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Switchable Diffraction Gratings Based on the Periodic Binary Alignment of a Nematic Liquid Crystal

K. G. Kamiak[a, *], O. S. Kabanova[a], I. I. Rushnova[a], E. A. Melnikova[a], and A. L. Tolstik[a]

[a] *Belarus State University, Minsk, 220030 Belarus*

**e-mail: fiz.komyak@bsu.by*

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Abstract—The patterned photoalignment of nematic liquid crystal is used to produce one-dimensional diffraction gratings. The effect the orientation of molecules in adjacent liquid crystal domains has on the diffraction properties of the fabricated binary structures is established. Diffraction gratings based on the binary alignment of nematic liquid crystal are characterized by electrically switchable optical properties and control the spatial and polarization characteristics of light beams effectively.

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INTRODUCTION

Liquid crystals (LCs) are a unique class of soft organic materials that combine the properties of liquids with a certain degree of molecule alignment. Being birefringent optical media, LCs allow us to perform a series of the most important operations related to the generation, detection, and transformation of optical polarization states. Along with high responsiveness to the action of external fields (electric, thermal, and optical), the ability to organize themselves into complex structures results in the demand for LC materials for creating such competitive photon components as optical filters, switches, diffraction gratings, lens arrays, vortex retarders, and spatial light modulators [1–7].

Switchable diffraction LC gratings are used successfully as optical elements for spatial switching, multiplexing, and transforming the polarization of light beams [8–11]. The principle of generating such structures is based on creating a locally inhomogeneous (multidomain) distribution of LCs on a current-conducting surface. Electrodes of special configuration, the microrubbing of aligning films, and the patterned photoalignment of photosensitive azo dyes are used to control the orientation of LC materials.

The patterned photoalignment of LC materials [12, 13] has enjoyed great success in recent decades as the best way of fabricating periodically ordered one-, two-, and three-dimensional optical structures that control the spatial, phase, and polarization characteristics of optical fields [14–16]. Noncontact photoalignment offers the possibility of locally controlling the distribution of an LC director on a surface with high spatial resolution (several microns). Azo dyes are the leading photoaligned materials used for fixing the boundary conditions of LC director distribution. Photosensitive azo dyes are a universal platform of materials in the development of modern technologies for micro- and nanostructuring in photonics. The advantages of photoaligned azo dyes are high azimuthal energy of cohesion with LC materials (~10^{-4} J m^{-2}), photo- and thermostability of aligning properties, and high photosensitivity in the visible range of the spectrum. It is therefore important that we study the possibilities of using photoaligned azo dyes to produce local inhomogeneous LC structures that enable light beam steering.

This work presents switchable one-dimensional gratings with binary alignments of nematic LCs fabricated via the patterned photoalignment of AtA-2 azo dye films. The intensity and state of polarization of radiation diffracted into the zero and first orders are switched by a variable external electric field that realigns the LC director in the volume of a layer.

EXPERIMENTAL

The functional base of our electrically switchable diffraction gratings was thin nematic LC layers characterized by local-inhomogeneous (binary) molecule orientation. This work considers two varieties of binary structures with different types of molecule orientations in the adjacent LC domains (Fig. 1). The first structure is based on periodical alteration of LC domains with a twisted/planar molecule orientation (Fig. 1a). A typical feature of the second structure is a twisted/twisted orientation with LC rotation in in opposite directions in adjacent domains (Fig. 1c).

Sandwich-type LC cells were fabricated by using glass substrates covered uniformly with a conducting

