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V-shaped electro-optical mode based on deformed-helix ferroelectric liquid crystal with subwavelength pitch

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Abstract — V-shaped electro-optical response is shown, both theoretically and experimentally, to be an inherent property of a deformed-helix ferroelectric liquid-crystal cell (DHFLC) under a special choice of the applied rectangular alternating-electric-field waveform, frequency, and cell geometry. In contrast to other known V-shaped ferroelectric liquid-crystal (FLC) modes, the discovered V-shaped switching is observed in a broadband frequency range including 1 kHz, and not at a certain characteristic frequency. This type of V-shaped switching allows for a drastic increase in the operating frequency of field-sequential-color (FSC) LCD cells in comparison with fast nematic liquid-crystal (NLC) modes.

Keywords — Ferroelectric liquid crystal, deformed helix, V-shaped response, field sequence color.

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1 Introduction

Nowadays, liquid-crystal displays (LCDs) are the prevailing display devices. Therefore, their optical efficiency is of high demand because of the vital importance of energy-saving technologies. As a matter of fact, LCDs still have a low optical throughput. The main reason is that color filters, which are built into the pixel structures of the LCD to form full-color images, transmit only one third of the backlight. This drawback can be alleviated by using the field sequential-color (FSC) approach extended to LCDs¹, where full-color images can be observed without using filters by displaying sequentially red, green, and blue subimages faster than the time resolution of human eyes.^{2,3} For this purpose, fast NLC modes have been previously used.⁴ However, the response time of LCDs are still inferior to that of existent competing technologies, such as plasma-display panels (PDP) or organic light-emitting diodes (OLEDs). The target LC-cell response time for FSC and 3-D displays should be at least less than 1 msec (240-Hz frame frequency) to provide a high resolution, low power consumption, and extended color gamut, while even higher operating frequencies are required to avoid the color break-up effect.⁵ A twisted-nematic (TN) 1.6- μm thin cell for color-sequential LCDs with a response time of about 1 msec have been demonstrated but at a temperature higher than 45°C.⁶

A good candidate for the new generation of FSC LCDs is the FLC,⁶ which is considerably faster than NLC modes. Producing full-color displays requires the electro-optical response to be continuous, hysteretic-free, and insensitive to the sign of the applied voltage. But the prob-

lem is that the hysteresis is a characteristic property of FLCs.⁷

Nevertheless, under certain conditions, the FLC electro-optical response can satisfy the above requirements. This effect is known as V-shaped switching⁸ and is observed usually with a triangular voltage waveform at a certain characteristic frequency f_i corresponding to the inverse of the electro-optical hysteresis direction from the normal to the abnormal one.^{9–12} The phenomenon has been shown to be an apparent effect in the optical transmittance^{13–15} whereas the liquid-crystal director reorientation exhibits normal hysteresis even at f_i . Such a V-shaped response at a fixed frequency f_i can hardly be useful for LCD applications that require a rectangular alternating driving voltage which is equivalent to a broad spectral range of electrical signal.

In this paper, we discuss another type of V-shaped mode which, by contrast to the known modes^{6,7,9,13,16,17} is observed in the DHFLC cells^{18–21} with a certain geometry and is characterized by a broad operation frequency range under rectangular alternating-voltage waveform as we already reported.²² The latter is a key advantage that makes this effect promising for applications in FSC displays, especially ones based on FLCs with a subwavelength helix pitch.^{23,24}

The novelty of this paper compared to our earlier report on the same subject²² involves two aspects. First, in this paper, we propose, for the first time, a simple theoretical method to describe the considered electro-optical mode, as well as to prove good agreement between theory and experiment. Secondly, here we report for the first time the development of an FSC display cell based on V-shaped

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DHFLC cells, with red-, green-, and blue-light-emitting diodes (LEDs) providing a color frame frequency of 1 kHz.

