Dynamic and optical properties of novel helix-free ferroelectric liquid crystals

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Abstract. These materials are the helix-free ferroelectric liquid crystals (FLCs) with small spontaneous polarization (less than 50 nC / cm²) and high viscosity (from 0.3 to 1.0 Poise). They were specially designed for fast low-voltage displays and light modulators operating in transparent or scattering mode. The FLC director reorientation is due to motion of solitons at the transition to Maxwellian mechanism of energy dissipation. Such FLCs are able to efficiently modulate the visible and near IR radiation at frequencies up to 7 kHz at the electric field strength of the order of 1-2 V/μm. The hysteresis-free and smooth dependence of the optical response on the external electric field is in the frequency range up to 6 kHz. In the bistable light scattering mode one can memorize an optical state for the time exceeding the switching time up to six orders of magnitude. Besides, the spatially inhomogeneous modulation of the light phase delay is demonstrated that is able to suppress the speckle-noise in images formed by a laser beam. Novel FLC- materials are compatible with FLCOS, 3D and FSC technologies.

1. Introduction

The frame rate is one of the most important parameters of the display screen material. To avoid flickering and blurring of images, the frame rate was raised from 25 to 60 Hz and then to 90 Hz, which already meets the medical requirements for the eyes. However, three-dimensional technologies require double the speed, about 180-200 Hz, otherwise watching 3D images is not comfortable, and buyers refuse from 3D TV. The Field Sequential Color (FSC) technology makes it possible to get brighter and uniform (unstructured) color images and reduce the number of display pixels by a factor of three. However, it requires three times more frame rates, that is, 270-300 Hz. Thus, in the 3D display using the FSC technology we need the frame rate 540÷600 Hz.

Modern liquid crystal displays use LC of nematic type (NLC), for which the maximum frame rate is 120-160 Hz only. However it is long known that ferroelectric liquid crystals (FLC) of smectic type possess a sub millisecond electro-optical response [1, 2]. Problems limiting earlier FLC application were solving gradually, and last researches showed that the new specially designed helix-free FLC are the most promising for future applications [3-6]. These materials distinguish with the rather low spontaneous polarization (less than 50 nC / cm²) and high viscosity (0.3÷1.0 P). In contrast to the helix FLCs, where the electric field deforms the helix [7-10], in our helix-free FLC the electric field changes the periodic deformation of smectic layers and FLC birefringence (Figure 1). Such deformation exists even in the field absence, and its pitch is 1.5 ÷ 5.0 μm depends on FLC essential parameters and closely relates with FLC physical properties.
Figure 1. The electro-optical cell with helix-free FLC (a) and the fragment of a deformed smectic layer (b). 1 – glass substrates with conductive covers, 2 – smectic layers, $\Theta_0$ – the angle of molecule’s tilt in smectic layers, $\psi$ - angle of the tilt of a smectic layer, $P_S$ – vector of the spontaneous polarization, $d$ – FLC cell thickness, $l$ – smectic layer thickness.

Really, fast electro-optical response with continuous gray scale in the transparent mode, which could be used in display devices, is observed in FLC compositions with the rather long deformation pitch, more than 3 μm. Intensive light scattering, which could be used in polarized-free devices is manifested in compositions with the rather short deformation pitch, of 1.5 ÷ 2.0 μm. FLC compositions with the deformation pitch of about 3 μm are more preferable for fast changing the phase delay (initiated by light scattering switching on) due to arising the spatially inhomogeneous phase structure, which could be used for suppressing the ability of a laser beam to the interference with speckle-noise formation.

Below authors present the brief review of results of experimental studying the dynamic and optical properties of electro optical cells with the helix-free FLC. Notice here that any electro-optical FLC cell is a product of nanotechnology since the thickness of basic layers is in nano-region, namely: 80-100 nm for transparent electrodes, about 60 nm for the dielectric layer, and 20-50 nm for the polymer-orienting layer. The thickness of smectic layers is a few nm as well.

