Nonlinear Phenomena in Complex Systems, vol. **25**, no. 1 (2022), pp. 73 - 81

Patterned Photoalignment-Based One- and Two-Dimensional Liquid Crystal Forked Gratings

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(Received 2 March, 2021)

Based on the technology of patterned photoalignment of polymerizable nematic liquid crystal, one- and two-dimensional fork-dislocation gratings which enable formation of singular light beams (optical vortices) have been fabricated and examined. The proposed approach to the formation of a two-dimensional optical structure presents itself a combination of two one-dimensional gratings with mutually orthogonal orientations of the grooves. Phase structures of the formed singular beams as well as their spatial and polarization characteristics have been studied experimentally. The obtained results offer new potentialities in design of optical devices and systems for transformation of phase and polarization structures of light beams.

PACS numbers: 42.79.Dj, 42.70.Gi, 42.79.Kr
Keywords: diffraction grating, optical vortices, patterned photoalignment, polarization characteristics, diffraction efficiency
DOI: https://doi.org/10.33581/1561-4085-2022-25-1-73-81

1. Introduction

In the last decades the formation methods of particular light beams, including singular, helical, vector and the like, have been intensively studied by the leading scientists because the unique properties of these beams offer new potentialities for their application in laser processing of different materials, optical manipulation of bio- and macroparticles (optical tweezers), high spatial resolution visualization of microobjects, cryptography, astronomical research, and so on [1–6].

Thin-film liquid crystal (LC) microstructures, with binary molecular alignment or with azimuthal molecular alignment constantly varying within the plane of a diffraction element, are widely used during the development and manufacturing of photonic devices which transform the amplitude and phase profile of light beams [7, 9]. Photonic LC structures have several advantages such as compactness, low cost, polarization-controlled energy distribution, applicability to the short-pulse and high-intensity light modulation [10–13].

The use of the light-sensitive azo dyes, featuring the unique photochemical properties and offering efficient optical recording with a spatial resolution on the order of a few microns, as functional media for the production of LC photonic devices had facilitated evolution of the modern technological platform for the development of optical micro- and nanostructures [14]. In particular, the diffraction optical elements based on azo dyes are successfully applied to solve the problems associated with the formation of light beams having the desired polarization-phase topology [15, 16].

The present paper is devoted to designing, manufacturing of diffractive optical elements on the basis of polymerized LC microstructures, intended for the formation of one- and two-dimensional sets of light beams with different phase topologies, and to experimental determination of their optical characteristics. The novelty of the research refers to the development of a new method of fabrication

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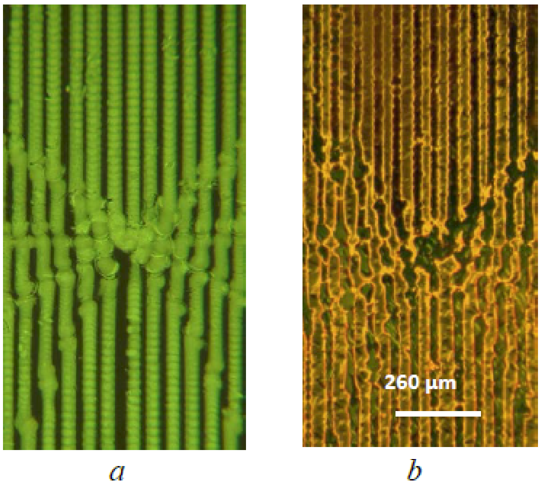
of multidimensional diffractive optical elements based on layer-by-layer patterned photoalignment of polymerizable liquid crystal using azo dyes as photoaligning materials. The proposed 2D diffractive microstructure consists of a superposition of two orthogonal 1D phase LC gratings. Using a combination of two phase LC gratings (with and without forked dislocation) one can obtain both singular and Gaussian light beams in the diffraction pattern of a 2D grating.

2. Materials and methods

Formation of light beams with phase singularity (optical vortices) is commonly realized with the use of diffraction gratings characterized by the fork dislocation (fork-dislocation gratings). In the process of work the authors have fabricated 1D and 2D fork-dislocation gratings based on the technology of layer patterned photoalignment of a polymerizable nematic liquid crystal (PLC) [17].



a *b*

FIG. 1: (color online) Micrographs of the amplitude fork-dislocation photomask (a) and of the diffraction PLC grating manufactured on its basis (b). A period of the structure is $\Lambda = 65\,\mu$m.

