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Electrooptical Modes of Photoaligned of Ferroelectric Liquid Crystals: New Trends

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Abstract
Ferroelectric liquid crystal display (FLCD) is the fastest LC (liquid crystal) mode, which can work with both fast responses time and low driving voltages and is highly suitable for photonics and display applications. Fast switching ferroelectric liquid crystal (FLC) displays (FLCD) is a good candidate for the new generation of field sequential color (FSC) LCD, which proved to be better in response time, than usually used nematic LC. The best FLC parameters can be obtained on the basis of new electrooptical modes for photoaligned FLC. The basic electrooptical mode called Surface Stabilized FLC (SSFLC) mode known for a long time is not the best mode in FLC due to a poor contrast, high sensitivity to mechanical shock and nonuniform domain black state. All these problems are solved if the photoalignment technology based on nanosize azodye layers is applied for FLC cells fabrication. Novel photoaligned FLC devices may include FSC FLC with a high resolution, low power consumption and extended color gamut, which can be used in the screens of portable PCs, mobile phones, PDAs. The switchable goggles and lenses based on new FLC prototypes can be efficiently applied in the new generations of switchable 2D/3D LCD TV. FSC FLC, which is now one of the most advanced technologies for micro-displays can be also made on the basis of new materials and electrooptical modes in FLC. The photoalignment technology enables to solve the key problems usually faced in FLCD applications, such as (i) quality of FLC alignment on sufficiently large surface area; (ii) appropriate adjustable anchoring energy and pretilt angle; (iii) low losses in the alignment layers due to their small thickness and mechanical stability of FLC cells etc. The new fast responded FLC can be successfully applied in LC photonics devices such as switches, filters, lenses, and sensors.

Key Word and Phrases
Ferroelectric Liquid Crystals, Photoalignment, Electrooptical Modes, Displays, Photonics.

Introduction

Fast tunable display and photonic elements are one of the hot research topics these days [1]-[3]. While nematic liquid crystal (LC) devices are the dominant technology, because of its easy manufacturing, devices based on ferroelectric liquid crystals (FLCs) have grown in importance because they can switch up to 100 times faster than standard nematic LCs at the cost of less power consumption. FLCs have found applications in diffractive optics for the generation of digital holograms, adaptive beam steering systems, and polarization gratings. Additionally, high-speed communication systems, producing elements (such as switches, attenuators, polarization rotators) demand extremely fast response, stable, low loss, operable over a wide temperature range, and that require small operating voltages and extremely low power consumption. Thus, fast switching ferroelectric liquid crystal (FLC) is a good candidate for the new generation of photonic and display devices, which proved to be better in response time, than usually used nematic LC. However the FLCs are less popular for real applications because of difficult alignment process.

The photoalignment technology enables to solve the key problems usually faced in FLCD applications, such as (i) quality of FLC alignment on sufficiently large surface area; (ii) appropriate

adjustable anchoring energy and pre-tilt angle; (iii) low losses in the alignment layers due to their small thickness etc. The goal of this review is the further clarification of novel photoaligned fast ferroelectric LCD and photonics devices aimed at: (i) further fundamental study of the new appropriate electrooptical modes used for switching such as Electrically Suppressed Helix (ESH) FLC and Deformed Helix FLC (DHFLC); (ii) understanding of physical mechanisms of FLC interaction with a photoaligned surface of different photosensitive nature (diffusion, photo-crosslinking, photo-degradation) to produce a stable alignment with a controllable anchoring energy and pre-tilt angle over sufficiently large surface area; (iii) description of new fast responded FLC materials with fast switching and low power consumption; (iv) review of fast response optical FLC elements for photonics applications [3],[4], such as switches, gratings, Fresnel lenses, Circular Dammann (CD) grating, Spatial Light Modulators, attenuators and polarization rotators; (vi) description of regimes of operation to allow to use efficient addressing of FLCD. We are sure, that FLC is a future of LC research and applications, while photoalignment is the only possibility to solve all the existent FLC problems: stability, uniformity, high contrast and fast response time switching.

1. FLC Photoalignment

Since the beginning of the development of ferroelectric LCD's the techniques to align them has been a major issue [1]-[3]. Anchoring strength, tilt angle, homogeneity and the required small cell gaps are crucial problems to be solved to render ferroelectric displays manufacturable. Ferroelectric LC (FLC) display cells are extremely sensitive to dust particles that induce nucleation centers for dislocations especially at a very small cell gap (less than 2μm) which provides the best optical transmission of the cells [2],[5]. Moreover, buffing non-uniformity very often results in the appearance of large domains with opposite FLC directors (typical dimension is about 0.5÷3 μm). The domain formation leads to a poor reproducibility in manufacturing of FLC display devices. This is why the photoalignment FLC technology, which enables to avoid mechanical brushing, looks very promising.

A remarkable property of azo-dye aligning layers gives a good chance to provide a high photoalignment quality of FLC using the azo-dye layer [2]. The photoaligned FLC cell appeared to be better than prepared by buffing, if the UV-irradiation time of the azo-dye layer is high enough [2].

Zigzag defect-free Surface Stabilized Ferroelectric Liquid Crystal (SSFLC) cells were prepared using a photodegradable polyimide (PI) irradiated by Polarized Ultraviolet Light (PUVL) at normal incidence to the surface [6]. After irradiation, the FLC molecules were well aligned homogeneously, and the FLC cells showed a uniform texture without zigzag defects, which also indicates a well aligned layer structure. Zigzag defect-free alignment may result from the flatter surface, the much smaller and more constant pretilt angles, and the bigger cone angle than those achieved by rubbing. The higher contrast ratio was obtained for a zigzag defect-free sample obtained by the photo-induced alignment method than by the rubbing method. Faster response times of the order of 300 μs, which are fast enough to realize high quality moving images with video-frame rate, was also obtained [7].