2. Reorientation of the FLC director

Process of the FLC main optical axis (director) reorientation under the action of an alternating electric field depends on which of the two dissipative coefficients – rotational or shear viscosity predominates [11]. When the electric field of the frequency $f$ acts on the FLC, and $\tau_m f << 1$ in comparison with the Maxwellian relaxation time $\tau_m$, then the FLC behaves as a liquid with a rotation viscosity $\gamma_\psi$. In the case when the frequency is $f \sim 1 / \tau_m$, in addition to the viscous flow a fluid undergoes the elastic shear deformation, and its properties can be characterized by the viscosity coefficient $\gamma$ and some shear modulus $\mu$. At sufficiently high frequencies ($\tau_m f >> 1$), the FLC behaves as an amorphous solid, and its dissipative coefficient is the shear viscosity $\gamma_\mu$.

In the case of small frequencies the time of the director reorientation [12] is $\tau_R \sim \gamma_\psi / (P_S \cdot E)$, where $E$ is the strength of an external electric field, and $P_S$ is the FLC spontaneous polarization. Correspondingly, a time of an electro-optical response $\tau_{0.1-0.9}$, which is proportional to the time $\tau_R$, is determined by the ratio of the viscosity $\gamma_0$ to the polarization $P_S$ and does not depend on the frequency of an electric field change.

Increasing the electric field frequency and the transition to the Maxwellian mechanism of energy dissipation, which is to the shear viscosity, is accompanied by a strong frequency dependence of the electro-optical response time. The combined influence of the medium nonlinearity and its deformation waves (or displacement ones) results in a spatial redistribution of the excitation energy and its
localization – to the soliton waves. In contrast to topological solitons [13], such dynamic soliton is continuously transformed into the homogeneous major state. The shape of dynamic solitons is definitely relates to independent parameters, in particular, the motion velocity [14, 15]. Motion of solitons results in the FLC orientation. For the first time a director reorientation through solitons was proposed in [16].

3. Experimental results

3.1 Transparent mode

The experimental results and theoretical model proposed in [5, 6] demonstrate the presence of FLC spatial-periodic deformation, the mechanism of FLC director reorientation based on the motion of soliton waves arising upon the transition to the Maxwellian mechanism of energy dissipation as well as the character of the frequency dependence of the optical response \( \tau_{0,1-0,9} \) (Figure 2) on small and rather high frequencies. In the soliton mode, this dependence is rather weak. The maximum light modulation frequency at the electric field strength of 1 V/\( \mu \)m is 7 kHz at the response time of about 25 \( \mu \)s (Figure 3).

![Figure 2](image1.png)

**Figure 2.** Frequency dependence of the optical response time for the composition HF-32B at \( V = \pm 1.5 \) V. Bipolar voltage is of rectangular shape (meander). The thickness of the electro-optical cell is 1.7 \( \mu \)m.

![Figure 3](image2.png)

**Figure 3.** Oscillogram of the bipolar control voltage (zero level – digit 3) and optical response (zero level – digit 1) for the electro-optical cell with the composition HF-32C at the voltage amplitude of \( \pm 1.5 \) V and frequency of 7.0 kHz. The upper level of the optical response is the closed state; the lower one is the light transmission state.

Due to the constant change in the director position along smectic layers the FLC electro optical cell shows the smooth substantially hysteresis-free dependence of the light transmission on the control voltage in a wide frequency range when two conditions are satisfied [6]. Firstly, the frequency control voltage corresponds to the frequency interval of the soliton mode existence (it extends from 100 Hz to 7 kHz for the composition of HF-32C). Secondly, this frequency must not belong to the static portions (Figure 4) of the frequency dependence of the FLC birefringence. This means that the top frequency of the hysteresis-free interval does not exceed 6 kHz that was confirmed experimentally (Figure 5).
Figure 4. Frequency dependence of the birefringence of the FLC composition HF-32C. On the inset: the low-frequency part of this dependence. The thickness of the electro-optical cell is 1.7 μm. The amplitude of the bipolar control voltage (meander) is ± 1.5 V.

Figure 5. Dependence of the light transmission on the electrical voltage for the frequency of 6 kHz at decreasing (1) and increasing (2) the voltage amplitude. The thickness of the electro-optical cell with the FLC composition HF-32C is 1.7 μm.

