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ELECTRICALLY CONTROLLED LIQUID CRYSTAL TWIST-PLANAR FRESNEL LENS

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Based on the method of photo-orientation of the azo-dye AtA-2, an electrically controlled Fresnel lens has been developed which is a microstructured liquid crystal element made up of alternating rings with twist- and planar orientations of the liquid crystal director. It is shown that the use of a control voltage makes it possible to control the efficiency of the focusing of laser radiation, as well as to turn off the lens. An optimum control voltage (~3 V) is determined at which a maximum focal efficiency and satisfactory quality of image construction over a wide spectral range from 530 nm to 1.1 μm are attained.

Keywords: *Fresnel lens, diffraction lens, nematic liquid crystal, photo-orientation, electrically controlled diffraction.*

Introduction. Studies associated with the development of liquid-crystal lenses are among the promising problems in modern photonics. Liquid crystals (LC) are a unique class of materials in which optical anisotropy can be controlled as a consequence of the reorientation of molecules by an external electric field, which makes them ideal for the creation of dynamic lenses [1–3] and ensures the feasibility of adaptive focusing and control of the optical properties of a lens as a function of specific requirements and conditions without a need for physical replacement of the optical element [4]. Electrically controllable lenses are convenient for use and integration in electronic systems. Dynamic lenses are widely used in microscopy [4], optical systems for self-focusing cameras [5], optical scanners [6], and laser processing of materials, and systems for virtual and supplementary reality [7].

Many scientific groups are working on improvements in the productivity, energy efficiency, and reliability of lenses, as well as on extending their applications in different areas [8–12]. Despite the successes that have been attained, studies in this area are continuing with a goal of creating LC lenses with improved technical characteristics (control of focal distance [2, 6, 9], shortening of the operating time for LC components [1, 13]).

The important task is optimization of the topology of optical anisotropy and simplification of the technology for the creation of components. One of the main ways of creating LC Fresnel lenses is to use textured electrodes in the form of annular zones [14]. An annular distribution of the electric field makes it possible to control the orientation of the director in the LC layer, forming a concentric anisotropic structure which represents the Fresnel lens. This method has shortcomings associated with the technological difficulties of forming annular electrodes on the surface of the substrates of the component. A second approach to creating LC lenses is based on the use of a photo-orientation method [15] for creating an initial annular structure for orientation of the director of the LC layer in the component. The main advantage of photo-orientation is the possibility of creating high quality lenses with high precision and control. This method ensures good reproducibility of the process for fabricating the lenses and makes it possible to obtain lenses with high optical purity and efficiency [16].

The existing technologies for creating electrically controlled LC lenses have a number of shortcomings. Thus, the materials used for photo orientation are, as a rule, sensitive in the UV region of the spectrum [17–19]. The use of thin phase relief lattices on one of the surfaces of an LC component requires the inclusion of an additional operation in the technological process for forming a relief on a substrate [20, 21]. The use of a doped dichroic dye as the functional material for an LC [22, 23] leads to a deterioration of the optical stability of LC components of this type.

In this paper a simple and cheap technology for creating an electrically controlled photon LC device based on the use of an azo-dye that is sensitive in the blue region of the spectrum is proposed in the form of a zoned Fresnel wafer which

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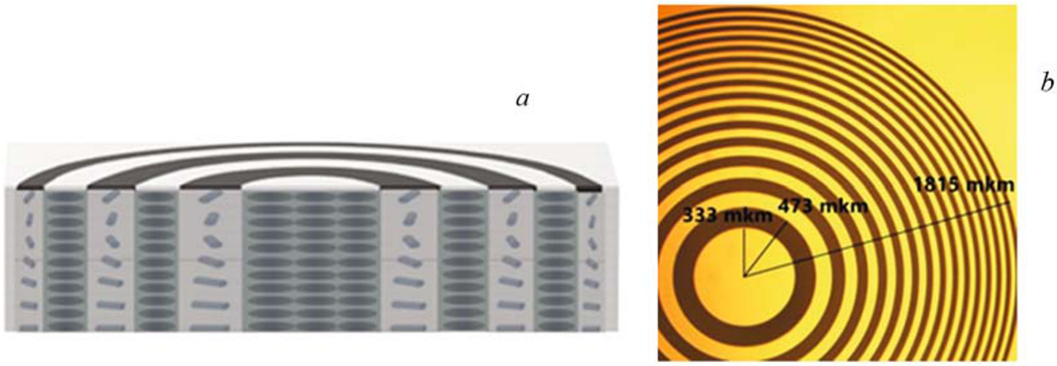

Fig. 1. The topology of the orientation of the director in the twist-planar LC Fresnel lens: (a) the distribution of the orientation of the director of the LC in the structure; (b) the geometry of the amplitude mask (focal distance f = 17.6 cm for λ = 0.633 nm).

is based on setting alternating twist and planar orientations of the director of the LC. The operating regimes of the proposed component are studied experimentally and its focal properties and the ability to construct images in the visible and near IR ranges are demonstrated.