Kobayashi et al. has obtained very interesting results in defect free FLC using photoaligned UV irradiated PI films [8]-[11]. It was shown, that the defect structure can be suppressed by proper choosing of the FLC pretilt angle and anchoring energy [8]. In particular a relatively small FLC pretilt angle, large cone angle and high azimuthal anchoring energy is necessary to promote uniform C2 state in SSFLC samples [9]. Half V-shape FLC state, which is useful for active matrix addressing FLC was promoted in photoaligned FLC cells by using weak azimuthal anchoring energy and polymer stabilization [10]. By doping newly synthesized photo-curable monomers into FLC media and performing an appropriate photo-curing a novel Polymer-Stabilized FLCDs exhibiting V shaped switching (PSV-FLCDs) with response time of 100 μs and a field sequential full color LCD capable of displaying moving images without blurring and break were made [11],[12].

The FLC row addressing response time of $\tau \approx 100$ μs at the voltage pulse amplitude of U= ±15V was demonstrated using sulfonic azo-dye SD1 nanosize aligning layers [13],[14]. The thickness of azo-dye layer should be optimized to have the highest uniformity of FLC cell (Fig. 1).

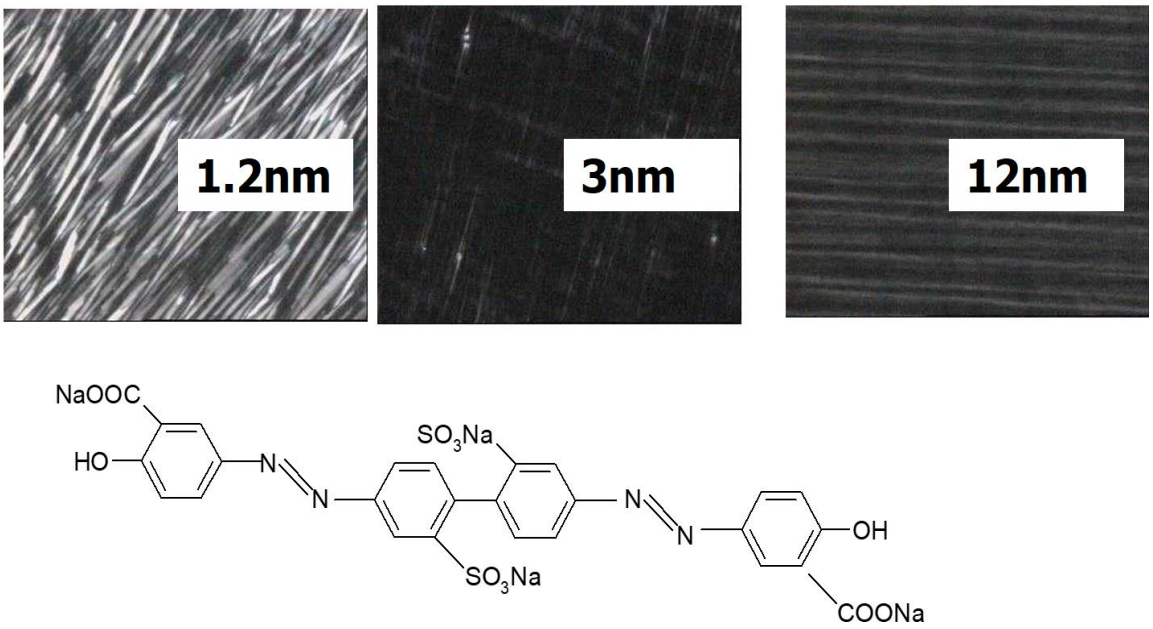

Fig. 1 Textures of 1.5μm FLC cells with photoaligned layer azo-dye SD1of different thickness 1.2nm focal-conic domains caused by film discontinuity; 3nm completely continuous film with high uniformity 12nm obvious regular striped domains. The chemical formula of azodye SD1 is given below [12].

The quality of FLC alignment strongly depended on the azo-dye layer thickness and rather poor aligning texture with irregular focal-conic domains appeared at very thin azo-dye SD1 layer, shown in Fig.1 [13]. The domains occurred due to the broken SD1 layer, whose evaluated apparent thickness was about 1.2 nm, i.e., approximately two SD1 mono-layer were attached to the ITO surface. The texture when the thickness of SD1 layer was about 3 nm of a completely continuous film. This uniform texture was a consequence of the perfect uniformity of the azo-dye aligning layer. Increasing of the azo-dye layer thickness resulted in the appearance of regular striped domains possessing a periodicity along a normal to smectic layers of the FLC, as shown in Fig.1. These domains are known as ferroelectric domains in FLC cells [14], which created the modulation of the FLC apparent birefringence. The FLC layers became not perfectly uniform because of the domains appearance. The large number of stable states of the FLC structure is related to the presence of ferroelectric domains [14]. At a sufficiently high spontaneous polarization and in the absence of helical twist in a FLC layer, modulation of ferroelectric domains by electric-field pulses is observed. This modulation results in the appearance of a large number of stable states of the domain structure [15].

However, it is possible that not only ferroelectric domains but also other spatially inhomogeneous structures are responsible for the FLC multistability with an unlimited number of memorized states (Fig.2) [13]-[15]. Thus by switching either the amplitude or the width of the voltage pulse any average gray level of the transmission of FLC cell can be obtained (Fig.3) [15]

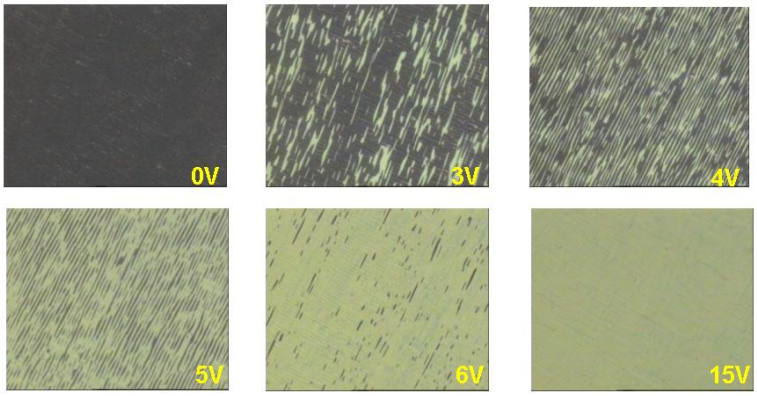

Fig. 2 Optical appearance of FLC cells with ferroelectric domains dependent on the applied voltage [13]-[15]. The image area is 350x400 μm^2.