One-dimensional forked gratings were fabricated utilizing the photosensitive azo dye AtA-2 as an alignment material [18, 19]. The azo dye was synthesized at the Laboratory "Materials and Technologies of LC Devices" of the Institute of Chemistry of New Materials of the National Academy of Sciences of Belarus. Thin films of the AtA-2 azo dye were deposited onto the preliminary cleaned surface of glass substrates by means of the rod coating method. The alignment properties of the selected azo dye were imparted on its irradiation by linearly polarized light with the wavelength $\lambda = 465$ nm the direction of the induced surface alignment being perpendicular to the activating radiation polarization direction. Due to reversibility of the AtA-2 azo dye photoactivation process, one can form different topologies of the LC alignment conditions on its surface.

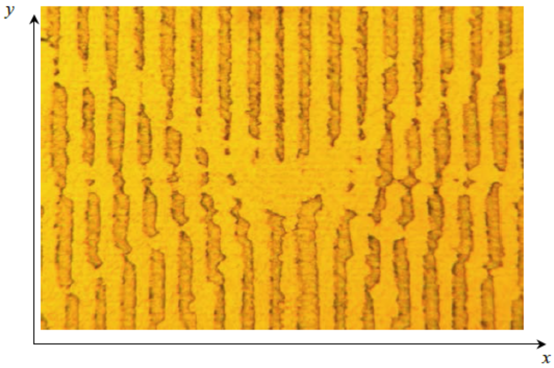


FIG. 2: (color online) Polarized-light micrograph of the 2D fork-dislocation PLC grating (polarizer and analyzer are parallel).

PLC diffraction elements were formed using the double-exposure irradiation method described in [17]. The substrates were initially illuminated by homogeneous polarized radiation and then by orthogonally polarized radiation, with the use of an optical photomask representing a periodical amplitude grating. In the case under study the authors have used the amplitude fork-dislocation grating with the period $\Lambda = 65\,\mu$m. A thin ($d \sim 1.0 - 1.5\,\mu$m) PLC layer (RM257 Merck, USA) applied to the AtA-2 azo dye alignment layer was fixed using for exposure radiation of an ultraviolet light-emitting diode ($\lambda = 365$ nm) to ensure the formation of a stable one-dimensional

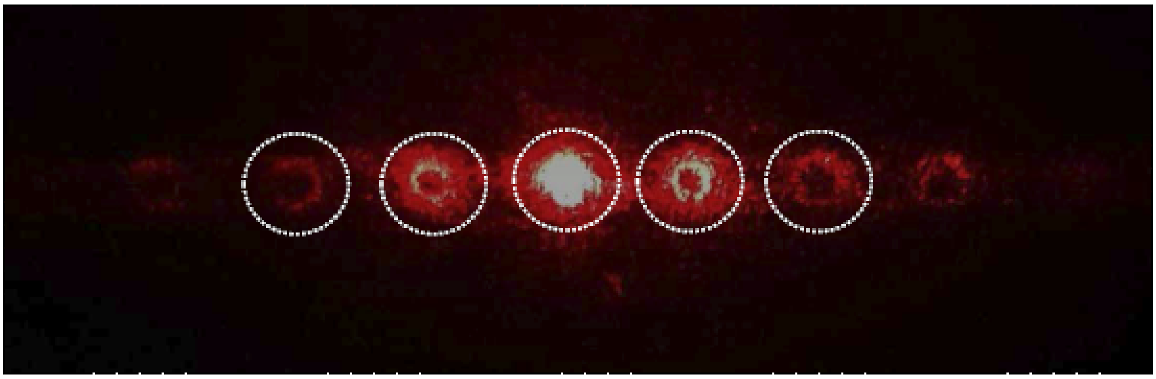


FIG. 3: (color online) Diffraction pattern of a Gaussian beam at the output of the one-dimensional fork-dislocation PLC grating.