3.2 Scattering mode

The scattering occurs on boundaries of spontaneously ordered regions, which are formed in the process of arising the soliton waves. Scattering occurs after changing the sign of the electric field and disappears when the motion of solitons reorients the director in all smectic layers. A change of the electric field direction induces the transient domain formation again, and the process is repeating. The frequency dependence of the optical response time for light scattering is similar to that in the transparent mode (Figure 2).

The light scattering and light transmittance of an electro-optical cell are defined both by a frequency and amplitude of the control voltage. For fixed electric field strength (or the amplitude of control bipolar pulses) the maximal efficiency of light scattering (contrast ratio) and maximal light transmission are achieved at a different duration of pulses [5]. Maximum light scattering is achieved, when the regular structure of scattering centers arises in the form of circular domains distributed evenly over FLC volume.

Depending on the time of the electric field action (on the duration of control voltage pulses) and the thickness of the electro-optical cell, there may be a few maxima of light scattering (Figure 6). They are defined here as “C” – scattering efficiency or contrast ratio. The appearance of the second and third maxima of light scattering efficiency occurs with increasing the thickness of the electro-optical cell to 16 - 20 μm [17]. Increasing the pulse duration results in increasing the length of domain walls and leads to irregular scattering structures. As a consequence, the density of scattering centers reduces, that is a reason light scattering efficiency decreasing.
Figure 6. Dependences of light scattering $C$ (curve 1) and light transmission $I$ without scattering (curve 2) on the duration of bipolar voltage pulses with a fixed amplitude ($\pm 50$ V). The thickness of a cell with the FLC composition HF-32 is 18 μm.

In the bistable light-scattering mode, realized at the definite relations of the FLC essential parameters and electric pulse duration the state with intensive scattering can be turned on and off for a few tens of μs and memorized for the time exceeding the switching time up to six orders of magnitude (for several tens of seconds) or until a pulse of opposite polarity appears [5].

Light scattering can be used not only for electrically controlled light modulation. A short-term scattering switching on can initiate the formation in FLC layer the structures with an almost random distribution of refractive index gradients which cause a spatially inhomogeneous phase modulation of the light beam passing through the electro-optical cell. Modulated phase delay of the order $\pi$ and more allows to destroy the phase relationships in the laser beam and to suppress the speckle-noise in the laser image as a result of interference [4].

The selection of the parameters of the FLC composition, the increase in the layer thickness to $18 \div 20$ μm and the choice of the control mode with the duration of bipolar pulse corresponding to different maxima of light scattering, made it possible not only to reduce the contrast of speckle structures (to 0.07 with a gain of 10.2 dB) but also to increase the frequency of phase delay modulation to 2 kHz [18]. Though the amplitude of the control voltage increased to $60 \div 65$ V such an electro-optical despeckler can find applications due to its simplicity and high efficiency.

4. Conclusion

Basing on our research results we considered the dynamic and optical properties of novel helix-free FLC developed at the Lebedev Physical Institute, Moscow. They are characterized by the spatially periodic deformation of smectic layers, small value of spontaneous polarization and high viscosity. Besides, the FLC director reorientation is due to the motion of solitons arising at the transition to the Maxwellian mechanism of energy dissipation.

For modulating the light transmission at the electric field of about 1 V / μm (the voltage of $\pm 1.5$ V), the smallest response time (25 μs) and the highest modulation frequency interval (up to 7 kHz, including 6 kHz for hysteretic-free modulation with the continuous grayscale) were realized experimentally for the first time.

In certain compositions of the new FLC, intensive light scattering on transient domains was realized, including the discovered bistable scattering with a memory time that can exceed optical switching time (tens microseconds) by six orders of magnitude (up to tens seconds).

The spatially inhomogeneous phase light modulation initiated by the short-time switching on of light scattering results in forming the random small-scale gradients of the FLC refractive index and essentially (with a gain of 10.2 dB) suppresses the speckle-noise in images formed by a laser beam.

Possible applications of these research results are in the fast LC displays and video projectors, especially based on FLCoS (FLC on silicon), 3D and FSC technologies, in polarizer-free optical shutters and modulators (including IR ones), in screens of electronic books and 3D visualizers of volumetric displays, in electro-optical devices suppressing laser speckles etc.

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