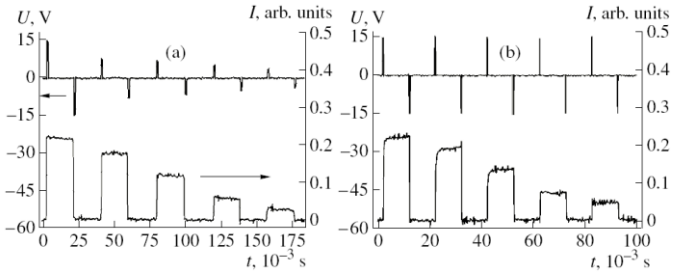

Fig. 3 Dependences of the change in the light transmission state memorized by FLC layer on (a) the amplitude of 1-ms-long alternating driving pulses and (b) the duration of alternating driving pulses ranging from 250 to 50 μs. The FLC layer thickness is 7 μm; the ferroelectric-domain period is 5 μm [15].

Anchoring energy also plays an important role in the realization of perfect FLC switching [16]-[18]. It is very simple to understand, that FLC is switching between the two positions of ±Θ, while it is oriented along Θ=0. This is why both weak and strong FLC anchoring energy is not good for a high contrast ratio (Fig.4).

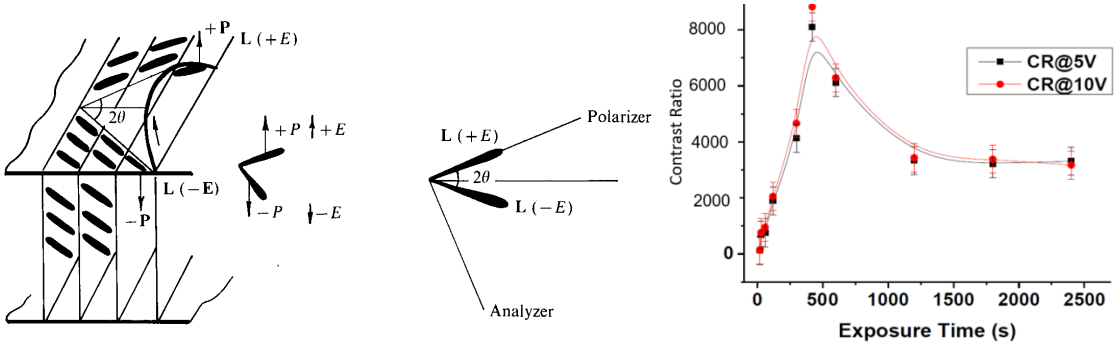

Fig. 4 Left: FLC switching between the two positions of ±Θ while it is oriented along Θ=0; Right: FLC contrast ratio as a function of exposure time, which is proportional to the anchoring energy [2].

Photonic crystal fiber (PCF) is a polymer or glass fiber with an array of tiny air holes running along the length of the fiber. The waveguide properties of such fibers can be controlled by filling an additional material into the air holes [19]-[21]. The refractive index of the LC can be easily tuned by electric field or temperature, therefore LC is suitable for that purpose. The technique of

light reconfigurable alignment of LC in glass micro-tubes and in PCF was developed (Fig. 5) [19]-[21]

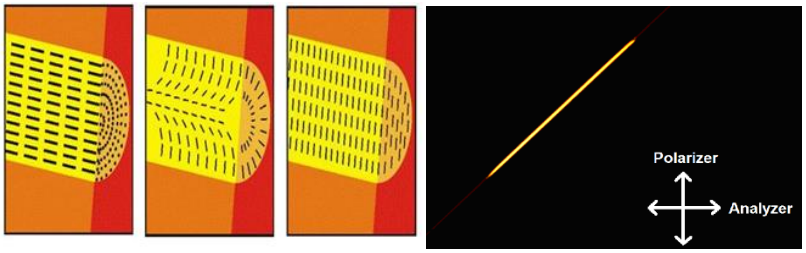

Fig. 5 From left to right: Typical LC molecules alignment in micro-capillary: planar, splay (axial, escaped radial), transverse; Single-frame excerpt from video recording of micro-capillaries filled with LC, in which two stable alignments (planar and tilted at 45º) has been obtained simultaneously [18]-[20].

2. New Electrooptical Modes based on Photoaligned FLC

Six electrooptic modes in ferroelectric liquid crystals (FLC), Clark-Lagerwall mode is Surface Stabilized FLC (SSFLC) structure, Bi and Multistable FLC switching, Deformed Helix Ferroelectric (DHF), Electrically Suppressed Helix (ESH) mode, FLC orientational electro-optic Kerr effect and ESHFLC diffraction mode were proposed for fast FLCD [1]-[3]. The very promising possibility to obtain a high contrast ratio and uniform FLC cell is to use the optimal anchoring energy, which is easy to get by using a photoalignment technology.