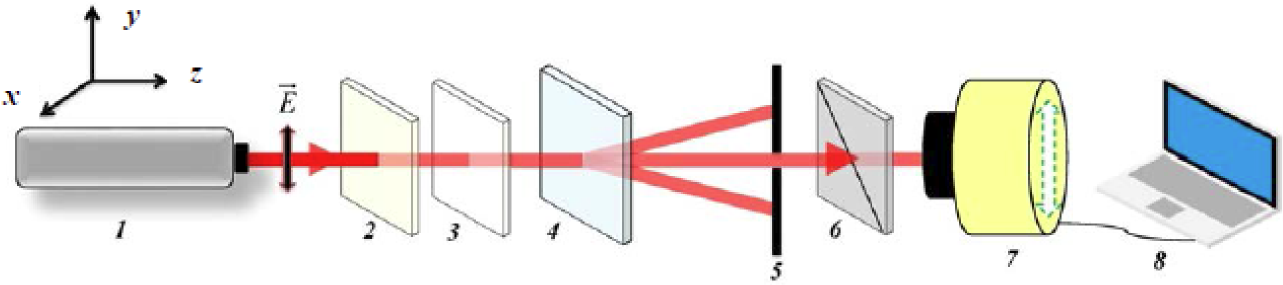


FIG. 4: (color online) Scheme of an experimental setup used to study the diffraction and polarization properties of PLC gratings: 1 – He-Ne laser; 2 – neutral density filter; 3 – half-wave plate; 4 – PLC grating; 5 – iris diaphragm; 6 – analyzer; 7 – photodetector; 8 – personal computer.

fork-dislocation pattern with the desired phase structure.

Figure 1 shows a micrograph of the amplitude photomask and a polarization micrograph of the experimental sample fork-dislocation diffraction PLC grating. Localization of a forked-dislocation in the spatial structure of the grating results in a non-zero topological charge l of the optical field, whose value corresponds to the number of fork branches ($|l| = 2$).

The singular diffraction PLC structure, representing a combination of two phase gratings with mutually orthogonal directions of their vectors, was manufactured using layer patterned photoalignment of the azo dyes AtA-2 and AbA-2522. Owing to the water solubility property, liquid deposition of the AbA-2522 azo dye films onto the surface of a photohardened PLC layer was realized without the use of a buffer layer that is an important technological advantage. The proposed 2D structure was created with the help of the two-mask process including four irradiation stages of alignment films. To form the fork-dislocation grating in a PLC layer, at the irradiation stage of the AtA-2 azo dye film the authors have used the corresponding amplitude photomask ($\Lambda_1 = 65\,\mu\text{m}$) with the topological charge $|l| = 2$. The grating formation process at this stage is similar to that previously described for one-dimensional structures. Subsequent irradiation of the alignment AbA-2522 layer through the amplitude photomask ($\Lambda_2 = 10\,\mu\text{m}$) without fork dislocation enabled the creation of a one-dimensional diffraction grating, with the period

$10\,\mu$m and with the orthogonally oriented grooves, in the PLC layer.

Figure 2 demonstrates a polarization micrograph of a two-dimensional fork-dislocation PLC grating. As seen, the manufactured 2D diffraction structure represents superposition of two one-dimensional phase PLC gratings at an angle of 90°. The vector of the fork-dislocation PLC grating with the period $\Lambda_1 = 65\,\mu$m and the topological charge $|l| = 2$ is directed along the axis OX. The vector of the second PLC grating is directed along the axis OY, the period of the structure coming to $\Lambda_2 = 10\,\mu$m.

As seen in Figures 1 b and 2, one- and two-dimensional diffraction structures are characterized by the perfect (defect-free) PLC alignment due to a high azimuthal anchoring energy between the material and molecules of the photoaligned azo dyes. In this way the layer patterned PLC photoalignment technology makes it possible to manufacture diffraction structures based on combinations of phase gratings with vortex optical elements for the transformation of the spatial and phase characteristics of light beams.

3. Results and discussion

In the process of work the authors have studied experimentally the diffraction properties of the developed one- and two-dimensional fork-dislocation PLC gratings. Figure 3 illustrates the diffraction pattern of a Gaussian light beam with the wave length 632.8 nm on the one-dimensional fork-dislocation PLC grating (Figure 1, b). In zero-order diffraction the initial Gaussian beam is visualized, whereas in the ± first-order and ± second-order diffraction singular light beams characterized by the intensity dip in the central region.