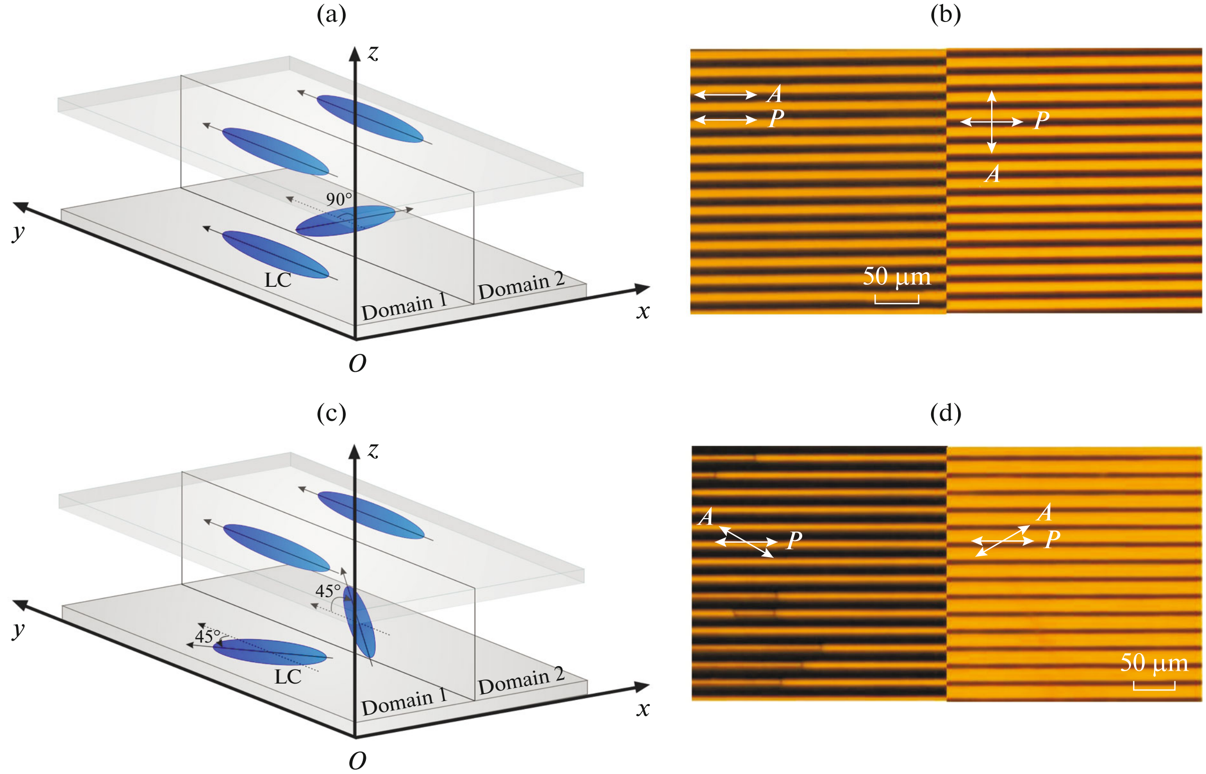

Fig. 1. (a, c) Schematic and (b, d) corresponding polarization microphotographs of binary diffraction structures with (a, b) twisted/planar LC orientation and (c, d) twisted/twisted orientation characterized by opposite direction of LC rotation in adjacent domains at voltage $U = 0$.

layer of indium tungsten oxide (ITO) that had resistance of 50 Ohm/sq. Photosensitive AtA-2 azo dye [17] synthesized at the Materials and Technologies of LC Devices Laboratory at the Belarus National Academy of Sciences' of Institute of the Chemistry of New Materials was used as a photoaligned material. Thin films of AtA-2 azo dye were applied onto the thoroughly cleaned surfaces of substrates by means of rod coating using an automated laboratory facility [18]. The aligning properties of AtA-2 azo dye emerged upon irradiation by linearly polarized light with a wavelength of 465 nm. The direction of the induced surface orientation was perpendicular to the direction of the polarization of the activating radiation. Two types of substrates were prepared for producing cells with binary LC alignment: *A* had substrates with uniform planar alignment of the azo dye, and *B* had substrates with binary (twisted/planar or twisted/twisted) alignment of the azo dye. A one-mask process that included two-stage irradiation of the *B*-type substrates with linearly polarized radiation from a light-emitting array ($\lambda = 465$ nm, $P = 60$ mW cm^{-2}) was used to form structures of binary surface alignment. After the first stage of the uniform irradiation of a film's surface (radiation dose $D_1 = 2.0$ J cm^{-2}), it was irradiated for the second time ($D_2 = 9.0$ J cm^{-2}) through an amplitude photomask with a period of $\Lambda = 20$ μm, which allowed us to change the direction of the alignment structures in the unmasked regions via rotating the plane of polarization of activating radiation by a specified angle. The *A*-type substrate was exposed uniformly to linearly polarized radiation. The one-mask exposure process for azo dye films allowed us to produce binary diffraction LC structures with (1) alternating twisted ($\beta = 90°$) and planar domains and (2) alternating oppositely twisted domains ($\beta_1 = 45°$ and $\beta_2 = -45°$), where β is the angle of LC rotation. The thickness of the air gaps in the cells was controlled by fiber spacers with thickness $d = 20$ μm. The cells were filled with nematic LC material of the ZhK-1282 type ($n_e = 1.678$, $n_o = 1.509$; Scientific Research Institute of Organic Preproducts and Dyes, Russia) through capillaries in the isotropic phase. It was established by means of polarization microscopy that the fabricated gratings were characterized by the defectless orientation of nematic LCs (Figs. 1b, 1c). The period of the diffraction structures was $\Lambda = 20$ μm, which agrees with that of the amplitude photomask used during the patterned photoalignment of azo dye films.