2.1 Clark-Lagerwall Effect

Let us consider the main electrooptical phenomena in FLC. The best known is the Clark-Lagerwall effect [22], which results in director reorientation from one bistable state to the other when an external electric field changes its sign (Fig.4, left). In this case, the FLC layers are perpendicular to the substrates and the director moves along the surface of a cone whose axis is normal to the layers and parallel to the cell substrates. In each final position of its deviation the director remains parallel to the substrates, thus transforming the FLC cell into a uniaxial phase plate. The origin of electrooptical switching in the FLC cell is the interaction of the polarization **P** perpendicular to the director with the electric field **E**. The maximum variation of the transmitted intensity is achieved when the FLC cell is placed between crossed polarizers, so that an axis of the input polarizer coincides with one of the final director positions. The total angle of switching equals the double tilt angle θ (Fig.4, left). The Clark-Lagerwall effect is observed in the so-called Surface Stabilized FLC structures (SSFLC). In SSFLC cells the cell thickness d is smaller than FLC helix pitch R_o, $d << R_o$ and we come to the situation where the existence of the helix is unfavorable, i.e., the helix is unwound by the walls.

The response times in the Clark-Lagerwall effect are determined by $\tau_\varphi \propto \gamma_\varphi/PE$, where γ_φ is FLC rotational viscosity [23], P-FLC spontaneous polarization, and E-applied electric field (Fig.4, left) [24]. Comparing the response times in nematics (N):

$$\tau_r^{(N)} \propto 4\pi\gamma_1/\Delta\varepsilon E^{2,} \quad \tau_d^{(N)} \propto d^2\gamma_1/K\pi^2 , \tag{2.1}$$

where K is elastic constant in nematic LC, γ_1 is rotational viscosity, d is thickness of the layer, and ferroelectric liquid crystals (FLC):

$$\tau_r^{(FLC)} \propto \tau_d^{(FLC)} \propto \tau_\varphi \propto \gamma_\varphi/PE, \tag{2.2}$$

we come to conclusion that the electrooptical switching in the Clark-Lagerwall effect in FLCs is much faster than in nematic LC. Slower response of nematic LCs is mainly due to the relatively large decay times $\tau_d^{(N)}$, which in FLC case can be very short in sufficiently high electric fields E. The optical transmittance I in the Clark-Lagerwall effect is calculated as follows [1]-[3]:

$$I = \sin^2 4\theta \sin^2 \Delta\Phi/2 \qquad (2.3)$$

where $\Delta\Phi = \Delta nd/\lambda$ the phase difference, $\Delta n = n_{\parallel} - n_{\perp}$ is FLC birefringence, λ-is the wavelength. As follows from (3), the maximum contrast is obtained for $0 = \pi/8$ (22.5°), $\Delta nd/\lambda = 1/2$, which, for $\Delta n = 0.125$, $\lambda = 0.5$ μm, gives $d \approx 2$ μm. We should note, that the variation of the cell thickness $\Delta d = \lambda/8\Delta n$ from the optimum value $d = \lambda/2\Delta n$ results in a considerable difference in the FLC electrooptical response (Fig. 6) [3]. The practical criteria of an FLC display quality, however, require more precise limitations $d = 2 \pm 0.2$ μm.

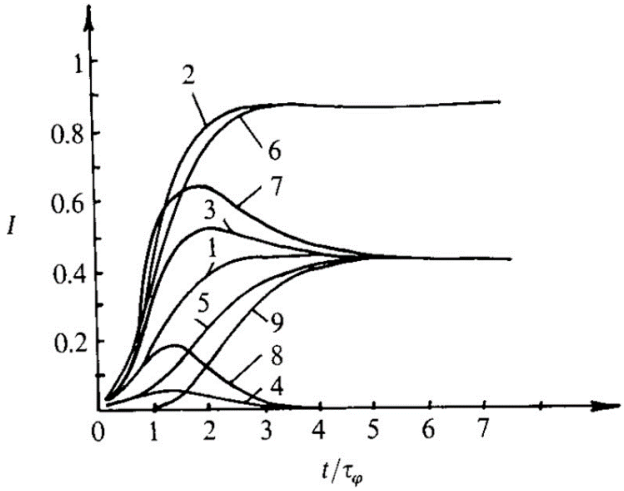

Fig. 6 Electrooptical response of the FLC cell in Clark-Lagerwall effect for different phase factors $d\Delta n/\lambda = k/4$, k= 1…9 [24].

SSFLC mode is very unstable and has low contrast and brightness due to zig-zag defects, caused by different angles of FLC layers deformation as well as ferroelectric domains causing parasitic diffraction effect (Fig.7)

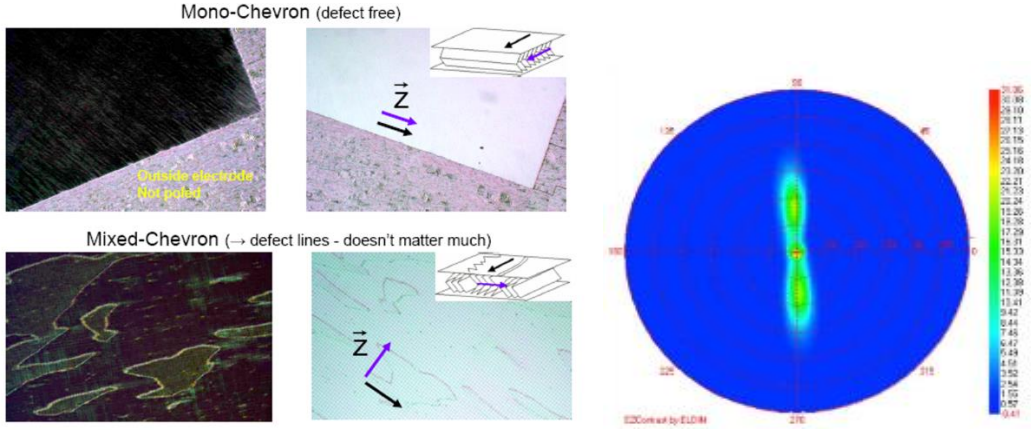

Fig. 7 Left: Zig-zag defects, caused by different angles of FLC layers deformation, right: parasitic diffraction of FLC in the dark state between crossed polarizers due to FLC domains [1]-[3].