2 Experimental

In our experiments, the FLC-587 with a helix pitch $p_0 = 150$ nm (at 22°C) from P. N. Lebedev Physical Institute of Russian Academy of Sciences was used, whereas the thickness of the FLC layer $d_{FLC} = 1.7$ μm was greater than the FLC helix pitch. The phase transition sequence of this liquid crystal at heating from the obtained solid-crystalline state is

while cooling down from the smectic C* phase, crystallization occurs at about -10 to -15°C . Other necessary measured characteristics of the FLC such as spontaneous polarization, rotational viscosity, *etc.*, are given below.

In the framework of this approach, ITO surfaces of glassy substrates used for the preparation of DHFLC cells were covered with dielectric 50-nm SiO_2 layers performed by using the Plasma Enhanced Chemical Vapor Deposition (PECVD) method. The SiO_2 surfaces were covered with 20-nm layers of photo-aligning substance – azobenzene sulfonic dye SD-1.^{25,26} The photoaligning substance 1% solutions in N,N-dimethylformamide (DMF) were spin-coated onto SiO_2 layers at 3500 rpm and dried at 155°C. The UV light was irradiated onto surfaces of SD-1 layers for 1 hour using a super-high-pressure Hg lamp, an interference filter at 365 nm, and a polarizing filter. The polarized light intensity on the surface of the layers was 6 mW/cm².

FIGURE 1 — Experimental setup for electro-optical measurements of DHFLC cells. A cell placed between crossed polarizers is illuminated with light from a He–Ne laser ($\lambda = 632.8$ nm) and the output is collected by a photodetector.

The thickness of the azo-dye layer has been measured by using the AFM method.

Assembled DHFLC cells exhibit no light diffraction in the visible spectral range when the applied electric field $\mathbf{E}$ is below the critical field E_c of the helix unwinding because of the subwavelength helix pitch.^{23,24} It is very beneficial to improve the optical quality of the cells.

The electro-optical measurements were performed in an automatic regime. The set-up scheme used in experiment is shown in Fig. 1. The basic element of this experimental set-up is a computer data acquisition (DAQ) board NIPCI 6251 from National Instruments. This board has 16 analog inputs and two analog outputs that provide, in reality, a minimal registration time of 1 μsec and a minimal voltage step of 0.1 V, forming any given form of electrical pulses and their necessary sequence. A photodetector was connected to an input board plate for the optical measurements.

In order to investigate the hysteretic properties of DHFLC cells, we have arranged several sequences of different rectangular alternating electric voltage V waveforms as shown in Figs. 2 and 3 (see corresponding diagrams in the figures). The requirement

$$\int_0^{T'} V(t') dt = 0 \quad (1)$$

FIGURE 2 — (a) Top – the applied voltage; bottom – the electro-optical response of the cell, placed between crossed polarizers at $\beta = 0$, the angle β is defined in Fig. 4; (b) V-shaped mode in the saturation levels of light-transmission levels measured at a rectangular alternating voltages, $f_{el} = 2$ kHz and 500 Hz. The light transmission T evaluated in comparison with the transmission of an empty cell placed between parallel polarizers. Solid black and dotted red lines are calculated transmissions at $f_{el} = 500$ Hz and 2 kHz, respectively.

FIGURE 3 — (a) Bottom is the electro-optical response of the DHFLC placed between crossed polarizers at $\beta = 0$; T_R , T_G , and T_B are transmissions of the primary red, green, and blue lights. Top is the driving voltage applied to the DHFLC and synchronized sequentially with corresponding red, green, and blue light-emitting diodes; (b)–(e) basic colors; (f)–(i) intermediate colors transmitted by the DHFLC as a result of sequential colors processing.

was satisfied at any waveform (here t' is time and T' is the waveform period). At any fixed frequency of waveform repetition, we arranged, due to the board NIPCI 6251, an automatic change in the voltage amplitude with the steps of 0.1 V from $-V$ to $+V$ through 0 and vice versa. Both the voltage amplitude and the light transmission of the cells placed between crossed polarizers were recorded automatically.