RESULTS AND DISCUSSION

The diffraction and polarization properties of the fabricated binary LC structures were studied on an

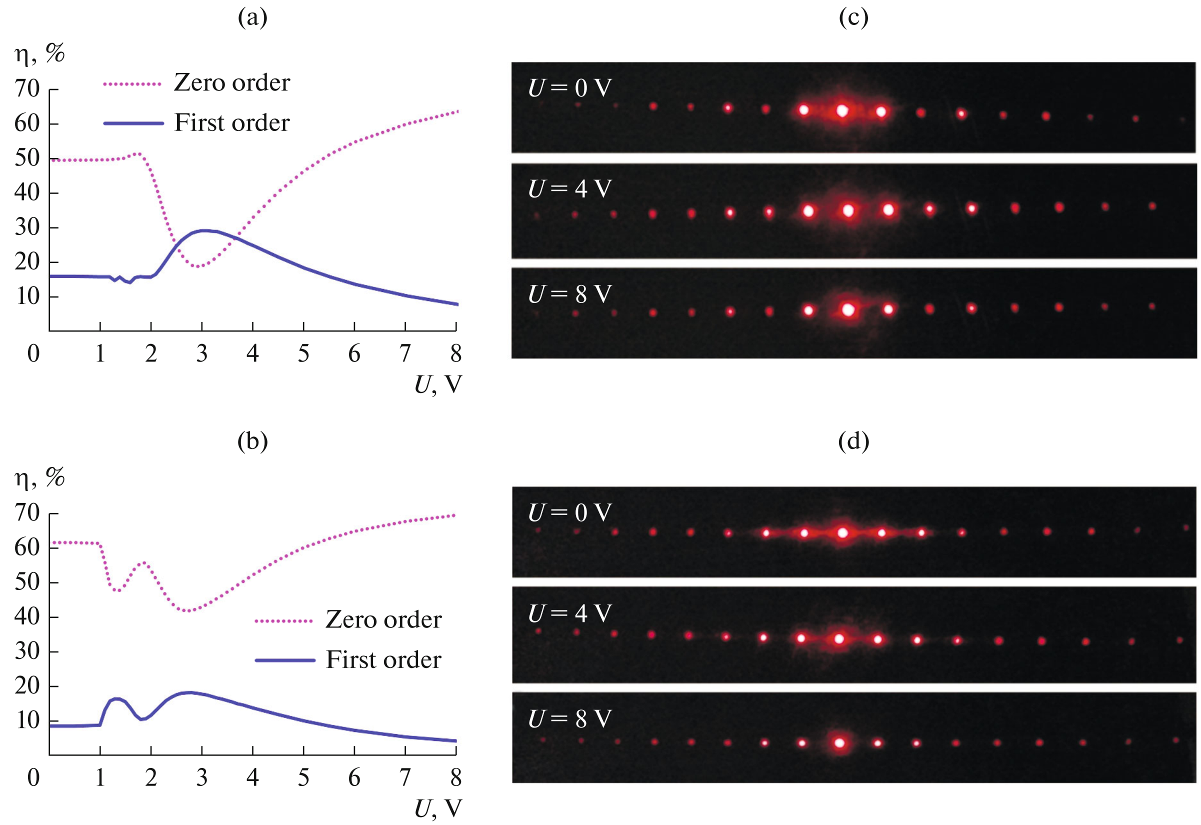

Fig. 2. Dependences of (c, d) diffraction patterns and (a, b) efficiencies of diffraction of the zero and first orders on voltage U for the binary gratings with (a, c) twisted-planar LC orientation and (b, d) oppositely rotated twisted-twisted LC orientation.