Experimental studies of the developed PLC gratings were realized using a scheme shown in Figure 4. Linearly-polarized radiation of He-Ne-laser “1” with the wavelength 632.8 nm was directed perpendicularly to the plane of PLC grating “4”. Half-wave plate “3” was used to rotate the input-radiation polarization plane. The intensity of radiation diffracted into the m-th order was recorded by a high-sensitivity photodetector. Polarization states of the diffracted light beams were studied with the use of an analyzer rotated over the range 0..360° by steps of 10°.

The diffraction efficiency η_m characterizing the energy distribution of transmitted light according to the diffraction order m may be calculated as $\eta_m = \frac{I_m}{I_0} \cdot 100\%$, where I_m is the light intensity in the m-th diffraction order, I_0 is the intensity of the light beam incident on the grating. Experimental values of the diffraction efficiency in the 0, ±1, and ±2 diffraction orders of the 1D fork-dislocation grating come to η_0=52%, η_1=18%, η_2=2%, respectively.

Figure 5 demonstrates polar polarization diagrams of the transmitted beam and the first or second-order diffracted light beams. It is seen that ellipticity of the polarization state is nonzero only for the second-order diffraction, being determined by the phase incursion in a PLC layer, whereas in the first-order diffraction a minor rotation of the polarization plane by several degrees is observed.

Figure 6 presents the experimental diffraction pattern of laser radiation on the 2D diffraction PLC grating manufactured by layer patterned photoalignment of azo dyes. The distinctive characteristic of the obtained diffraction pattern is the presence of diffraction maxima along the vertical (OY-axis) and the horizontal (OX-axis) axes within the observation plane. Similar to the 1D diffraction PLC grating, the inituial beam is visualized in the zero-order diffraction, whereas singular light beams with the intensity dip in the central region are visualized along the vertical direction in the ± first- and ± second-order diffraction. Diffraction maxima formed by a periodical PLC grating without fork dislocation are observed along the horizontal direction.

The diffraction efficiencies for the zero-, first-, and second-order along the horizontal axis (OX-axis), and for the first and second-order

Table 1: Diffraction efficiency of the 2D fork-dislocation PLC grating with the topological charge $|l| = 2$.

Diffraction efficiency, %			
Spatial axis	Zero-order diffraction	First-order diffraction	Second-order diffraction
OX	78.0	6.8	1.7
OY	78.0	6.7	1.5

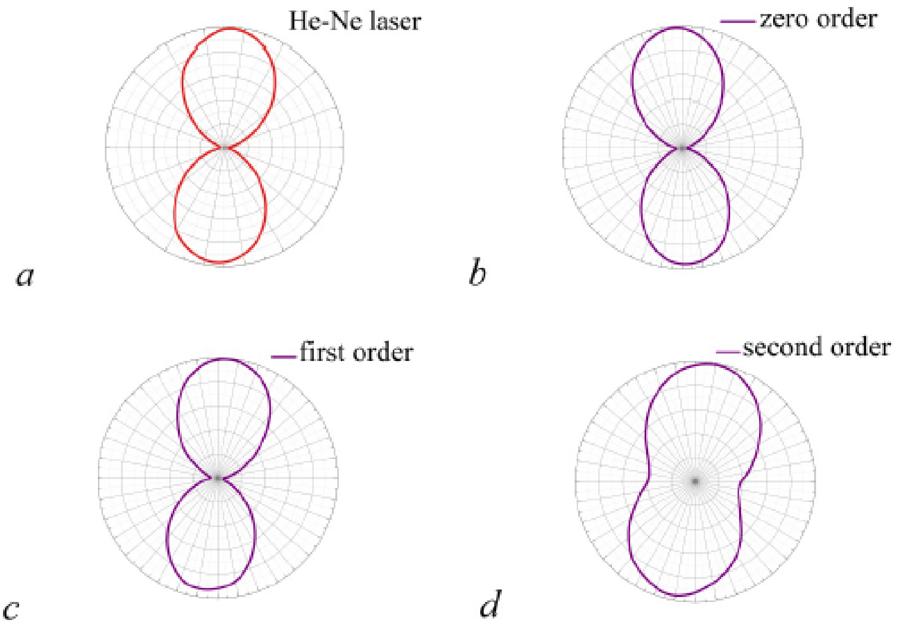


FIG. 5: Polar polarization diagrams for the initial (a), transmitted (b), and diffracted (c, d) light beams at the output of a 1D fork-dislocation PLC grating.