Materials and Technology. The proposed electrically reversible anisotropic LC component is a "sandwich" type cell [24–26] made of two glass substrates with a transparent homogeneous electrically conducting indium–tin oxide (ITO) coating. The current-carrying coating enables electrical control of the orientation of the director of the LC. The component was filled with the LC VIN-7. The thickness of the LC layer d = 20 μm, the threshold voltage U_t = 1.1 V, and the optical threshold U_{op} = 1.5 V. The electrically controlled LC-component is a Fresnel zone plate with an initial alternating twist- and planar orientation of the director of the LC (Fig. 1).

For setting the initial binary annular topology of the orientation of the LC, thin (~30 nm) layers of AtA-2 azo-dye that are sensitive in the blue (450–520 nm) [27] were used for the directive coating. The exposure employed linearly polarized light from a light emitting diode at λ = 450 nm (activation dose P = 0.3 J/cm^2). The layers of the photo-orienter were deposited on an electrically conducting layer formed on the glass substrates of the component. The reversibility of the mechanism for orientation of the employed AtA-2 azo-dye [28, 29] made it possible to form, on one of the substrates, a microstructure of orthogonal planar directions of the surface anisotropy in a layer of the dye by means of double exposure of the photo-orienting material by radiation with mutually perpendicular directions of the polarization plane. Initially the azo-dye is illuminated by uniform linearly polarized radiation and the second time, by orthogonally polarized light through an amplitude mask. The mask was chosen to be a specially calculated and fabricated Fresnel zone plate (15 concentric rings) with transparent odd zones and opaque even ones. After exposure the substrates were glued using spacers which set the gap thickness. After drying, the component was serviced with a nematic LC in the isotropic phase. A variable rectangular voltage at a frequency of 1 kHz was delivered to the LC component for electrical control.

Results and Discussion. Figure 2 shows images of the fabricated LC component in a polarization electron microscope (PEM) for different values of the control voltage. One can see the formation of an annular structure that repeats the topology of the driver amplitude mask (Fig. 1b); here the voltage applied to the LC component determines the optical properties of the component. In the range of voltages from 0–1.5 V, at which the plane of the polarization plane of the light turns, the component operates as a binary amplitude fine lattice with a diffraction efficiency of 20% over the entire optical range [30]; here the PEM images of the component in parallel polarizers reveals alternating light and dark annular zones (Fig. 2a). Further increases in the amplitude of the external voltage leads to a reorientation of the director of the LC along the lines of force of the applied field, which leads to a transformation of the initial amplitude diffraction structure in the phase anisotropic lattice (Fig. 2b–d) with a maximal diffraction efficiency (~30%) [30]. When the control voltage is increased to >20 V, the orientation of the director over the entire LC layer becomes homeotropic, which leads to the disappearance of the diffraction structure in the LC layer (Fig. 2e).

Experimental studies of the focal properties of the LC component were conducted using the arrangement shown in Fig. 3. The light from a He–Ne laser (1) was used. The size of the laser beam was matched to the aperture of the LC Fresnel

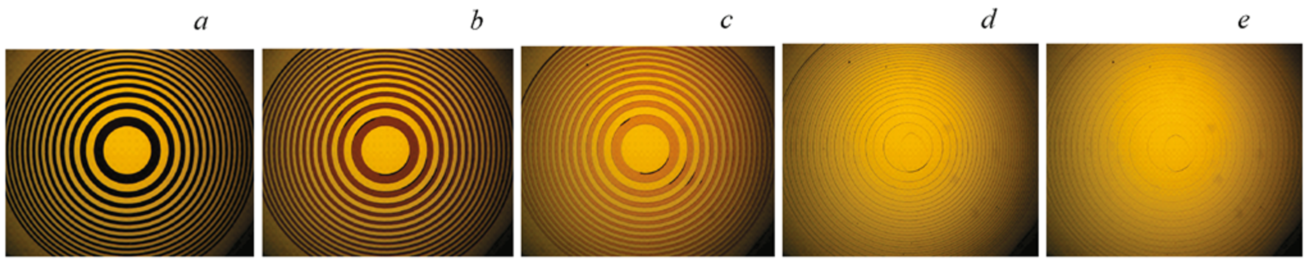

Fig. 2. PEM images of a nematic LC component in a polarization microscope (the polarizers are parallel).

