



# Electrically switchable photonic liquid crystal devices for routing of a polarized light wave

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## ABSTRACT

The new mode of LC alignment based on photoalignment AtA-2 azo dye where the refractive interface between orthogonal orientations of the LC director exists without voltage and disappeared or changed with critical voltage has been proposed. The technology to fabricate electrically controlled liquid crystal elements for spatial separation and switching of linearly polarized light beams on the basis of the total internal reflection effect has been significantly improved. Its distinctive feature is the application of a composite alignment material comprising two sublayers of Nylon-6 and AtA-2 photoalignment azo dye offering patterned liquid crystal director orientation with high alignment quality value  $q = 0.998$ . The fabricated electrically controlled spatially structured liquid crystal devices enable implementation of propagation directions separation for orthogonally polarized light beams and their switching with minimal crosstalk.

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## 1. Introduction

At the present time the integrated optics technologies are actively developed because they enable designing of innovative functional elements to control the spatial and polarization characteristics of radiation being compact, reliable, and efficiently produced [1,2]. Among the materials for the creation of such devices, liquid crystals (LC) are very promising due to their high birefringence ( $\Delta n \sim 0.1\text{--}0.5$ ) and due to the possibility for its control by low applied voltages (1–10 V) [3,4]. With the use of liquid crystals, various imaging systems [5], optical switches [6,7], spatial light modulators [8], diffractive elements [9] are manufactured; LC integrated components having sophisticated optical anisotropy are developed for fiber optical communication lines and for the data processing and communication devices (compact optoelectronic waveguides, dividers, multiplexers, etc.) [10]. The operation principle of these LC devices is based on the effect of refraction and reflection of a light wave propagating within the LC layer, at the interface of two LC regions with different orientations of the director [11].

Analysis of different combinations for mutually orthogonal orientations of the LC director in the adjacent domains of a nematic liquid crystal has made it possible to find the optimum configurations for realization of the total internal reflection (TIR) effect of linearly polarized light beams [12]. Using a planar orientation of the director in the perpendicular directions, and also the planar and homeotropic

orientations of the director in adjacent regions of the element, spatial separation of *s*- and *p*-polarization of the light beams at the domains interface is realized.

It should be noted that the early attempts of such LC elements manufacturing [12,13] were successful at realization of the polarization separation effect but failed to ensure a low level of crosstalk. Besides, a thickness of an LC layer in the manufactured LC elements was about 200  $\mu\text{m}$  and required the use of high control voltages (50–100 V).

This paper presents a technological innovation to produce LC elements with the electrically controlled interface between two LC domains with orthogonal orientations of the director. Three options of director orientation in LC cells have been chosen to provide reflection of one polarized radiation component and full (almost full) transmission of the orthogonally polarized component as well as their switching when the reflected and transmitted beams interchange their positions under the effect of an applied electric field.

## 2. LC cells and their fabrication technology

To realize the total internal reflection effect, we select two geometries associated with a planar orthogonal orientation of the director in two regions of the element (Fig. 1(a)) and with the planar and homeotropic orientations of the director (Fig. 1(b)). As noted, such

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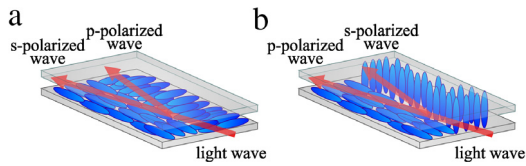


Fig. 1. Options of the LC director orientations: (a) — planar orthogonal orientation of the director in adjacent regions; (b) — planar and homeotropic orientations of the director in adjacent regions.

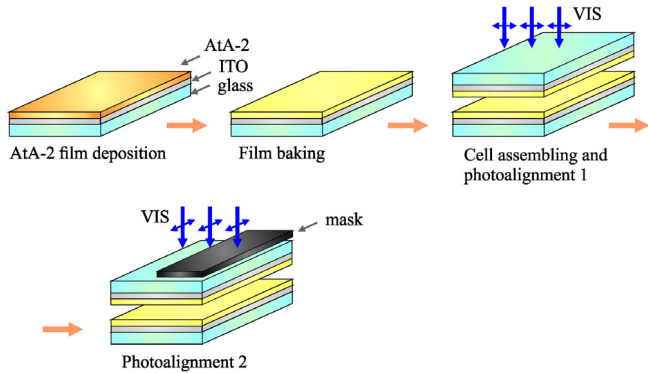


Fig. 2. Process flow of the LC cell fabrication with two domains planar photoalignment of LC.

options of the director orientation enable design of LC devices for separation of the polarized light beams [13].

The initial molecular orientation of a nematic LC was set by the contactless photoalignment method [14,15]. The AtA-2 azo dye [16] synthesized at the Institute of Chemistry of New Materials of the Belarusian National Academy of Sciences, that is characterized by high azimuthal anchoring energy ( $>1 \times 10^{-4} \text{ J/m}^2$ ), thermostability and photostability [17], was selected as an alignment material. LC photoalignment direction of AtA-2 film is efficiently induced by linearly polarized 440–460 nm LED light. Opportunity of visible light utilization for photoalignment offers exposure of the assembled LC cells with glass substrates on both sides, thus simplifying fabrication and reducing the price of photonic LC devices.

The planar orthogonal orientation of the director in both regions of LC cells was created by the two stage photoalignment method illustrated in Fig. 2.