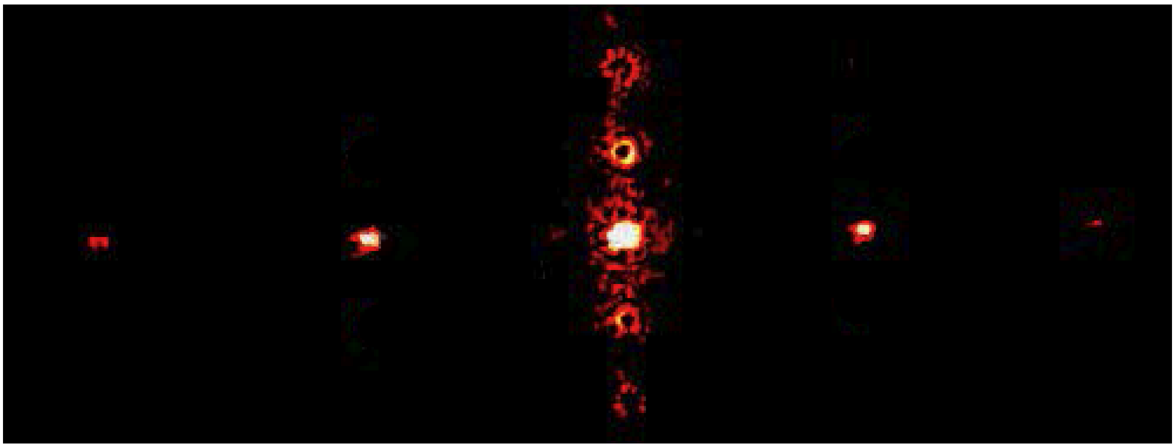


FIG. 6: (color online) Diffraction pattern for the combined 2D PLC grating.

diffraction along the vertical axis (OY-axis) are given in the Table below.

Figure 7 presents diffraction diagrams for the transmitted beams and for the light beams diffracted into the first and second order along the spatial axes OX (horizontally) and OY (vertically). The polarization state of light beams at the output of the 2D PLC grating, similar to the case of linear polarization of the initial radiation along the OX-axis and along the OY-axis, remained practically unaltered (with a minor rotation by an angle of several degrees for the zero- and first-order diffraction). At the same time, for the beams in the second-order diffraction one can observe nonzero ellipticity of the polarization state.

A phase structure of the light beams diffracted from fork-dislocation PLC gratings was analyzed using the optical interferometry method. A Mach-Zehnder interferometer was used to obtain interference patterns of the diffracted light beam with a plane and a spherical wave. A CCD-camera was used for recording of experimental interference patterns.

Figure 8 shows the intensity distribution profile and the corresponding interference patterns of a singular beam ($|l| = 2$) with a plane or with a spherical wave obtained in the first-order diffraction in the case of a 1D fork-dislocation grating.

The interference pattern of a singular beam with a plane wave is characterized by the formation of a fork (Figure 8, b) and the number of its bifurcations determines the topological charge $|l|$. When a singular beam interferes with a coherent spherical wave, one can observe the formation of helices (Figure 8, c), the number of which corresponds to the topological charge $|l|$, whereas the torsion direction (clockwise/counter-clockwise) corresponds to a sign of the topological charge (+/−, respectively). As demonstrated by the experimental data in Figure 8, at the output of a 1D fork-dislocation diffraction grating in the first-order diffraction an optical vortex is formed with the topological charge $l = 2$.

Figure 9 illustrates the intensity distribution profile and the associated interferograms with a plane and a spherical wave of the singular beam ($|l| = 2$) produced in the first-order diffraction in the case of the 2D fork-dislocation diffraction structure.