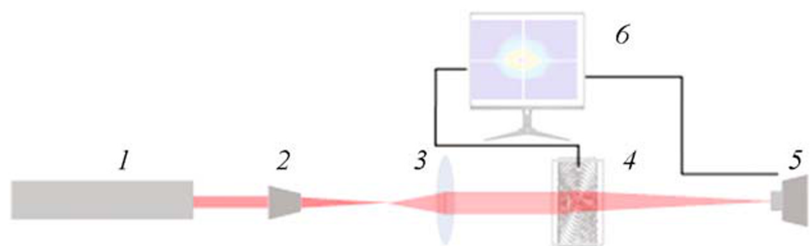

Fig. 3. A sketch of the experimental apparatus: (1) He–Ne laser (λ = 632.8 nm), (2) 20× objective, (3) lens, (4) LC component, (5) profilometer, (6) computer.

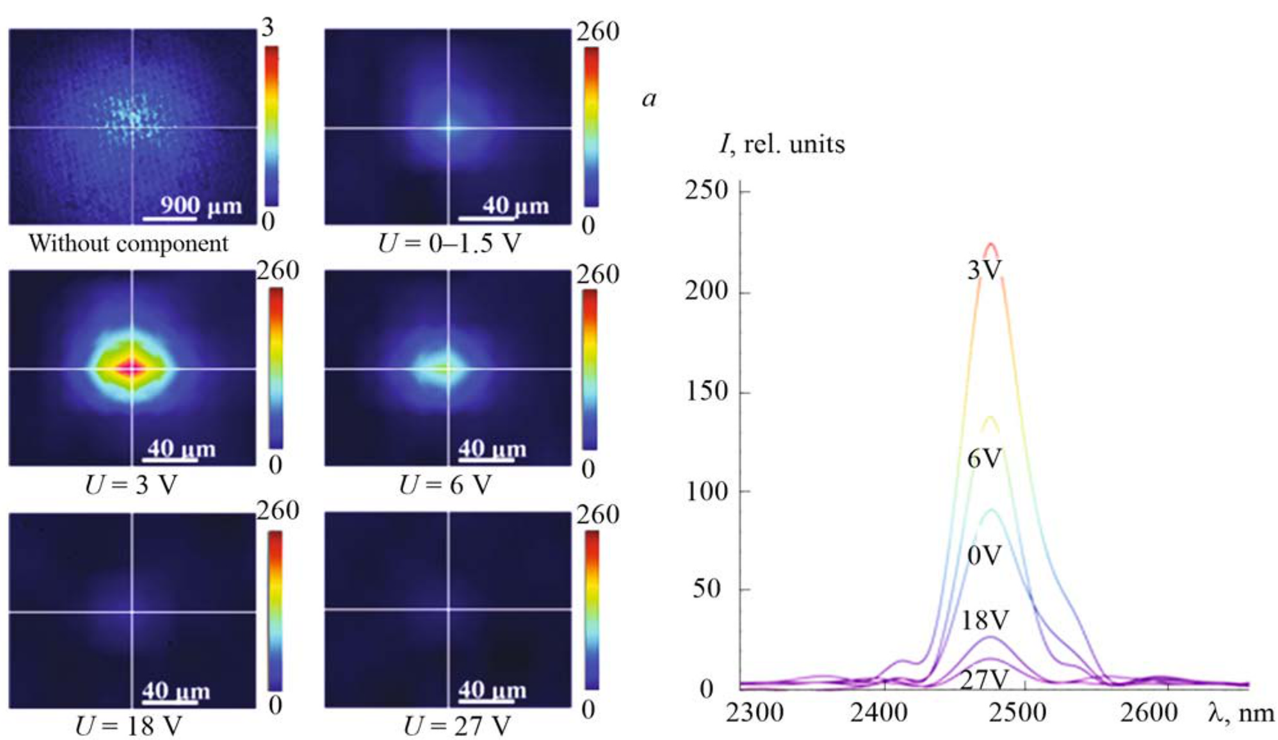

Fig. 4. The focal properties of the LC Fresnel lens: (a) the two-dimensional distribution of the intensity in the focal plane of the LC lens; (b) the cross sections of the corresponding beam profiles.

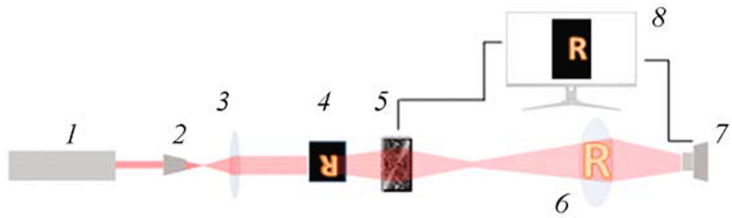

Fig. 5. A sketch of the experimental apparatus for construction of the image: (1) He–Ne laser (λ = 632.8 nm); (2) 20× objective; (3) lens; (4) amplitude transparency; (5) LC Fresnel lens; (6) lens; (7) CCD camera; (8) computer.