2.2 Bistable and Multistable switching in FLC cells

The bistable switching in SSFLC geometry (Fig. 4, left) takes place above a certain threshold field $E_{th} \propto W_d/K^{1/2}$, where K is an average elastic constant and W_d is a dispersion anchoring energy and polar anchoring energy is taken equal to zero $W_p=0$ [24]. Thus, with increasing anchoring we have to increase the switching amplitude of the electric field. As the energy of switching electric torque is proportional to the product of the spontaneous polarization P to the electric field E: PE, the bistability threshold is inversely proportional to the value of the FLC spontaneous polarization P.

The problems we meet using the Clark-Lagerwall effect include not only severe restrictions to the optimum layer thickness and requirements of defectless samples, but also difficulties in the realization of a perfect bistability or optical memory switched by the electric field and also providing the grey scale. The latter problem is one of the most crucial, because it is very inconvenient to provide the grey scale using either complicated driving circuits or increasing the number of working elements (pixels) in an FLC display [1]-[3],[24]. This problem arises in the Clark-Lagerwall effect because the level of transmission is not defined by the amplitude of the driving voltage pulse U, but by the product $U\tau$, where τ is the electric pulse duration.

A surface-stabilized FLC (SSFLC) structure with bistable switching cannot provide an intrinsic continuous gray scale, unless a time- or space-averaging process is applied [1]-[3],[24]. The inherent physical gray scale of passively addressed FLC cells can be obtained if the FLC possesses multistable electro-optical switching with a sequence of ferroelectric domains, which appear if the spontaneous polarization *Ps* is high enough [25]. Ferroelectric domains in a helix-free FLC form a quasi-periodic structure with a variable optical density as it appears between crossed polarizers (Fig. 7). The bookshelf configuration (Fig.4, left) of smectic layers is preferable for the observation of these domains. If the duration of the electric pulse applied to a helix free SSFLC layer containing ferroelectric domains is shorter than the total FLC switching time, the textures shown in Fig. 2 are memorized after switching off this pulse and short-circuiting of the FLC cell electrodes. The domains appear as a quasi-regular structure of bright and dark stripes parallel to the smectic-layer planes. The bright stripes indicate the spatial regions with a complete switching of the FLC director, while the dark stripes indicate the regions that remain in the initial state. The sharp boundaries between the black and white domain stripes seem to illustrate the fact that only two stable director orientations exist. The variation of the occupied area between bright and dark stripes depends on the energy of the applied driving pulses. The total light transmission of the structure is the result of a spatial averaging over the aperture of the light passed through the FLC cell and is always much larger than the period of the ferroelectric domains. Both the amplitude and the duration of the driving pulses can be varied to change the switching energy, which defines the memorized level of FLC-cell transmission in a multistable electro-optical response. Therefore, any level of the FLC-cell transmission, intermediate between the maximum and the minimum transmissions, can be memorized after switching off the voltage pulses and short-circuiting of the cell electrodes (Fig. 2).

The necessary conditions of multistable switching modes, are (i) sufficiently high FLC spontaneous polarization $Ps > 50$ nC/cm^2 and (ii) a relatively low energy of the boundaries between the two FLC states existing in FLC domains (Fig.2), which is usually typical for the antiferrroelectric phase [1]-[3],[24]. The multistability is responsible for three new electro-optical modes with different shapes of the gray-scale curve that can be either S-shaped (double or single dependent upon the applied-voltage pulse sequence and boundary conditions) or V-shaped dependent upon boundary conditions and FLC cell parameters (Fig. 8).

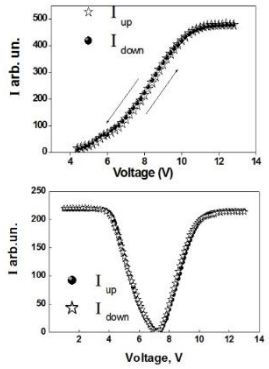

Fig. 8 S-shaped (above) and V-shape (below) FLC multi-stable switching [25].

The theoretical and experimental investigation of reversible and memorized S and V-shaped multistable FLC electro-optical modes was proposed in Ref. [25]. New electro-optical modes are based on the multistable electro-optical modes in FLC cell [14],[15],[25] (Fig.8).

2.3 Deformed Helix Ferroelectric Effect

The geometry of the FLC cell with a DHF effect is presented in Fig. 9 [26]. The polarizer (P) on the first substrate makes an angle with the helix axis and the analyzer (A) is crossed with the polarizer.

The FLC layers are perpendicular to the substrates and the layer thickness d is much higher than the value of the helix pitch R_o:

$$d >> R_o. \tag{2.4}$$

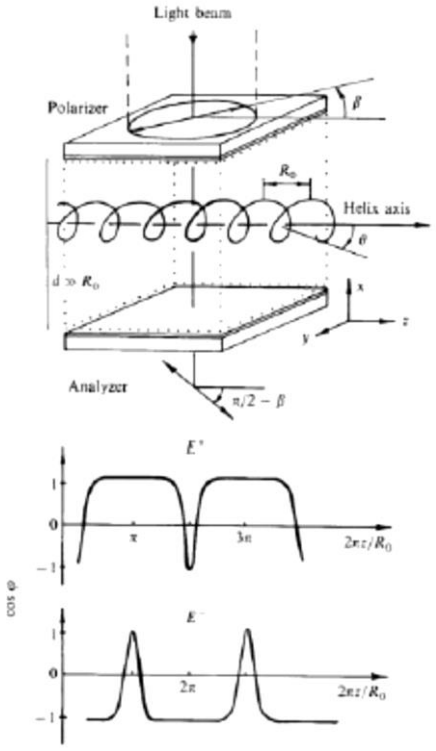

Fig. 9 Deformed Helix Ferroelectric (DHF) Effect [24],[26].