experimental facility consisting of a He–Ne laser generating a narrow beam of linearly polarized (along axis OY) light with a wavelength of 632.8 nm, an iris diaphragm, a generator of variable square-wave signals (frequency, 1 kHz), and an analyzer and a photodetector that recorded the intensity of radiation diffracted into the mth order. We calculated the efficiency of diffraction η_m that characterized the distribution of the transmitted light energy according to orders of diffraction m using the formula

$$\eta_m = \frac{I_m}{I_0} \times 100\%, \qquad (1)$$

where I_m is the intensity of light in diffraction of the m-th order, and I_0 is the intensity of the light beam incident on the grating. Figure 2 presents the dependences of the efficiency of diffraction of the zero and first orders on voltage for the two variants of binary LC gratings.

A typical feature of the diffraction pattern of the binary structure with twisted/planar LC alignment was a considerable drop in the intensity of the even diffraction maxima when there was no cell voltage (Fig. 2c), testifying to the rectangular profile of the grating. At a cell voltage of <1.5 V, the efficiency of diffraction for the zero and first orders remained unchanged at $\eta_0 = 49\%$ and $\eta_1 = 16\%$, respectively (Fig. 2a). The reorientation of LC molecules, accompanied by a change in optical anisotropy, began at voltage $U = 1.5$ V, which corresponds to the threshold voltage of the twist effect for our nematic LC. In the 1.5...3.0 V range of the control voltage, we observed a considerable increase (from 16 to 29%) in the efficiency of diffraction of the first order, while the efficiency of diffraction of the zero order fell from 49% to 19% (Fig. 2a). Upon a further increase in the external electric field, the LC molecules changed their orientation from periodic binary to uniform homeotropic, accompanied by an increase in intensity of the transmitted light beam and a considerable drop in the intensity of light beams diffracted to the first order.

The binary structure with oppositely rotated twisted/twisted LC alignment was characterized by relatively lower values of the efficiencies of diffraction in the off mode: $\eta_0 = 61\%$ and $\eta_1 = 8\%$ (Fig. 2b). The efficiency of diffraction of the zero order fell at cell voltages $U_1 = 1.35$ V and $U_2 = 2.70$ V, while the efficiency of diffraction of the first order rose. At fairly high voltages ($U > 8.0$ V), phase advance $\varphi = 2\pi\Delta n d/\lambda$, where Δn and d are the birefringence of the LC and the cell thickness, respectively, tended to zero, resulting in the disappearance of diffraction properties.

