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# NEW GENERATION OPTICAL ELEMENTS WITH CENTRALLY SYMMETRIC ORIENTATION BASED ON LIQUID CRYSTAL POLYMERS

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The synthesis of new photo-orienting liquid crystal polymers made it possible to create a completely new type of optical elements consisting of ultrathin layers with a spatially structured orientation of the optical axis. In this paper the optical elements based on centrally symmetric periodic structures with cylindrical orientations of molecules are described. These elements are implemented using the recording method that provides a smooth change of optical axis in a thin film of a liquid crystal polymer. The optical elements on the base of described structures have new functionalities and may be assigned to the class of optical elements of a new generation.

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***Keywords*****:** liquid crystal polymers, photo-orientation, optical elements.

**Introduction.** In 1888 Reinitzer discovered that synthesized substance melts not into transparent liquid, but into a muddy one, and the softness of these crystals allows calling them liquid. Thus was born a substance called "liquid crystals" (LC), which was destined to revolutionize the technology of the twentieth century. LC are something intermediate between ordinary crystals and liquids. Polymer is a substance, in which small molecules form a long flexible chain in any way. LC polymers are materials, combining the birefringence of liquid crystals and mechanical properties of polymers.

When making optical elements based on LC, one of the main technological operations is LC molecules orientation. Conventional methods of orientation [1–4] are based on the application of surface-active substance, rubbing or oblique evaporation of orienting layer.

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Rubbing techniques [4] have evolved over many decades. Modern rubbing machines are unrecognizable in comparison to the simple methods used in the 1960s. But with advancement of LC display technology it become more difficult or even impossible to issue problems related to high pixel density, or to the requirement for multiple alignment domains on each pixel, or to the use of spacers, which are deposited on to the display substrate in the gaps between pixels at a point prior in the process to the alignment step. Rubbing, no matter how well controlled, produces some defects and these become a bigger problem as pixel size decreases.

So much research and development effort has gone into developing LC technologies that do not require a rubbed alignment layer. The most obvious exemplar of this is the family of multi-domain vertically aligned nematic LC displays [2].

However, many other LC technologies require precise directional alignment of the LC molecules at one or both of the substrates. Two non-contact methods have been proposed. One uses ion beams [3], the other uses light (photo-alignment methods) [1]. Both produce alignment, which can be superior to that produced by mechanical rubbing. However, ion beam methods are costly, because they operate only under high vacuum. Because they do not require a high vacuum, photo-alignment methods are of lower cost. Photo-alignment is a non-contact method allowing to obtain high quality orientation with small defects. The uniqueness of the method lies in the possibility of forming both discrete and continuously changing orientations.

The synthesis of novel photo-orienting LC polymers [1] has created a major basis for making of optical elements of new generation [5–13] such as phase retarders with planar orientation, centrally symmetric planar elements with radial and azimuthal distribution of LC director, vortices of different orders, polarization diffraction gratings, centrally symmetric polarization periodic structures, elements with more complex geometric phases (elements of Pancharatnam–Berry). Some of the new generation optical elements implemented in our laboratory are described below.

**Description of Realized Elements.** All the described elements were implemented by the following technique. The 1 *mm* thickness BK7 optical glass substrates were used, onto which a layer of linearly photo-polymerized polymer ROLIC ROP-103 was deposited by the spin coating method. To form the planar orienting boundary conditions, substrate was exposed to linearly polarized He:Cd KIMMON laser beam at 325 *nm* wavelength. Then the LC pre-polymer ROLIC ROF-5102 was applied, the orientation of the molecules of which repeats the predetermined.