The light beam with the aperture a >> R_o passes parallel to the FLC layers through an FLC cell placed between the polarizer and analyzer. In an electrical field the FLC helical structure becomes deformed, so that the corresponding dependence of the director distribution cosφ, as a function of coordinate $2\pi z/R_o$, oscillates symmetrically in ±E electric fields [24],[26] (Fig.9). These oscillations result in a variation of the effective refractive index, i.e., electrically controlled birefringence appears.

The effect takes place up to the fields of FLC helix unwinding [24],[26]

$$E_U = \pi^2/16\ K_{22}q_0^2/P_s, \tag{2.5}$$

where K_{22} is FLC twist elastic constant, $q_0 = 2\pi/R_0$ –helix wave vector.

The characteristic response times τ_c of the effect in small fields $E/E_u << 1$ are independent of the FLC polarization P_s and the field E, and defined only by the rotational viscosity γ_φ , and the helix pitch R_o:

$$\tau_c = \gamma_\varphi/K_{22}q_0^2 \tag{2.6}$$

The dependence (2.6) is valid, however, only for very small fields E. If $E \leq E_u$, the FLC helix becomes strongly deformed and $\tau_c \propto E^{-\delta}$, where $0 < \delta < 1$ [27]. If E is close to the unwinding field E_u the helical pitch R sharply increases R >> R_o. Consequently, the times of the helix relaxation τ_d to the initial state also rise:

$$\tau_d /\tau_c \propto R^2/R_0^2 \tag{2.7}$$

i.e., for $E \approx E_u$ it is possible to observe the memory state of the FLC structure [24]. In this regime the electrooptical switching in the DHF effect reveals a pronounced hysteresis especially for $E \Rightarrow E_u$.

However, if the FLC helix is not deformed too much, fast and reversible switching in the DHF mode could be obtained [24],[26]. The switching time, less than 10 μs at the controlling voltage of ±20V can be provided, which is temperature independent over the broad temperature range [24]. The fast ferroelectric LC cells (deformed helix ferroelectric-DHF effect) with the response time less than one microsecond in a broad temperature range from 20 to 80 degrees were developed [28]. We believe, that DHF FLC are the fastest electrooptical mode in LC cells for photonics and display applications.

The optical transmission of the DHF cell could be calculated as follows:

$$I = \sin^2(\pi\Delta n(z)d/\lambda)\sin^2(2(\beta-\alpha(z)) \tag{2.8}$$

where β is the angle between the z-axis and the polarizer (Fig. 9),

$$\alpha(z) = \arctan(\tan\theta\cos\varphi(z)) \tag{2.9}$$

is the angle between the projection of the optical axis on the y, z-polarizer plane and the z-axis, and $\Delta n(z) = n_{eff}(z) - n_\perp$ is the effective birefringence:

$$n_{eff} = n_\parallel n_\perp/[\ n_\perp^2 + (\ n_\parallel^2 - n_\perp^2)\sin^2\theta\sin^2\varphi]^{1/2} \tag{2.10}$$

(Diffraction of light on the helical structure is avoided, because the helical pitch of the FLC mixture $R_o \propto 0.1\text{-}0.3\ \mu m < \lambda = 0.5\ \mu m$ is in the visible range).

The switching times in DHF effect (6) are shown in Fig.10 below.

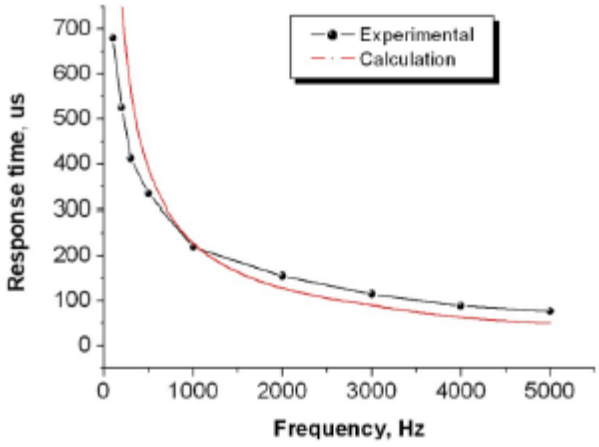

Fig. 10 Switching time of deformed helix ferroelectric (DHF) LC cells [28].

In the case of small angles $|\theta| << 1$, the transmission in (8) can be expanded in θ series:

$$I \propto (\sin^2 2\beta - 2\theta \sin 4\beta \cos\varphi + 4\theta^2 \cos 4\beta \cos^2\varphi)\sin^2 \pi\Delta nd/\lambda \qquad (2.11)$$

As shown in [24] for the small values of the applied field $\cos\varphi \propto E/E_u$ and changes its sign for the field reversal $E \Rightarrow -E$ (Fig. 9). Thus, according to (2.11) for $\sin 4\beta = 0$ we have a quadratic grey scale, i.e.

$$\Delta I \propto \theta^2 \cos^2\varphi \propto \theta^2 E^2/E_u^2 \qquad (2.12)$$

and for other values of θ the grey scale is linear. For $\cos 4\beta = 0$ the quadratic component in the modulated intensity I is absent , i.e.

$$\Delta I \propto \theta \cos\varphi \propto \theta E/E_u \qquad (2.13)$$

If $E(t) = E_o \cos\omega t$, then in the case of (12) we come to the modulation regime, which doubles the frequency of the applied field. The relationships (12), (13) were confirmed in experiment [28]. Using a "natural" grey scale of the DHF mode many grey levels have been obtained with fast switching between them [29]. New ferroelectric mixtures with the helix pitch $R_0 < 0.3\mu m$ um and tilt angle 0 > 30° have been developed for the DHF effect [29],[30]. The helix unwinding voltage was about 2-3 V. Short-pitch FLC mixtures could be also used to obtain pseudo-bistable switching in FLC samples. Using these new FLC's, the electrically controlled V-shaped switching in DHF mode can be applied for new active-matrix LCD with Field Sequential Colors (FSC) [1],[24].