As expected, at the output of the 2D diffraction fork-dislocation grating in the first-order diffraction an optical vortex is formed, with the topological charge $l = 2$. Thus, the proposed 2D grating based on a polymerized LC microstructure allows for the simultaneous generation of Gaussian light beams and optical vortices in a diffraction pattern. Using the polarization optical microscopy technique it was found that the fabricated forked-dislocation gratings are characterized by a defect-free alignment of the liquid crystal and the period value of the diffractive structure coincides with the period of the amplitude photomask used during the patterned photoalignment process.

4. Conclusion

In summary, based on the technology of layer patterned photoalignment of PLC, one- and two-dimensional optical diffraction structures offering the formation of singular light beams with the desired topological charge, have been manufactured. The use of the water-soluble azo dye AbA-2522 allowed the application of photoaligning films directly onto the surface of photocured PLC material without use of a buffer layer, thus providing an important technological advantage.

The developed 2D diffraction structures represent superposition of two 1D phase PLC gratings with orthogonal directions of the grooves. Owing to the use of a combination of two phase PLC gratings (with or without fork dislocation), one can form both singular and Gaussian light beams in the diffraction pattern of an optical vortex.

Among the advantages of the proposed method is the possibility to manufacture one- and two-dimensional or more complex optical

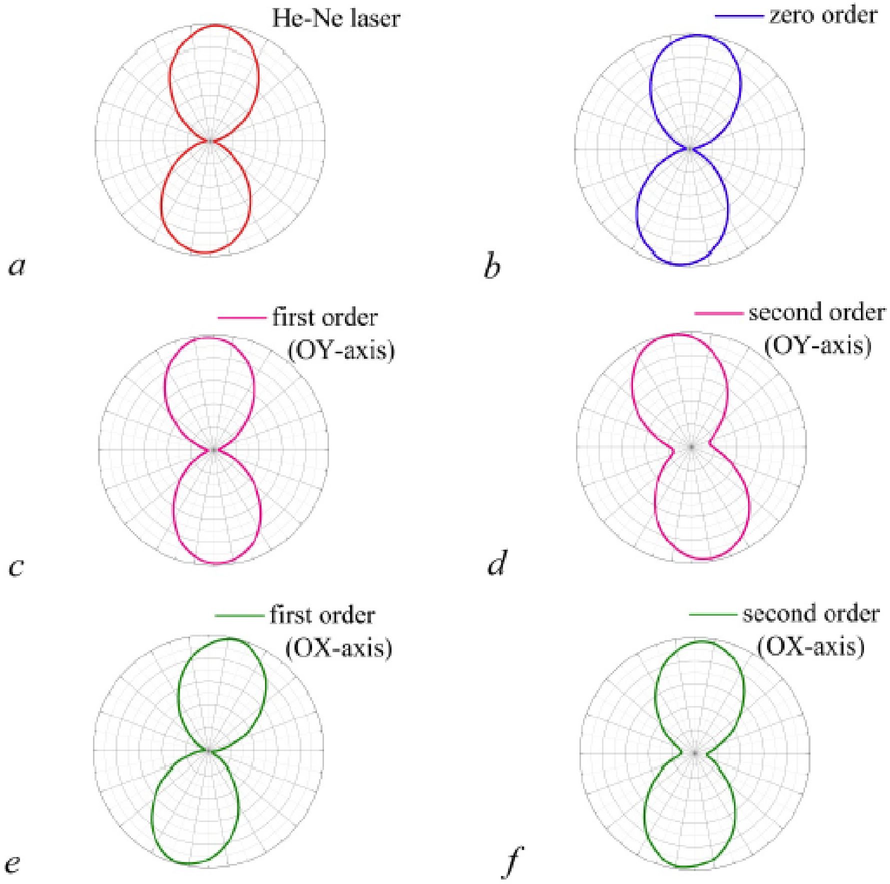


FIG. 7: Polar polarization diagrams for the transmitted beam and for the diffracted light beams at the output of the 2D fork-dislocation PLC grating. Polar polarization diagrams for the for the initial (a) and transmitted (b) laser beam and for the diffracted light beams (c-f) at the output of the 2D fork-dislocation PLC grating.

