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Light modulation characteristics of a single-polarizer electro-optical cell based on polymer dispersed ferroelectric liquid crystals

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Features of the light passing through a single-polarizer electro-optical cell based on a uniaxially oriented film of a polymer dispersed ferroelectric liquid crystal have been studied. The optical response as a function of the applied electric field is shown to depend on the cell geometry. A detailed analysis is presented of the dependence of the maximum light transmission, modulation depth and contrast ratio on the angle between the light polarization and the film orientation direction, on its optical anisotropy and on the molecular tilt angle. An approximate formula is proposed to estimate the highest attainable contrast. Parameters under study have been measured for PDFLC films varying in optical anisotropy value. The experimental results prove to be in good agreement with theoretical estimations.

1. Introduction

A consistent development of experimental techniques to produce uniaxially oriented films of polymer dispersed liquid crystals (PDLCs) [1–4] has made it possible to introduce a new electro-optical material based on ferroelectric liquid crystals (FLCs) [5–7] and offering a combination of the known advantages of composite films [8, 9] with the rapid response inherent in chiral smectics. In the new material, FLC droplets of a micron-scale size are dispersed in a polymer matrix in such a way that the director in the entire ensemble of droplets is oriented in one direction in the film plane or at a slight angle to it.

Polymer dispersed ferroelectric liquid crystal (PDFLC) materials are currently used in light modulation devices in a variety of modes of application. When placed between crossed polarizers, the PDFLC film can act as a phase plate [7], similar to the planar-oriented FLC layer in the Clark–Lagerwall cell [10]. Operation of such a cell is due to the interference effect, which predetermines certain unavoidable drawbacks such as a strong spectral dependence of the light modulation characteristics and also the need for two polarizers, that significantly reduces the transmittance of the device.

Electro-optical devices employing light scattering as a basic effect appear to be more promising for this purpose. Devices of this type can have either just one polarizer [5, 6, 11] or no polarizer at all [12]. Figure 1 illustrates schematically a single-polarizer PDFLC cell.

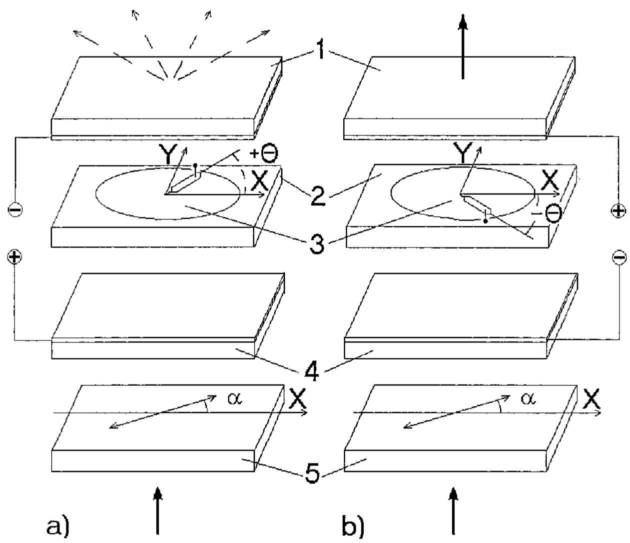

Figure 1. The design and principle of operation of a single-polarizer PDFLC cell [5, 6, 11]. 1 and 4 are the substrates with transparent electrodes; 2 is the polymer matrix; 3 is the FLC droplet; 5 is the polarizer.

