ELECTRICALLY CONTROLLED LIQUID CRYSTALIC FRENEL LENS AND DETERMINATION OF TOPOLOGICAL CHARGE OF OPTICAL VORTICES

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Abstract. A new simple and effective interference method for determining the phase topology of optical vortices is proposed using a developed and manufactured microstructured twist-planar oriented nematic liquid crystal Fresnel zone plate. The developed method eliminates the need to use an additional reference wave and allows direct analysis of the vortex phase topology without an interferometer and without changing the optical scheme. The method was tested for operability in the spectral range from 532 nm to 1.1 µm using nanosecond laser pulse radiation. The efficiency of the developed method was confirmed both experimentally and theoretically.

Keywords: *Optical vortex, topological charge, fresnel lens, nematic liquid crystal.*

I. INTRODUCTION

The unique physical characteristics of nematic liquid crystals (NLCs) and the possibility of effective electrical control of the magnitude of optical anisotropy make them promising materials for the development of new photonic devices of flat optics, which are characterized by simplicity, compactness, reliability and affordable price [1-3]. Currently, the key areas of research for many research groups are the development of liquid crystal switchable lenses with improved characteristics [4] and the development of simple methods for determining the topological charge of phase singular beams [5].

Optical vortices (vortexes) find active application in various fields of photonics, such as cryptography, quantum communication and information, etc. Vortexes are interesting for their unusual properties – the existence of phase singularities of the wave front at special points (the phase of light oscillations is undefined and the amplitude vanishes). Research related to the development of methods for determining the phase topology of optical vortices is one of the most important applied problems of photonics. Today, there are a large number of interference [6-10] and diffraction [11-14] experimental methods for determining the phase topology of optical vortices, but they all have some drawbacks (for example, in interference methods, there is a need for a coherent reference wave, diffraction methods often have an upper threshold for the values of the topological charge that can be determined with their help, and not all diffraction methods allow one to determine the sign of the charge). All these drawbacks limit the scope of application of optical vortices. Therefore, the development of simple and effective methods for determining the topological charge of phase singular beams is of paramount importance for expanding the scope of application of optical vortices.

II. EXPERIMENTS

An electrically controlled photonic liquid crystal device (a Fresnel lens with focusing properties in the visible and near IR spectral ranges [15]) has been developed, manufactured based on the

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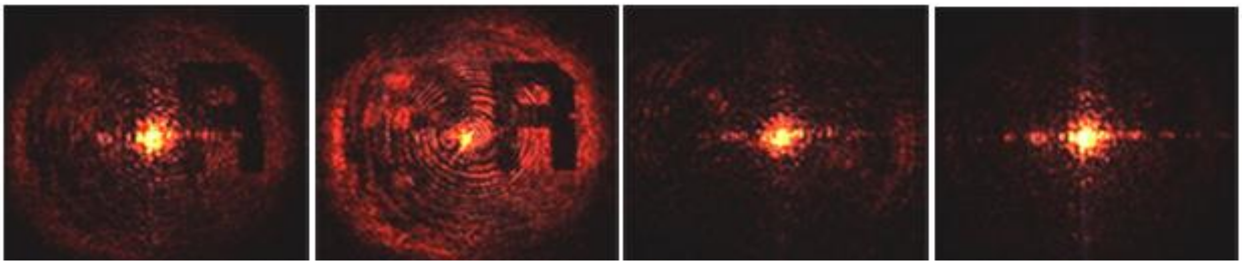
photoorientation method of the azo dye AtA-2 [16-19] and studied. The lens consists of two glued glass substrates with an air gap 20 µm thick filled with VIN-7 liquid crystal with a threshold voltage of U_t = 1.1 V and an optical threshold of U_{op} = 1.5 V. The manufactured device allows electrical control of the modulation depth of the mesogenic layer anisotropy by applying an external control voltage to transparent homogeneous conductive layers deposited on the inner surfaces of both glass substrates. The initial microstructured spatial modulation of the refractive index is represented by periodically alternating concentric twist and planar ring domains and is realized using photoinduced surface anisotropy of the orienting coating of the azo dye AtA-2 (the thickness of the photoorientant, with an absorption band in the wavelength range of 450-520 nm, is about 30 nm).

Fig. 1 shows phase transparant images constructed by the Fresnel LC lens at different voltages on the element. The formation of a clear image corresponds to a voltage amplitude of 3 V. Further increase of the electric field amplitude leads to decrease of the image quality, and at 20 V the camera captures theintensity distribution corresponding to the Fourier image of the transparant (diffraction in the far-zone).



U=0V *U=3V* *U=8V* *U=3V*

Fig. 1. *Transparant images constructed by the Fresnel LC lens at different voltages on the element*.