The AtA-2 alignment layer was wet deposited on glass substrate with transparent conducting layer (ITO) from 2% 2,2'-Dimethylformamide solution using rod coater. The sample was baked at  $T \sim 100\text{--}140^\circ\text{C}$  to remove the residual solvent. The reversibility of AtA-2 photoalignment makes it possible to change locally and to modify multiple times the previously formed direction of LC orientation. This feature forms the basis for the formation of planar orthogonal LC director domains. First, assembled cell is exposed with linearly polarized LED light with intensity  $I = 15 \text{ mW/cm}^2$  during the period  $t = 20 \text{ s}$ . Then the electrical vector direction is rotated by  $90^\circ$  and the cell is exposed again, through the amplitude mask that covers half of the sample, for  $t = 60 \text{ s}$ . Molecular orientation of the azo dye in the region of the cell covered by the mask is invariable, as distinct from the adjacent region, where AtA-2 layer forms new LC alignment direction perpendicular to the electrical vector of linearly polarized light exposure.

The alignment quality of the LC molecular orientation in the photoaligned samples was evaluated by the follow expression:

$$q = \frac{T_{\max} - T_{\min}}{T_{\max} + T_{\min}}, \quad (1)$$

where  $T_{\max}$  — maximal (in the case of parallel polarizers) and  $T_{\min}$  — minimal (in the case of crossed polarizers) transmittance of the sample.

Measured in this way quality parameter  $q$  for the manufactured samples is  $q = 0.996\text{--}0.998$  at the wavelength  $\lambda = 632.8 \text{ nm}$ .

In the LC cell shown in Fig. 1(b), the refractive index interface is formed due to the applied electric field. Using structured electrode at one of the cell substrates, one can set a homeotropic orientation of the director in the region of the electrode by application of electric field higher than the threshold value [18]. In the other part of the cell, the initial planar LC director orientation is maintained. To create a conducting layer covering a part of the cell, as a rule, the photolithographic method is used [19]. The difficulty in manufacturing of such LC devices is associated with the fact that, in the process of the pattern formation at the conducting layer, it loses homogeneity, at the boundary with the etched electrode some spikes are formed hindering deposition of a uniform thin film (20–100 nm) of the photoalignment AtA-2. In cells with the partial conducting layer, the orientation quality parameter  $q$  is usually below  $q \leq 0.930$  causing a high level of crosstalk when the light beams are switched over.

To improve the alignment quality of LC cell with patterned photoalignment the original technology is implemented based on a composite photoalignment material that combines Nylon-6 and photoalignment AtA-2 azo dye. Adding buffer layer (Nylon-6) allows improvement of photoalignment layer characteristics [20]. Fig. 3 demonstrates the manufacturing process flow of LC cells with the planar and homeotropic orientations of the director.

A glass plate with an opaque conducting layer of chromium is used as a lower substrate. First, the chromium layer is partially etched from a half of the substrate by the photolithographic method. Next Nylon-6 sublayer is uniformly deposited on top the substrate and baked at  $180^\circ\text{C}$  for 1 h. The Nylon-6 smooths the spikes formed at the interface of etched chromium and improves the sample surface. The uniform thin film of AtA-2 azo dye is deposited on top of Nylon-6 sublayer and baked at  $T \sim 100\text{--}140^\circ\text{C}$  for 5 min. The upper substrate is manufactured by the standard technology when the photoalignment material is deposited to a glass plate with a transparent conducting layer and then the sample is baking.

Assembled cell is exposed with linearly polarized LED light with intensity  $I = 15 \text{ mW/cm}^2$  during the period  $t = 20 \text{ s}$  to obtain a homogeneous planar orientation of LC molecules. The orientation quality parameter of the manufactured samples comes to  $q = 0.996\text{--}0.998$  at the wavelength  $\lambda = 632.8 \text{ nm}$  being much higher, when the Nylon-6 layer was not used. A thickness of the LC layer in the manufactured elements is about  $20 \mu\text{m}$ , enabling the control over the refractive interface at the voltages up to 5 V. The cells were filled with nematic liquid crystal LC-1289 (developed at the Research Institute of Organic Intermediate Products and Dyes, Moscow) with the refractive index anisotropy  $\Delta n = 0.156$  at the wavelength  $\lambda = 632.8 \text{ nm}$  ( $n_e = 1.69, n_o = 1.53$  for all cases of alignment materials in presented technologies). The order parameter  $S$  of the LC-1289 obtained from the multiple frustrated total internal reflection method of IR spectroscopy is  $S = 0.67$  [21]. The threshold voltage for realignment of the LC director is  $U_{tr} = 1 \text{ V}$ .

### 3. Experimental results and discussion

Linearly polarized radiation of a helium–neon laser with the wavelength  $\lambda = 632.8 \text{ nm}$  and the power  $P = 300 \mu\text{W}$ , focused by the 10 lens (waist diameter  $d = 16 \mu\text{m}$ ), was input into the end of LC cells at the incidence angle exceeding the critical angle for the TIR [22]. Table 1 presents experimental photographs of the laser radiation propagation in LC cells depending on polarization of the incident radiation and on the voltage applied to the cell. Indicated in Table 1 angle  $\alpha$  between the normal of the interface and the light beam differs from the incidence angle  $2^\circ$  only for set directions of LC orientation. The deviation of the incident angle from the light beam derives from the theoretical issue of the relation between wavenumber vector and Poynting vector in the anisotropic media [22]. It should be noted, the angular difference between the wavenumber vector and the Poynting vector is much less

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