A geometry with $\beta=0$ was selected in all experiments to provide non-sensitive to the driving voltage polarity electro-optical response. Maximal light transmission under this condition, as it follows from (2.8), occurs if $\alpha(z) = 45°$ and $\Delta n(z)d = \lambda/2$. It is easy to show from (2.8) that the tilt angle θ of the FLC should be close to 45º for providing of maximal light transmission at $\beta=0$. The typical V-shape symmetrical (voltage sign independent) DHF switching is shown in Fig. 11 [29].

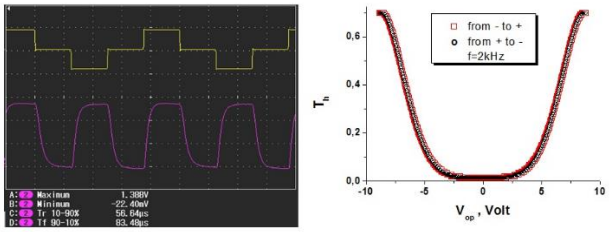

Fig. 11 Symmetric (voltage sign independent) electro-optic response of DHF –FLC [11]. Left: Top – the driving voltage waveform applied to the cell , bottom – the electro-optical response of the cell.

Right: V-shaped mode in the envelope curve of light transmission saturation states measured at electro-optical response frequency 2 kHz. The light transmission T_h evaluated in comparison with transmission of empty cell placed between parallel polarizers; this transmission is defined as T_h= 1.

Let us point to certain advantages of the DHF electrooptical effect for applications as compared with the Clark-Lagerwall mode.

1. High operation speed is achieved for low driving voltages. This takes place because a slight distortion of the helix near the equilibrium state results in a considerable change in the transmission. Consequently, the instantaneous response of the FLC cell is provided without the so-called delay time inherent to the Clark-Lagerwall effect.
2. The DHF effect is also less sensitive to the surface treatment and more tolerant to the cell gap inhomogeneity. As follows from experiment and qualitative estimations [3] the effective birefringence value Δn_{eff} is approximately twice as low as $\Delta n = n_{||} - n_{\perp}$ in the Clark-Lagerwall effect.
3. The DHF effect allows the implementation of a "natural," i.e., dependent on voltage amplitude, grey scale both linear and quadratic in voltage. Moreover, at E ≈Eu long-term optical memory states are possible.

In particular, a high quality dark state of DHF FLCD has been obtained as well as V-shape switching with a high frequency [31] (Fig.11). Two inherent properties of DHF-FLC have been observed (Fig. 11): (i) similar to NLC cells, the electro-optical response is insensitive to the driving voltage polarity, but the response time is two orders faster as compared with NLC, i.e., $\tau^{on}_{0.1-0.9} \cong 80\mu s$, $\tau^{off}_{0.1-0.9} \cong 60\mu s$; (ii) the response exhibits perfect V-shaped mode obtained for the case of rectangular alternating applied voltage pulses shown in Fig. 11. As is illustrated in Fig. 11, the electro-optical response frequency is twice higher than the driving voltage frequency. The cell was controlled by the voltage waveform appropriate for FSC displays. Figure 11 shows that the cell light transmission is continuously tunable for each color field independently at both voltage polarities.

Thus V-shaped electro-optical response is shown to be an inherent property of a DHFLC cell under a special choice of the applied rectangular alternating electric field waveform, frequency, and the cell geometry. In contrast to other known V-shaped FLC modes, the discovered V-shaped switching is observed in a broadband frequency range including one kilohertz, and not at a certain characteristic frequency. Frequency independent V-shaped DHFLC switching allows increasing drastically (up to 1 kHz) the operating frequency of FSC LCD cells.

A special software for an advanced design of new FLCD prototypes [32],[33]. Certain new FLCD prototypes can be optimized using our software, including the optimization of FLC configuration as well as the optical scheme. One of remarkable properties of DHF mode is independence of the response time on applied voltage at V<Vc. Another characteristic feature of DHF mode is frequency dependence of the electro-optical response time, which is really exists in

our case shown in Fig. 10. We have found that the switching time of DHF FLC decreases with frequency of the applied voltage, which is in a good agreement with our experimental results [1].

Recently DHF FLCs with subwavelength pitch was found to support pixel density up to 4233 PPI for displays, and up to 12,700 PPI for monochromatic photonic devices [34]. Thus, the fast switchable DHF FLCs with subwavelength pitch open the way for the high-pixel density display and photonic devices.

2.4 Electrically Suppressed Helix (ESH) mode

A new electrooptic mode, found recently was called Electrically Suppressed Helix (ESH) mode [35]. The mode is characterized by a high contrast ratio and very fast electrooptic response and is highly suitable for display and photonics applications. Deformed helix ferroelectric (DHF) mode exists at $V \le V_c = 0.4$V and the helix is completely suppressed by electric field at V≥1V, see Fig. 12 right part and linear dependence of the inverse response time at V>1V in Fig. 12, where the response time has absolutely the same behavior as in SSFLC mode. Despite of these similarities, it should be emphasized that at $V > V_c$, strictly speaking, there is no SSFLC mode but an electro-optical mode with completely electrically suppressed helix arises (ESH-mode). It would seem that between SSFLC and ESH modes there is only a formal difference in initial conditions (the helix is suppressed by surfaces in SSFLC, but this does not happen with ESH), as the dynamics of a completely identical. Actually, the presence of helix without applied voltage is the cause of the unique high alignment quality in ESH-mode (see top right insertions in Fig. 12). The contrast ratio in ESH mode is more than 12000:1 up to 1 kHz at ±1.5V and up to 2 kHz at ±3V; the light transmission is about of maximum in this case, see insertion to Fig. 12.