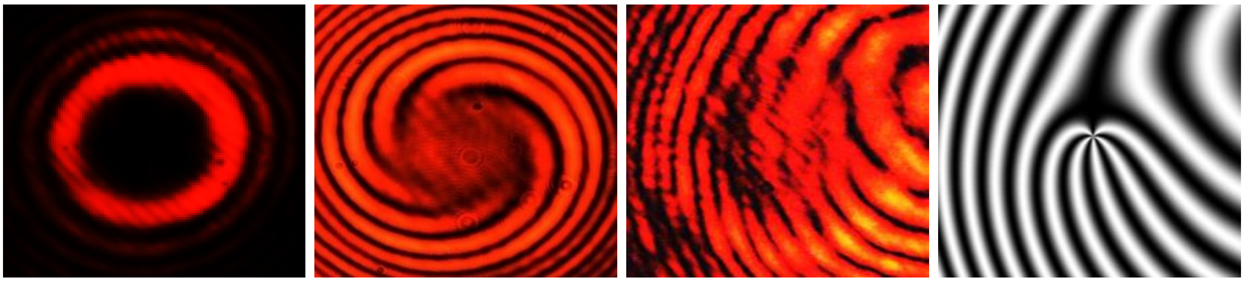
We have developed a method for determining the topology of a phase vortex using a Fresnel lens. To determine this parameter, the phase singular beam must diffract in a shifted position from the center of the NLC Fresnel zone plate. A forward-passing wave will propagate in the direction of the zero diffraction order, while diverging and converging waves will propagate in the directions of +1 and -1 diffraction orders, respectively. Each of these has the phase topology of the original wave.

Since the wave front of the phase singular beam has a helical shape and its transverse phase gradient is circulating (it has a very large value near the core and is insignificant at the periphery) [10], then at the periphery of the beam it can be considered as quasi-flat. In this regard, the formation of an anisotropic diffraction structure with a spatial frequency gradient in the LC element ensures coherent addition of the central part (“core”) and the periphery (“ring”) of the beams scattered in the directions of the minus first and zero diffraction orders. In this case, information about the topology of the optical vortex is encoded in the resulting interference pattern.

III. RESULTS AND DISCUSSION

The optical characteristics of the element can be controlled by applying an external electric field to the transparent electrodes of the NLC device. When applying an external control voltage below the optical threshold of the liquid crystal, the twist-planar oriented Fresnel zone plate has constant focusing properties (the power density at the focus increases 300 times). Increasing the voltage leads to a non-monotonic dependence of the focusing action of the device: maximum focusing is achieved at the optimal voltage (3 V), switching off the focusing mode of operation (switching off the diffraction structure) occurs at a voltage of about 25-27 V [18].

Fig. 2 shows the experimental (Fig. 2c) and theoretical (Fig. 2d) results of testing the developed method. An optical vortex with a topological charge $\ell = +5$ (Fig. 2a) passed through the NLC Fresnel zone plate. As a result of diffraction on the microstructured element, a signal (converging wave propagating in the direction of -1 diffraction order) and a reference (forward-propagating - 0 diffraction order) waves were formed. In the area of spatial overlay of the reference wave "ring" with the signal wave "core", a characteristic interference pattern, the so-called "twisted fork", is observed. The direction of the twist (clockwise or counterclockwise) allows one to uniquely determine the sign, and the number of branches - the value of the topological charge. Before the focal plane of the optical element, the sign of the charge entering the vortex element is preserved, after - it is inverted. The method was experimentally verified using coherent addition of an optical vortex with a spherical wave in a Mach-Zehnder interferometer (Fig. 2b).



a *b* *c* *d*

Fig. 2. *Intensity distribution:*

a) *in the cross section of a phase vortex with a topological charge ℓ=+5;*
b) *interference pattern of an optical vortex with a topological charge ℓ=+5 with a coherent spherical wave;*
c) *interference pattern of the "core" of an optical vortex with a topological charge ℓ=-5, propagating in the direction of -1 diffraction order, with the "ring" of an optical vortex propagating in the direction of 0 diffraction order (experimental results after the focal plane of the NLC lens);*
d) *interference pattern of the "core" of an optical vortex with a topological charge ℓ=-5, propagating in the direction of -1 diffraction order, with the "ring" of an optical vortex propagating in the direction of 0 diffraction order (theoretical results after the focal plane of the NLC lens).*

The conducted experimental studies using laser radiation with a parametric frequency converter showed the effective operation of the method in the visible and near-infrared range.

IV. CONCLUSION

A simple interference method for determining the phase topology of optical vortices based on preliminary diffraction on an electrically controlled achromatic NLC photonic device has been proposed and tested. The diffraction element is a compact Fresnel zone plate that can be switched off using low voltages. The conducted experimental and theoretical studies demonstrate the effectiveness

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and prospects of using the proposed electrically tunable NLC element to control the light field and to determine the topological charge of phase singular beams in the wavelength range 532-1100 nm.

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