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The light passes sequentially through the polarizer, the substrate with a transparent electrode, the uniaxially oriented PDFLC film and finally through a second substrate with a transparent electrode. The PDFLC orientation (the direction of the longer axes of the ellipsoidal droplets) is parallel to the X-axis. The planes of the smectic layers in the FLC droplet are normal to the X-axis. Under the applied bipolar electric signal, the FLC director rotates through a cone about the X-axis to change its orientation in the XY film plane by an angle of 2θ, where θ is the molecular tilt angle. A combination of the components of the PDFLC material is selected to ensure that the refractive index of the polymer, n_p, is equal to the FLC refractive index, $n_\perp$, for the light polarized perpendicular to the director. For the sake of convenience, the refractive indices of the ferroelectric smectic will be treated here in a uniaxial approximation. From this, it is obvious that if the angle α between the light polarization plane and the X-axis equals the angle θ, then the light will be intensely scattered by the PDFLC film due to the high gradient of the refractive index ($n_\parallel - n_p$) at the droplet interface; see figure 1 (*a*). Here $n_\parallel$ is the FLC refractive index for light polarized parallel to the director. In the case of an FLC with $\theta = 45°$, once the field direction has been changed the director becomes oriented perpendicular to the light polarization plane; see figure 1 (*b*). This being the case, the light will pass through the cell without scattering because of the optical uniformity of the PDFLC film ($n_\perp = n_p$). In other words, the uniaxially oriented PDFLC film acts essentially as a light polarizer based on the anisotropy of the light scattering, and the above-described switch-over process produces the same effect as does an azimuthal rotation of this polarizer from the crossed state into a parallel state, with respect to the incident light polarization plane.

At present, FLCs with an angle θ close to 45° are quite rare. For practical applications, ferroelectric smectics with an angle θ of about 22.5° that are optimized for the Clark–Lagerwall cell [10] are more readily available. This circumstance calls for a more detailed analysis of specific features of the process for light passing throughout a single-polarizer PDFLC cell with an arbitrary angle θ. The aim of the present work is to study theoretically and experimentally the dependence of the light modulation characteristics (such as the maximum light transmission, light transmission amplitude and contrast ratio) of such a device on its geometry (the angle α) as well as on the light transmission anisotropy of the PDFLC film for various values of the angle θ.

2. Sample preparation

The light modulators were made of a polymer dispersed ferroelectric liquid crystal material using the thermally induced phase separation (TIPS) method [1, 8, 9]. The widely known polyvinylbutyral (PVB) thermoplastic was used as the polymer matrix. The ferroelectric mixture ZhKS-285 (P. N. Lebedev Physical Institute, Moscow and Institute of Physical Chemistry, Darmstadt, Germany) was chosen for dispersion; the mixture has the phase transition temperatures:

$$\text{Cr–(}-2°\text{C)–SmC*–(}57°\text{C)–SmA–(}112°\text{C)–I},$$

the molecular tilt angle $\theta = 26°$, the spontaneous polarization $\mathbf{P}_s = 90\ \text{nC cm}^{-2}$ and the helical pitch $p_0 = 0.6\ \mu\text{m}$ at 20°C. The above-mentioned requirement of matching between the refractive indices is well satisfied for this composition. The PDFLC film was laminated between two indium tin oxide (ITO) coated glass plates, heated and aligned by shearing. After such treatment, the FLC droplets in projection on the film plane have an ellipsoidal shape with the longer axes aligned in one direction. Examination of the alignment structure of the director inside the droplets [13] showed that the smectic layers on average were perpendicular to the longer axis and had a slight wave-like deformation in the direction of the shorter axis (the axis Y in figure 1). The thickness of the films was about 9 μm. The mean size of the FLC droplets was 8 μm and the axial ratio of the droplets for various samples varied from 2 : 1 to 6 : 1 depending on the magnitude of the above deformation. As a consequence, the PDFLC film optical anisotropy (the ratio between the light transmission components polarized parallel and perpendicular to the orientation direction) also has a significant dependence on the degree of sample deformation.

3. Electro-optical response

The electro-optical measurements were performed by applying bipolar electric signals of a rectangular or sinusoidal shape. A linear polarized He-Ne laser beam passed sequentially through the PDFLC film and a narrow diaphragm before reaching the photodiode. The signal from the photodiode was analysed with a double-beam digital oscilloscope.

Figures 2 and 3 illustrate typical oscillograms of the optical response of the single-polarizer PDFLC cell as a function of its geometrical parameters for the rectangular and sinusoidal control signals, respectively. Figure 4 shows a block diagram of the arrangement of the various components in projection onto the cell plane for the case where the light polarization plane is perpendicular to the PDFLC film orientation, figure 4 (*a*), $\alpha = 90°$; for the case where it is parallel to the PDFLC film orientation, figure 4 (*c*), $\alpha = 0$; and for intermediate values of the angle α, figure 4 (*b*).

