vlokh R.]; writing – review and editing, [Skab I., Krupych O.]; project administration and funding acquisition, [Vlokh R.].

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Анотація. *У цій роботі ми експериментально та теоретично проаналізували коноскопічні картини, отримані для багатошарової («сендвіч») кристалічної системи, що складається з чотирьох одновісних кристалів ніобату літію (НЛ, $LiNbO_3$). Два з них (зовнішні) орієнтовані вздовж своїх оптичних осей (Z-зрізи), а між ними розміщено два кристали НЛ з X-зрізом. Наші результати показують, що коноскопічні картини, розраховані для лінійно поляризованого падаючого світла, добре узгоджуються з експериментальними спостереженнями. Встановлено, що коноскопічні картини складаються з восьми темних (або світлих — у випадку паралельних поляризаторів) плям, розташованих навколо центру. Як показали поляриметричні експерименти, ці темні плями відповідають восьми парам поляризаційних сингулярностей, що мають протилежні знаки та напівцілі значення топологічної сили; це призводить до появи С-точок у вихідному оптичному полі. Ці С-точки*

можуть генерувати оптичні вихори (ОВ) з одиничним топологічним зарядом. Загалом, карти розподілу кута еліптичності та азимута поляризації містять вісім ланцюжків таких С-точок, які утворюють восьмипроменевий «хрест». Якщо залишити лише один зразок, орієнтований вздовж осі Z, коноскопічна картина виглядатиме як чотири плями, розташовані між ізогірами. У цих плямах експериментально виявляються чотири пари С-точок. Топологічно ці пари ідентичні тим, що спостерігаються у чотиришаровій «сендвіч»-структурі. Однак у випадку одного кристалу «хрест», утворений ланцюжками поляризаційних сингулярностей, має лише чотири промені. Доведено, що кількість поляризаційних сингулярностей залежить від кількості та орієнтації зразків у багатошаровій структурі. Отже, змінюючи кількість зразків, можна керувати кількістю оптичних вихорів у багатовихровому пучку.

Ключові слова: *кристалічна сендвіч-структура, оптичний вихор, оптичний векторний пучок, композитні вихрові пучки, структуроване світло, орбітальний кутовий момент, анізотропні кристали, топологічний дефект*