3 Results and discussion

To the best of our knowledge, no chevron structure of smectic layers of DHFLC cells has been observed in particular for the photo-alignment technique.^{27,28} Taking into account the above considerations, we assumed the structure of the DHFLC cells such as shown in Fig. 4. Actually, the assumption regarding the proposed structure is quite necessary both for an accurate description of the experimental conditions and for an adequate explanation of our theoretical model. Of course, the validity of this assumption regarding the structure shown in Fig. 4 is proven in this paper as a consequence of good agreement between experiment and theory.

From the known properties of DHFLC^{18–21} and our recent knowledge, the conditions for the V-shaped DHF mode to be observed in the cell geometry shown in Fig. 4 can be summarized as follows:

FIGURE 4 — Drawing of the DHFLC structure, placed between crossed polarizer P and analyzer A, and the helix axis Z is parallel to the substrates: (a) 1 – glassy substrates, 2 – ITO covered with aligning layers, 3 – smectic layers, 4 – the voltage generator; (b) a definition of the smectic layer characteristics: director $\mathbf{n}$ on the smectic cone with cone angle θ rotates around the helix axis Z along with the vector of the spontaneous ferroelectric polarization $\mathbf{P}_s$, ϕ is the angle in XY plane, between the X axis (which is perpendicular to the substrates) and the $\mathbf{P}_s$ vector.

$$p_0 < \lambda < d_{FLC} < D, \quad (2)$$

$$E < E_c, \quad (3)$$

$$\beta = 0 \text{ or } \beta = \pi/2, \quad (4)$$

$$\omega_{av} < \omega_c = \frac{Kq_0^2}{\gamma_\phi}, \quad (5)$$

where $\lambda = 632.8$ nm is the wavelength of the He–Ne laser (Fig. 1), D is the light-beam aperture, ω_{av} is the applied-voltage frequency, ω_c is the helix characteristic relaxation frequency, $q_0 = 2\pi/p_0$ is the wave vector of the helix, $K \cong 10^{-11}$ N is the helix elastic module in one constant approximation, $\gamma_\phi = 0.2$ Pa-sec is the azimuthal rotational viscosity, β is the angle between the polarizer plane, and the helix axis is shown in Fig. 4(a).

Two inherent properties of DHFLC have been observed under conditions (1)–(5) for a rectangular alternating electric field. First, similar to NLC cells, the electro-optical response is insensitive to the driving voltage polarity (Figs. 2 and 3) but the response time is two orders faster compared with the NLC's: $\tau_{0.1-0.9}^{on} \cong 80$ μ sec, $\tau_{0.1-0.9}^{off} \cong 60$ μ sec, as can be evaluated from Fig. 2(a), bottom curve. Second, the response exhibits a perfect V-shaped mode [Fig. 2(b)] in the saturation levels of light transmission obtained for the case of rectangular alternating applied-voltage pulses shown in Fig. 2(a). As is illustrated in Fig. 2(a), the electro-optical

response frequency f_{el} is twice as high than the driving voltage frequency f_{av} .

The reason for the hysteretic-free response [Fig. 2(b)] is that inequality (5) means the voltage waveform provides the conditions when the hysteresis cannot be observed, since the addressing of the light transmission levels starts from the same non-deformed helix that formed at zero voltage in between two pulses [Figs. 2(a) and 3(a), top diagrams]. The insensitivity of the response to the voltage polarity arises due to requirements (2) and (4) represent DHFLC without light diffraction in the visible spectral range.