*Polarization sensitive diffractive axicon (axially symmetric LC polarization grating)* is made on the optical substrate, coated with axially symmetric periodically aligned liquid crystal polymer (LCP) layer. This element is polarization sensitive due to polarization patterned structure of LCP layer. At the output of diffractive axicon along the axis from a point light source (e.g. Gaussian laser beam) two rings shaped image, corresponding to left/right circularly polarized beams, is obtained. One of the rings is formed as in the case of plano-convex axicon, and the other corresponds to plano-concave axicon (Fig. 1). The diffraction image obtained by illumination of the axially symmetric polarization grating (ASPG) with monochromatic light with different polarization is given on Fig. 2, a. Fig. 2, b shows the diffraction image, obtained at the output of ASPG illuminated by white light.

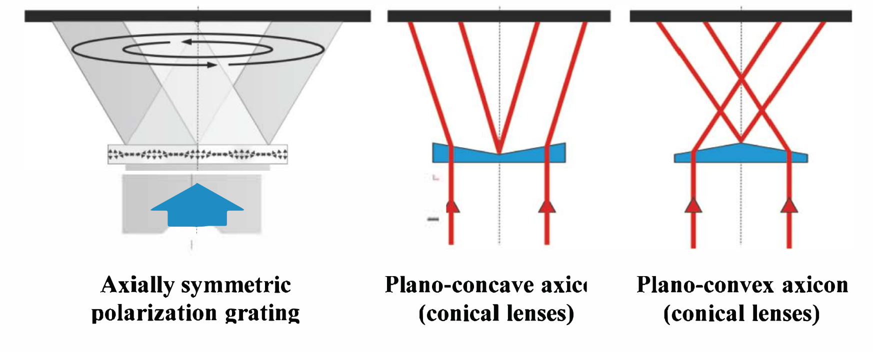


Fig. 1. Schematic, describing the principal of functioning of axially symmetric liquid crystal polarization grating.

Thus, as can be recapitulated, the described LC ASPG have the following features: polarization selectivity, operation in the plano-convex axicon mode (near field diffraction – Bessel beam, far field diffraction – ring shaped image), operation in the plano-concave axicon mode (far field diffraction – ring shaped image).

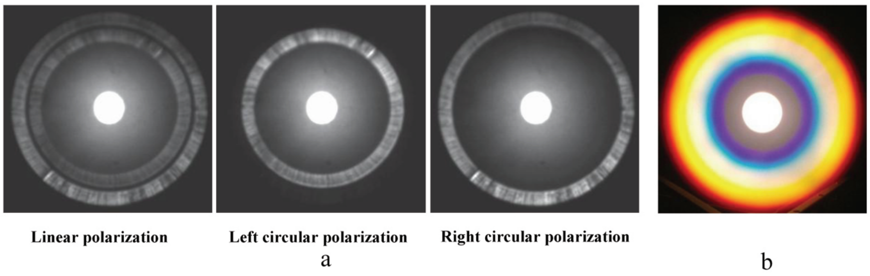


Fig. 2. Diffraction image at the output of axially symmetric polarization grating:
a) illumination by monochromatic light with different polarizations;
b) illumination by non-polarized white light.

*Geometrical phase optical elements* are implemented by unique laser polarization-structuring technique using LC photo-alignment method. The printing method is used for making multi-tailored polarization patterns. The micron scale patterned orientation, known as Pancharatnam–Berry phase element, can be achieved (Fig. 3).

These elements can be used to obtain custom birefringent patterns (half-wave or quarter-wave), to control the beam retardance according to the predefined function, as well as for tailored polarization conversion in beam shaping applications (radial, azimuthal, circular and elliptical polarizations). Custom birefringent patterns obtained using this elements have such advanced applications as stimulated emission depletion (STED) microscopy, tip-enhanced near-field coherent anti-Stokes Raman scattering microscopy, optical trapping and manipulation, surface plasmon excitation, laser beam shaping, micromachining and particle acceleration.