First it should be noted that the process of reorientation of the director in the FLC droplets, and hence the change

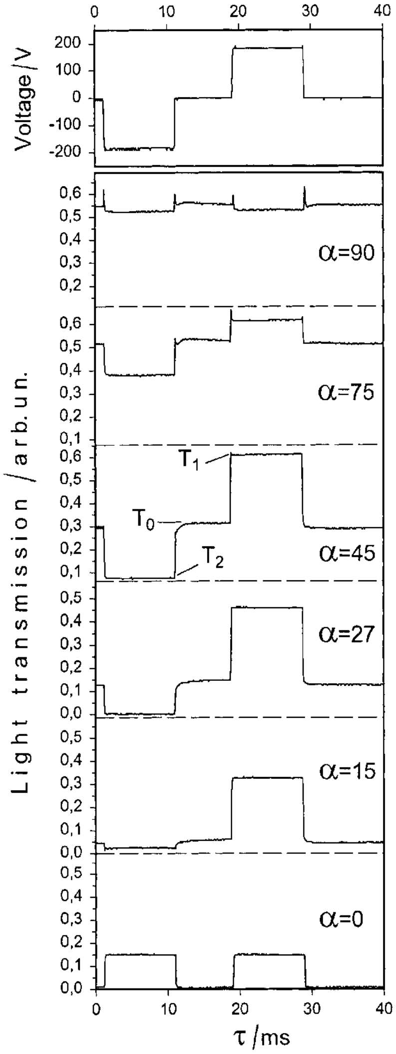

Figure 2. Oscillograms of the optical response of the PDFLC cell to an electric pulse of a rectangular shape obtained for several values of the angle α.

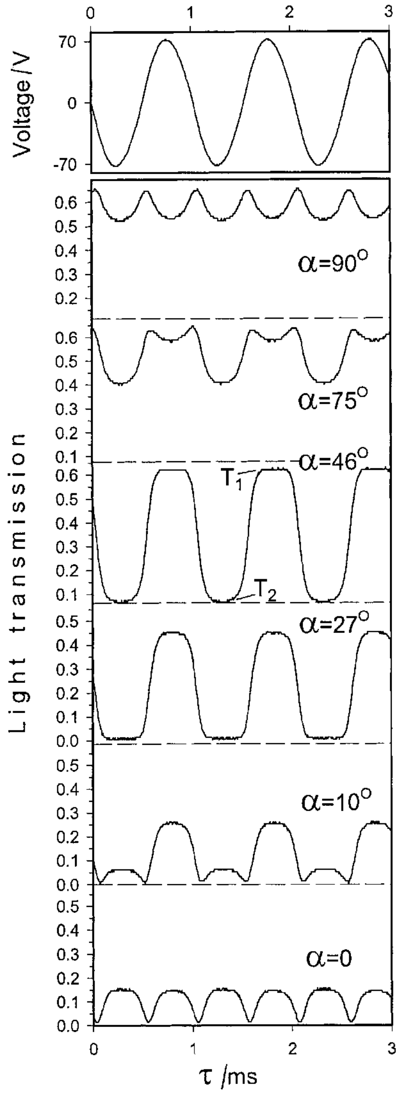

Figure 3. Oscillograms of the optical response of the PDFLC cell to an electric pulse of a sinusoidal shape obtained for several values of the angle α.

in the light transmission of the samples under study, induced by the applied electric field, differ qualitatively from those occurring in PDLC films based on nematics and cholesterics. For the latter, as is known [8, 9], a quadratic electro-optical effect is realized where the PDLC film becomes transparent (provided $\Delta\varepsilon > 0$, and the refractive indices of the composition match each other as indicated above) on separate application of both negative and positive pulses. The linear electro-optical effect taking place in PDFLC films eliminates degeneration along the direction of the electric field. Hence, a positive pulse will cause an increased transmittance of the sample (figure 2, $\alpha = 45°$) whereas a negative pulse will reduce the transmittance.

It is apparent that all the fundamental characteristics of the optical response such as the signal amplitude, the top level of transmittance determining the brightness of the device, and the contrast ratio depend critically on the orientation of the light polarization plane with respect to the direction of orientation of the PDFLC film.