The discovered mode can be modeled according to known approaches.^{29–31} So, the azimuthal angle φ [Fig. 4(b)] in a smectic layer is expressed as follows²⁹:

$$\varphi = q_0 z + \frac{P_s E}{K q_0^2} (\sin q_0 z) \cdot [1 - \exp(-t/\tau)], \quad (6)$$

where t is the electrical voltage pulse duration shown in Fig. 3(a), top; $P_s = 1.6 \times 10^{-3} \text{ C/m}^2$ is the FLC-587 spontaneous polarization at 22°C, $\tau = \gamma_\varphi / K q_0^2$ is a characteristic relaxation time of the helix. The light transmission T of the structure shown in Fig. 4(a) under conditions (1)–(5) is given by^{29–31}

$$T = \sin^2 \langle 2\alpha \rangle \sin^2 \left\langle \frac{\pi d_{FLC}}{\lambda} \Delta n_{eff} \right\rangle, \quad (7)$$

where $\langle \rangle$ stands for averaging over the helix pitch, α is the angle between the projection of the smectic-layer principle optical axis on the polarizer plane, and the normal to the smectic-layer plane [position 3 in Fig. 4(a)] is expressed as^{29–31}

$$\alpha = \arctan[\tan \theta \cdot \cos \varphi(z, t)]. \quad (8)$$

The effective birefringence Δn_{eff} of the smectic layer in Eq. (6) is given by³⁰

$$\Delta n_{eff} = \frac{n_{||} n_{\perp}}{\left[n_{\perp}^2 + (n_{||}^2 - n_{\perp}^2) \sin^2 \theta \sin^2 \varphi(z, t) \right]^{1/2}} - n_{\perp}, \quad (9)$$

where the measured parameters of FLC-587 are $\theta = 35^\circ$ and $n_{||} = 1.72$ ($n_{\perp} = 1.5$) is the extraordinary (ordinary) refractive index.

The light-transmission dependence on voltage $T(V)$ was calculated by using formulas (6)–(9) and the above listed parameters of FLC at $T = 22^\circ\text{C}$. The calculations were performed at two values of the voltage pulse duration: $t = 125 \mu\text{sec}$ corresponding to $f_{el} = 2 \text{ kHz}$ [dotted red line in Fig. 2(b)] and $t = 500 \mu\text{sec}$ corresponding to $f_{el} = 500 \text{ Hz}$ [solid black line in Fig. 2(b)]. The theoretical and experimental results are found to be in good agreement. So, the discovered V-shaped switching is observed in a broadband frequency range and a change in the transmission of the cell, with the frequency of the applied voltage well described in the framework of the proposed theoretical model.

This good agreement between experiment and theory confirms the suggested chevron-free geometry of Fig. 4. Additionally, it demonstrates that, under the above conditions (1)–(5) the hysteretic-free and insensitivity to the alternating rectangular voltage polarity electro-optical response can be regarded simply as an immediate consequence of the basic properties of the DHFLC structure.

Figure 2(b) exhibits a thresholdless hysteretic-free V-shaped mode while before²² a very evident optical threshold was observed using the same experimental method and with very similar DHFLC cell. We emphasize that it is only the optical threshold and there is no threshold for the dielectric response.

We already had rigorously proven, both experimentally and theoretically, that the electro-optical effect under consideration can be thresholdless and, on the other hand, can also demonstrate the optical threshold under certain physical conditions.³² Technologically, the transition from the optical threshold of the electro-optical response²² to the thresholdless mode [Fig. 2(b)] was realized due to the insertion of 50-nm SiO_2 layers between ITO and photo-aligning layers as it was previously described above.

The discovered mode exists in a broad temperature range at least within the temperature interval 22–67°C [Figs. 2(b) and 5]. The measured light transmission T at saturation of the V-shaped curves is about $T = 0.83$ –0.88 (Fig. 5), which is in good agreement with the values calculated from Eqs. (7)–(9). Indeed, the saturation of the light transmission is observed at complete helix unwinding, and in this case $\sin \varphi = 0$ and $\cos \varphi = 1$ [Eqs. (8) and (9)] according to Fig. 4. Hence, in this case, $\Delta n_{eff} = \Delta n = 0.22$ as it follows from Eq. (9) and measured parameters $n_{||} = 1.72$ and $n_{\perp} = 1.5$ while $\langle \alpha \rangle \equiv \theta = 35^\circ$ [Eq. (8)]. Substituting the values of these parameters in Eq. (7), we calculated the value of the light transmittance of a spatially homogeneous

FIGURE 5 — V-shaped mode in the saturation levels of light transmission at temperatures 26, 46, and 67°C, measured at rectangular alternating voltage shown in Fig. 2(a), at $f_{el} = 500 \text{ Hz}$. The light transmission T evaluated in comparison with the transmission of an empty cell placed between parallel polarizers. The voltage is changed automatically from – to + and vice versa with a step 0.1 V at any fixed temperature.

state $T = 0.81$ that corresponds to the light-transmittance saturation.