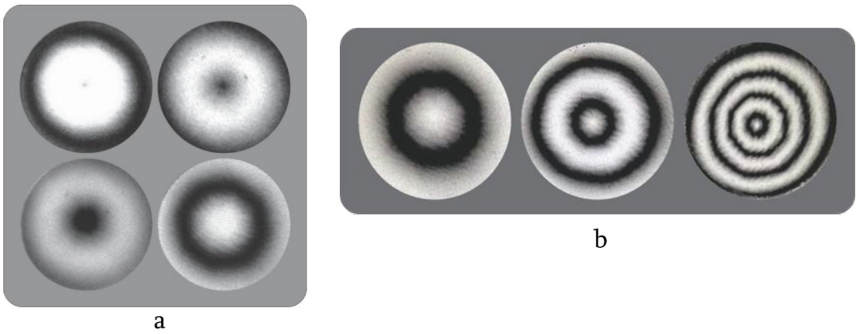


Fig. 3. Images of single-periodphase converter in cross-polarizers at different angles (a); images of quarter-period; half-period and single-period phase converters in cross-polarizers (b) .

*Vortex waveplates (polarization converter from linear to radial/azimuthal)* are components with uniform retardance, fast axis of which rotates around its center (Fig. 4). The first order vortex structure is a result of the transition from the radial to azimuthal distribution during one turn of azimuthal angle, when the fast axis itself make one complete turnaround. For the higher modes it is possible to determine how many times the conversion is realized, and, accordingly, the fast axis will turn around itself and the mode of vortex will be the same.

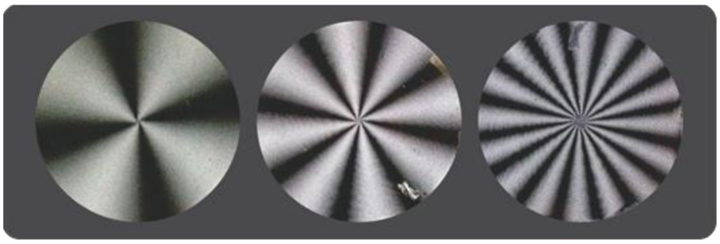
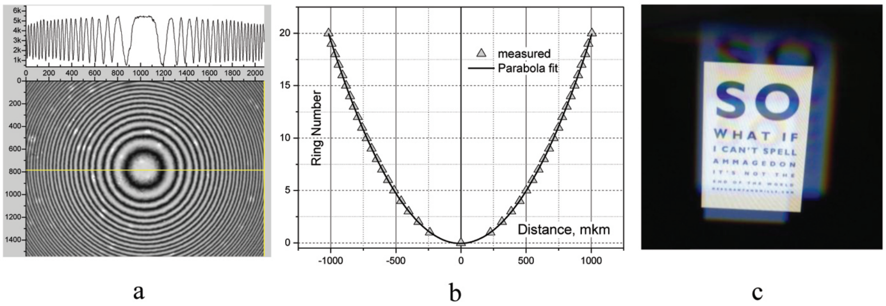


Fig. 4. Images of single, two and third order Vortex waveplates in cross-polarizers.

To generate the beams with radial or azimuthal polarization, it is necessary to place the converter into linearly polarized laser beam and align its center with the optical axis of the incident laser beam. Alignment mark, fabricated on converter should be aligned parallel to incident linear polarization orientation to get radial polarization, and perpendicular to get azimuthal polarization.

The described optical element can be used to convert linear polarization to radial or azimuthal, to create an optical vortex beam. Liquid crystal vortex waveplate have nearly 100% efficiency in polarization conversion for dedicated wavelengths, 30–90% transmission (depend wavelength), large aperture (up to 25 *mm*). The usage of this element in laser micro machining allows focusing into smaller spot size (using NA$>$ 0.9), ensures the same machining properties and cutting speed in all directions (if process is sensitive to incident polarization direction), increases cutting speed. The benefits of usage of vortex waveplate in optical tweezers are increasing of trapping force and possibility to trap particles with a lower refractive index comparing to surroundings.