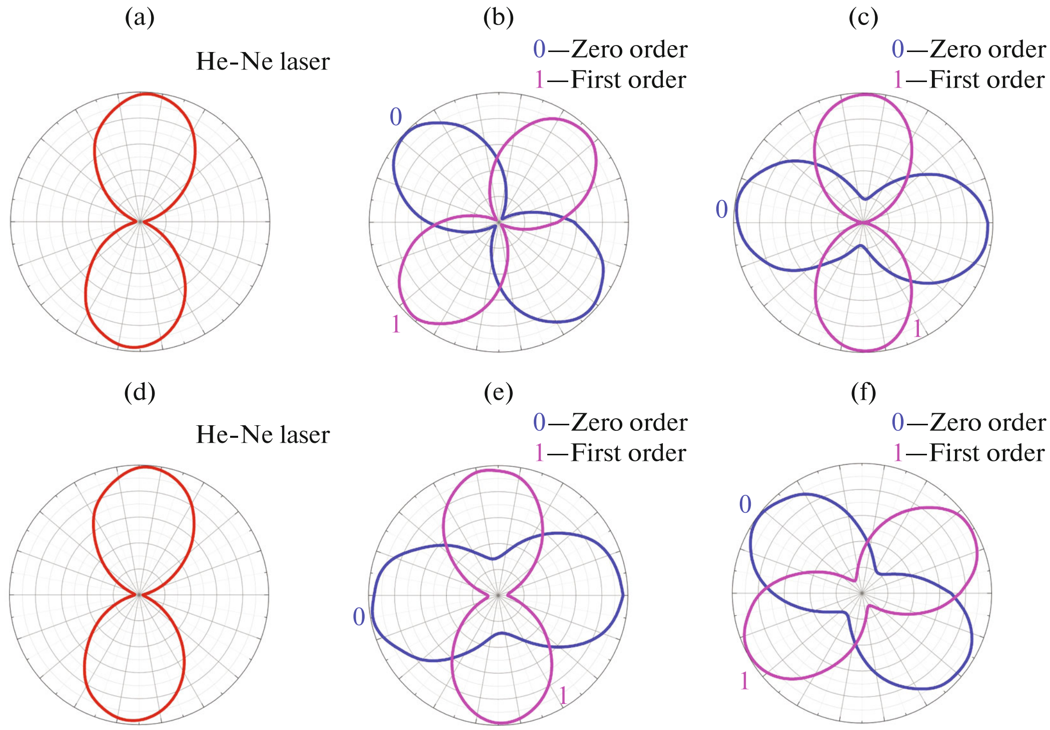

Fig. 3. Diagrams of the polar polarization of transmitted and first order diffracted light beams for binary gratings with (b, e) twisted-planar LC orientation and (c, f) oppositely rotated twisted-twisted LC orientation at voltages (b, c) $U = 0$ and (e, f) $U = 3.0$ V. Incident radiation was polarized linearly along axis OY (a, d).

Figure 3 presents the polar polarization diagrams of beams transmitted and diffracted into the first order at cell voltages $U = 0$ and $U = 3.0$ V. The incident radiation was polarized linearly along axis OY (Figs. 3a, 3d). In the off mode, the directions of the polarization of the transmitted beams rotated by 45° and 90° in the twisted/planar (Fig. 3b) and oppositely rotated twisted/twisted (Fig. 3c) gratings, respectively. In addition, the direction of polarization of the bean diffracted into the first order rotated by −45° for the twisted/planar LC structure and remained unchanged for the oppositely rotated twisted/twisted LC structure. The light beams transmitted and diffracted into the first order were characterized by orthogonal directions of polarization for both types of binary LC gratings (Figs. 3b, 3c).

When the voltage was raised to $U = 3.0$ V, the semimajor axes of the ellipses of polarization of transmitted light beams rotated by 90° and 45°, respectively (Figs. 3e, 3f). With the beams diffracted to the first order, the semimajor axis of the ellipse rotated by −45° only for the binary twisted/twisted LC structure (Fig. 3f). At the same time, the ellipticity of the state of polarization of the light beams differed from zero (Figs. 3e, 3f), due to the value of the phase advance in the LC layer.

CONCLUSIONS

The possibilities of the patterned photoalignment of AtA-2 azo dye for fabricating diffraction optical structures based on binary orientation of nematic LC were demonstrated. The diffraction and polarization properties of switchable LC gratings with twisted/planar and oppositely rotated twisted/twisted orientations of molecules in adjacent domains were studied. The efficiency of first order diffraction was controlled with an external variable electric field that allowed us to reach maximum values $\eta_1 = 29\%$ for twisted/planar and $\eta_1 = 19\%$ for twisted/twisted LC orientations at the optimum control cell voltages of 3.0 and 2.7 V, respectively.

We analyzed diagrams of the polarization of light beams transmitted and diffracted into the first order in the off mode and at voltage $U = 3.0$ V. It was established that diffraction of the zero and first orders is characterized by orthogonal states of polarization for both variants of the studied binary LC structures. The plane of polarization of transmitted radiation was rotated by 45° and 90°, depending on the control voltage, and the plane of polarization of the first order diffracted radiation was rotated by −45°.

The proposed binary LC gratings were characterized by electrically switchable optical properties and allowed the effective spatial-polarization control of light beams. Our results can be used in developing competitive photon devices and systems for controlling optical radiation.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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