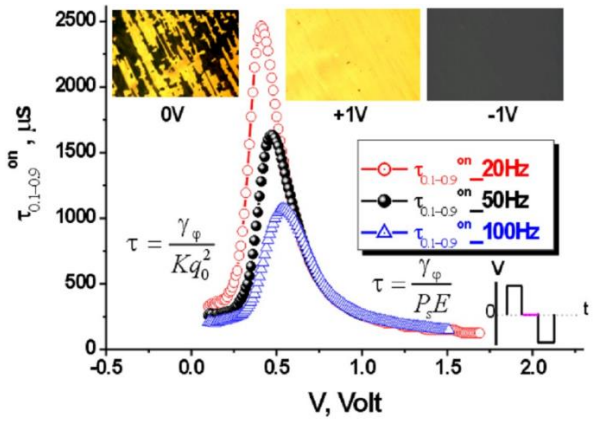

Fig. 12 Dependence of switching on time of 1.5 μm cell filled with the FLC-595 [31,35]. Insertions: bottom right is the driving voltage waveform; top the FLC layer textures between crossed polarizers, horizontal scale of all images is 200 μm; top left - the voltage is not applied, top right - textures at +1V and -1V.

The unique high alignment quality, however, is observed only if the helix elastic energy is comparable but obligatory not less than the anchoring energy normalized to d_{FLC}:

$$Kq_0^2 \ge \frac{2W_Q^0}{d_{FLC}} \tag{2.14}$$

where W_Q^0 is a coefficient the anchoring energy. We have measured $W_Q^0 = 4 \cdot 10^{-4}$ J/m^2 just for the cell whose properties are illustrated in Fig. 12, thus confirming the validity of inequality (14), when outstanding alignment quality (top right insertions in Fig. 12) is observed.

A very uniform FLC alignment exists just only in ESH-mode when $V > V_c$ (right top insertion in Fig. 12) while at $V<V_c$ it is worse because the FLC layer is divided into two-domain helical structures with the domains principal axes deployed at an angle around double FLC tilt angle 2θ. When observed with a polarizing microscope, these helical domains are perceived as homogeneous dark and light areas with their characteristic sizes around 10-50 μm, see left top insertion in Fig. 12. The domains are completely suppressed by a weak electric field $E_c<E<1V/\mu m$ (right top insertion in Fig. 12) thus forming perfect chevron-free alignment in ESH-mode.

In addition to this the shock stability has also been found good for the ESH mode. The contrast ratio was measured with time after removing the mechanical pressure. The contrast can be restored in very short time after removal of mechanical pressure (Fig.13). The electro-optical response manifests evident saturation at 500 Hz and ±1.5V with the response time $\tau_{0.1\text{-}0.9}$ =130 μs (Figs. 12, 13).

It looks like the theory of ESH modes and its optimal parameters are not completely understood and more work in this direction is required. ESH FLC mode shows excellent contrast, fast switching time and is mechanically stable [1]-[3].

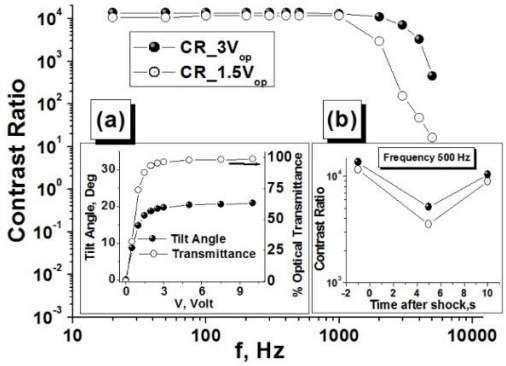

Fig. 13 Dependencies of the contrast ratio on driving voltage frequency at V=1.5V and V=3V. The FLC-595 [13],[17] layer thickness is 1.5μm, no SiO_2 layers, measurements have been carried out at T=22°C, wavelength λ=0.63 μm. Insertion left: Dependencies on voltage: measured tilt angle and the cell light transmission in comparison with transmission of empty cell placed between crossed polarizers. Insertion right: Contrast ratio dependence on time after the application of mechanical shock.

The recent development for the ESHFLCs revels that the ESHFLC shows that good optical quality i.e., high contrast, no diffraction lobe, in either bright or dark state, (Fig. 14.) and fast electro-optical response at small electric field, can be achieved only for the optimum anchoring energy in accordance with the eq.14 [36].

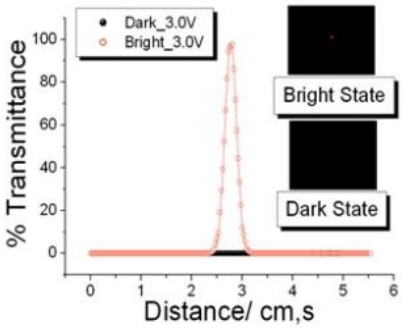

Fig. 14 The intensity profile of the natural diffraction for ESHFLC cell between crossed polarizers in bright and dark state and insertion shows photographs of the respective states.

3. Conclusion

Fast response time, high contrast ratio various FLC electrooptical modes, such as Clark-Lagerwall mode is Surface Stabilized FLC (SSFLC) structure, Bi and Multistable FLC switching, Deformed Helix Ferroelectric (DHF), Electrically Suppressed Helix (ESH) mode were proposed for modern photonics and fast FLCD, which are achieved through the application of photoaligning layers in FLC cells. Fast FLCD with a high resolution can be used in the screens field sequential color (FSC) FLC microdisplays, which are now one of the most advanced technologies for pico-projectors. The switchable goggles and lenses based on new FLC prototypes can be efficiently applied in the new generation of switchable 2D/3D LCD TVs. The further development of novel fast ferroelectric LCD aimed at : (i) development of new fast responded FLC materials with fast switching and a sufficient number of switchable gray levels (V-shape switching); (ii) implementation of the working prototypes of novel field sequential color (FSC) FLC displays, including the 3D version [12]; (iii) investigations of regimes of operation to allow to use efficient addressing of FLCD including TFT drivers enabling a high switching current; (iv) solving the problem of a mechanical stability of FLC layers; (v) mass production of new FLC materials with optimal characteristics.

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