*The Fresnel structure* is formed when the spatial period changes from the center to the edge according to a quadratic law (Fig. 5). During the recording of these elements, one of the interfering beams passes through the lens, which forms a spherical wave front and at a certain distance overlaps with a beam with a flat wave front. The substrate moves along the optical axis of the recording beam with uniform braking, which leads to a gradual increase in the distribution period of planar-oriented circles. Thus, the Fresnel structure is formed and the element functions as a lens. Unlike a conventional Fresnel lens, the obtained structure operates on a principle of geometric phase with a continuously changing periodicity and is unique in its polarization selectivity. For an incident light beam with one circular polarization, it will function as a collecting lens, and for a beam with orthogonal circular polarization it will function as a scattering lens.



a b c

Fig. 5. The image of the Fresnel structure obtained under a polarizing microscope (a); the distribution of rings away from the center (b); the image at the output of the realized structure, observed under natural illumination (c).

**Conclusion.** The use of photo-orienting LCP makes it possible to create a completely new type of optical elements consisting of ultrathin layers of anisotropic materials with a spatially structured orientation of the optical axis. The spatially modulated geometric phases have been formed using the recording method, developed by us providing a smooth change of optical axis in a thin film of LC polymer. The developed technique makes it possible to realize centrally symmetric periodic structures with cylindrical orientations of LC molecules. Such structures can be to create optical elements with new functionalities having a wide range of applications in various fields.

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## ՀԵՂՈՒԿ ԲՅՈՒՐԵՂԱՅԻՆ ՊՈԼԻՄԵՐԻ ՀԻՄԱՆ ՎՐԱ ԻՐԱԿԱՆԱՑՎԱԾ ԿԵՆՏՐՈՆԱՀԱՄԱՉԱՓ ԿՈՂՄՆՈՐՈՇՎԱԾՈՒԹՅԱՄԲ ՆՈՐ ՍԵՐՆԴԻ ՕՊՏԻԿԱԿԱՆ ՏԱՐՐԵՐ

Լույսով կողմնորոշվող նոր հեղուկ բյուրեղային պոլիմերների սինթեզը հնարավոր դարձրեց օպտիկական առանցքի փարածական կառուցվածքային կողմնորոշմամբ էապես նոր տիպի օպտիկական տարրերի ստեղծումը: Այս հոդվածում նկարագրված են մոլեկուլների գլանաձև կողմնորոշմամբ կենտրոնահամաչափ պարբերական կառուցվածքների վրա հիմնված օպտիկական տարրեր: Այս տարրերն իրականացված են հեղուկ բյուրեղային պոլիմերի բարակ թաղանթում օպտիկական առանցքի սահուն փոփոխությունը ապահովող գրանցման եղանակով: Նկարագրված կառուցվածքների հիման վրա օպտիկական տարրերը ունեն նոր ֆունկցիոնալ հնարավորություններ և կարող են վերագրվել նոր սերնդի օպտիկական տարրերի դասին:

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В. В. БЕЛЯЕВ, Д. Н. ЧАУСОВ, А. С. СПАХОВ

## ОПТИЧЕСКИЕ ЭЛЕМЕНТЫ НОВОГО ПОКОЛЕНИЯ С ЦЕНТРАЛЬНО-СИММЕТРИЧНОЙ ОРИЕНТАЦИЕЙ НА ОСНОВЕ ЖИДКОКРИСТАЛЛИЧЕСКИХ ПОЛИМЕРОВ

Синтез новых фотоориентируемых жидкокристаллических полимеров (ЖКП) сделал возможным создание оптических элементов совершенно нового типа, состоящих из ультратонких слоев с пространственно-структурированной ориентацией оптической оси. В настоящей работе описаны оптические элементы на основе центрально-симметричных периодических структур с цилиндрической ориентацией молекул. Для записи элементов использован метод, обеспечивающий плавное изменение оптической оси в тонкой пленке ЖКП. Оптические элементы на основе описанных структур обладают новыми функциональными возможностями и могут быть отнесены к классу оптических элементов нового поколения.