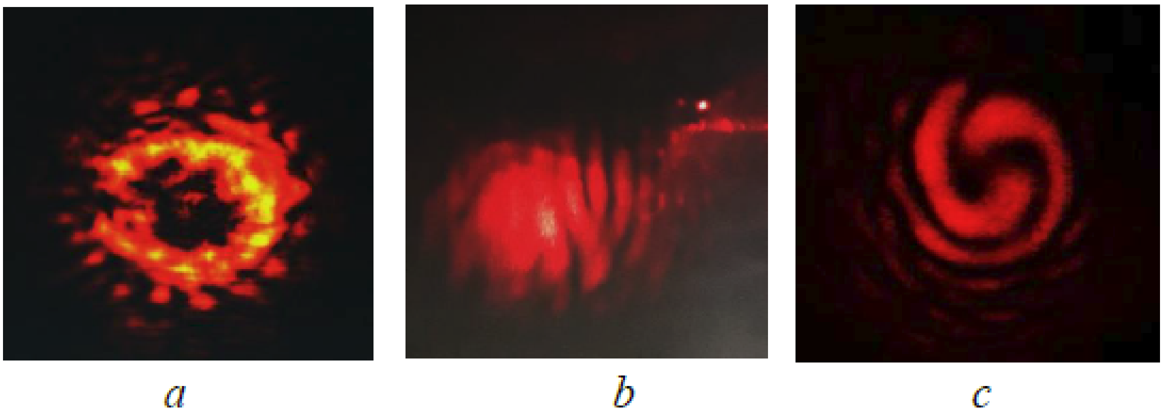


FIG. 8: The intensity distribution profile of a light field (a) and the corresponding interference patterns with a plane (b) and with a spherical wave (c) of the singular light beam in the first-order diffraction from the 1D fork-dislocation grating.

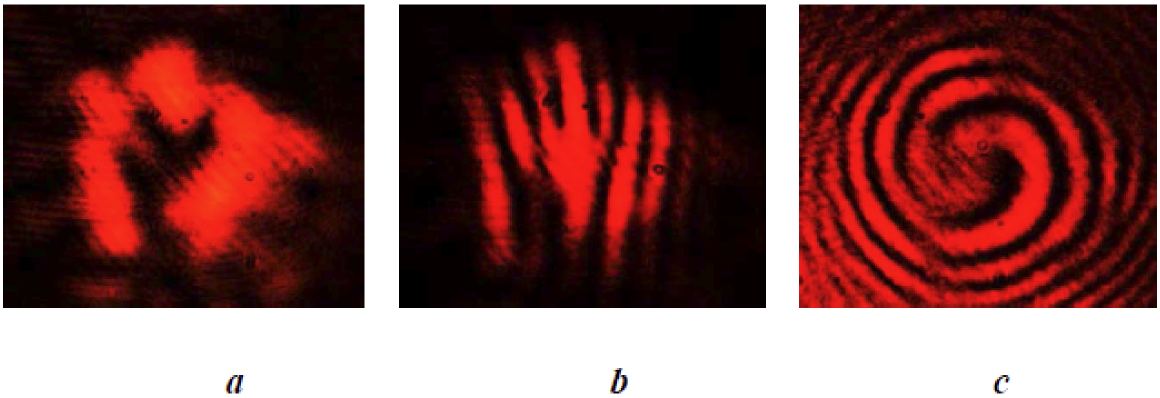


FIG. 9: The intensity distribution profile of a light field (a) and experimental interference patterns with a plane (b) and a spherical wave (c) of the light beam formed in the first-order diffrecation for the 2D fork-dislocation PLC grating.

diffraction structures with different topologies of the grooves and/or the periods of phase gratings. The obtained results may be applied for the development and manufacturing of systems aimed at the control of the phase-polarization structure of light beams; optical capture and manipulations with microparticles; visualization of biological objects with high spatial resolution; laser processing of materials; optical coding and information transmission.

Acknowledgment

The work has been performed owing to the financial support of BRFFR (Contract No.F20MC-034 “Diffraction liquid-crystal P—D elements for the control and steering of light beam”).

The authors are grateful to A. A. Muravsky, the Head of the “Materials and Technologies of LC Devices Laboratory” of the Institute of Chemistry of New Materials of the National Academy of Sciences of Belarus, for provision with the equipment and materials required to fabricate polymerized liquid-crystal diffraction gratings.

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