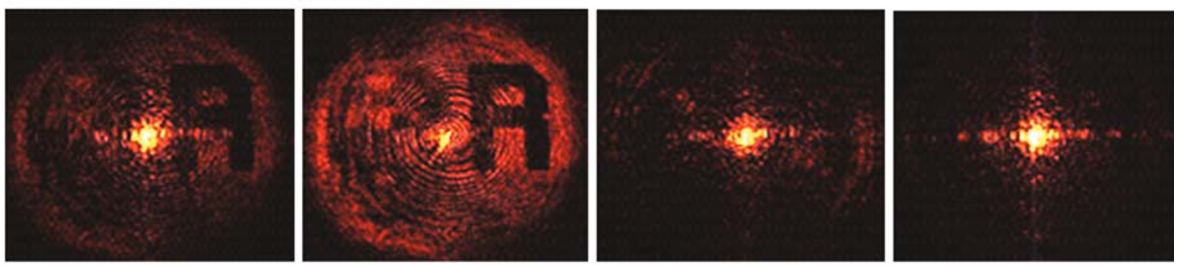

Fig. 6. CCD images of the amplitude transparency constructed by the LC Fresnel lens.

lens (4) (3.7 mm) using an optical system that included a micro-objective (2) and a focusing lens (3). The radiation passing through the LC lens (4) was directed onto a profilometer (5; Ophir Beamstar-V-Pci) located in the focal plane of the lens. Information about the intensity distribution was displayed on the computer screen (6).

The results obtained for different values of the control voltage are shown in Fig. 4. It is clear that the initial 3.7-mm diameter light beam is compressed on passing through the LC lens into a beam with a diameter of <100 μm. For voltages in the range U = 0–1.5 V the LC component has constant focal properties with an intensity at the focus of the lens (I_{0V} = 52 W/cm^2) that is ~300 times the intensity of the laser radiation at the input to the lens ($I_{He–Ne}$ = 0.18 W/cm^2). Further increases in the control voltage leads to a nonmonotonic dependence of its focal properties on the amplitude of the signal. The optimum external voltage is 3 V and is characterized by an intensity I_{3V} = 75 W/cm^2 which exceeds the input intensity by 420 times. A further increase in the amplitude of the control voltage leads to a monotonic reduction in the diffraction efficiency and shutting off of the focusing operating regime for the lens at a voltage of ~20 V.

An analysis of the reflecting properties of the Fresnel lens created here was made using an optical amplitude transparency in the form of the letter R. A sketch of the experimental apparatus is shown in Fig. 5. The laser radiation passing through the amplitude transparency (4) falls on the LC Fresnel lens (5). A lens (6) is used to reduce the size of the beam in order to match the size of the image to the aperture of the CCD camera.

Figure 6 shows PEM images of the amplitude transparency constructed by the LC Fresnel lens for different control voltages on the component. The formation of a distinct image of the transparency corresponds to a voltage amplitude of 3 V, at which maximal focusing of the laser radiation takes place (see Fig. 4). Further increases in the amplitude of the external electric field leads to a deterioration in the image quality, and at ~20 V the camera records an intensity distribution corresponding to the Fourier transform of the transparency (diffraction in the far field), which confirms the absence of focal properties in the LC component.

For analysis of the reflecting properties of the LC lens the formation of images at different wavelengths of the laser light was analyzed. A parametric light generator (pulse duration t = 15 ns, repetition rate ν = 10 Hz, pulse energy E = 40 mJ) with the ability to tune the wavelength from 400 nm to 2 μm was used. Figure 7 shows images of the amplitude transparency in the range from 530 nm to 1.1 μm constructed with the LC Fresnel lens at the optimum control voltage of 3 V. Wavelengths <530 nm may lead to reorientation of the azo-dye molecules used as a photo-orienter, so they were not examined. A satisfactory quality of the transfer of the image in the visible to the near IR ranges can be seen. The deterioration of the quality of the images in the 800–1100 nm range is related to a drop in the sensitivity of the CCD camera.

Fig. 7. CCD images of the amplitude transparency constructed by the LC Fresnel lens in the range from 530 nm to 1.1 μm.

Conclusions. A new electrically controlled liquid-crystal component with a sequence of Fresnel zones with alternating twist- and planar orientations of the director of the liquid crystal has been proposed. It has been shown that using an external electric voltage applied to the liquid-crystal component makes it possible to control the focusing efficiency of laser light and also to shut the lens off when a voltage of ~20 V is applied. A maximal focusing ability of the LC component is attained with a control voltage of ~3 V. The proposed tested technology for creating an electrically controlled LC Fresnel lens manifests a satisfactory quality of constructing images by the developed component and makes it possible to operate in the visible and near IR bands. The proposed diffractive LC component is an electrically controllable array of plane optical components that is distinguished by compactness, low electric power demand, and ease of fabrication.

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