So, the tilt angle should be 45° to provide light transmission $T = 1$ as the saturation for the developed V-shaped mode, but for increasing tilt angle, the rotational viscosity γ_ϕ grows drastically³³:

$$\gamma_\phi = a_\phi \sin^2 \theta \cdot \exp\left(\frac{J_0 \sin^2 \theta + J_1 \sin^4 \theta}{kT}\right). \quad (10)$$

Here, k is Boltzmann constant; a_ϕ , J_0 , and J_1 are parameters of the FLC, which depend on the molecular structure but are independent of the FLC tilt angle and temperature. The helix characteristic relaxation frequency ω_c given by Eq. (5) decreases with increasing γ_ϕ , thus limiting the operation frequency of the FSC display cells. The FLC-587, with a tilt angle $\theta = 35^\circ$, was selected in our experiments to keep sufficiently high both the FLC transmission and switching frequency. Improving the FLC material parameters is not easy, but possible, and will be reported in our further publications.

Another problem of the DHFLC V-shaped mode is the FLC alignment quality that is currently not quite uniform. Therefore, the contrast ratio of the FSC cells was about 50:1, see Fig. 2(b). Nevertheless, the current level of the photoalignment technology and the optimization of FLC material parameters, which is in progress now, allow us to create the improved FSC DHFLC display cells, in particular by increasing the anchoring strength in thin FLC layers.

4 Elaboration of field-sequential-color DHFLC display cells

A model of an FSC display cell with red, green, and blue light-emitting diodes (LEDs) forming sequential fields of backlight about 100 μ sec in duration of each color has been elaborated. The cell was controlled by the voltage waveform appropriate for FSC displays [see Fig. 3(a), top].

LEDs were placed in the position labeled in Fig. 4 as “light beam $D > p_0$ ” and synchronized to the driving voltage pulses with the specially designed software. Figure 3(a) (bottom) shows that the cell light transmission is continuously tunable for each color field independently at both voltage polarities. A view of the basic and intermediate colors transmitted by the FSC cell at a color frame frequency of 1 kHz is illustrated in Figs. 3(b)–3(i).

A portable FSC display device based on the discussed V-shaped mode have been designed to illustrate an applications potential for this electro-optical mode. The device can be easily taken and stored because its size is less than 5×5 cm. Color images can be selected from the platform of a computer and transferred to the device at color frame frequency of 1 kHz using wireless communications. Typical color pictures of the FSC display device are shown in Fig. 6. Operation of the device was successfully tested within the temperature range $+20^\circ\text{C}$ to $+60^\circ\text{C}$.

FIGURE 6 — Photos of color images of the developed portable FSC display device operating at a color frame frequency of 1 kHz. The size of the display cell is 1.3×2 cm.

5 Conclusions

In conclusion, the DHFLC-based V-shaped switching was demonstrated and theoretically modeled in a broadband frequency range, including 1 kHz. The V-shaped electro-optical response is shown both theoretically and experimentally as an inherent property of DHFLC based on a special choice of the applied rectangular alternating-electric-field waveform, frequency, and the cell geometry. In contrast to the other known V-shaped FLC modes, the discovered V-shaped switching was observed in a broadband frequency range, and not at a certain characteristic frequency of the applied voltage.

The DHFLC application drastically increases the color frame frequency of the FSC LCD. We demonstrated the generation of full color images at the color frame frequency up to 1 kHz.

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