The optical response of a single-polarizer PDFLC cell has been found to feature an interesting behaviour at $\alpha = 0$ and $\alpha = 90°$. In both cases, reorientation of the sample under changing polarity results in optically equivalent states, because the FLC director after rotating through a cone becomes oriented in the film plane at the same angle—either the angle θ at $\alpha = 0$, see figure 4 (*c*) or the angle $(90° - \theta)$ at $\alpha = 90°$, see figure 4 (*a*)—to the light polarization plane for both positive and negative pulses. However, it should be noted that in these geometries too the optical response is still modulated. For example,

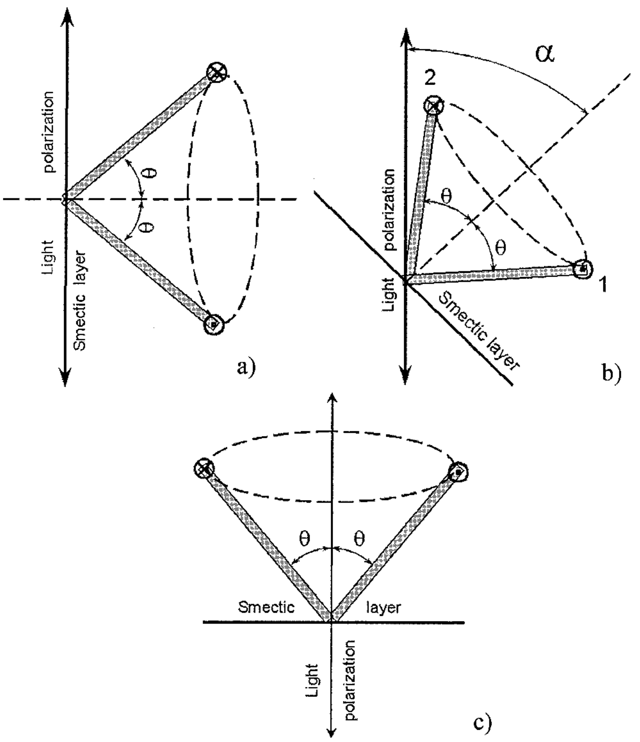

Figure 4. Arrangement of the light polarization plane, smectic layers and FLC director for the angles: (*a*) $\alpha = 90°$; (*b*) $0 < \alpha < 90°$; (*c*) $\alpha = 0$.

at $\alpha = 0$ the light transmission of the sample in an unpowered state is close to zero (see figures 2 and 3), but under the applied electric field pulse (either positive or negative), it grows up to 0.15. In both cases, the optical response oscillograms of the device under study resemble in shape those of PDLC films based on nematics and cholesterics.

4. Theory

We shall introduce the following notations. T_1 is the light transmission (the intensity ratio of radiation directly passing to the incident radiation) of the PDFLC film under the applied positive electric pulse. T_2 is the light transmission under the application of a negative pulse. It is clear that the display brightness in this case (see figures 2 and 3) will be determined by the light transmission, T_1, of the cell. $T_{\parallel}$ is the parallel component of the light transmission. This parameter must be measured at the moment when the sample is under an applied electric pulse of magnitude high enough to saturate the volt–contrast curve (VCC), and the light polarization plane should also be aligned parallel to the FLC director. From the above, it follows that $T_{\parallel}$ is the minimum on the $T_2(\alpha)$ curve. $T_{\perp}$ is the perpendicular component of the light transmission. This parameter is found in a similar manner, but the light polarization plane in this case must be orthogonal to the FLC director. Hence, $T_{\perp}$ corresponds to the maximum on the $T_1(\alpha)$ curve.

Let us denote the light transmission amplitude (the modulation depth) as $\Delta T = (T_1 - T_2)$, and the contrast ratio as $C = T_1/T_2$. One should be very careful in calculating these values experimentally to avoid confusion between T_2 and T_0, particularly in the vicinity of $\alpha \approx 0$ and $\alpha \approx 90°$.

The relations describing those characteristics of the light passing through the PDFLC cell that depend on the cell geometry are derived similarly to those of the classical approach [14] applied to light passing through a system of two polarizers oriented at an arbitrary angle with respect to each other. The only difference is that in our case the second polarizer (the PDFLC film) is not ideal though the difference between the polarized transmission components of the uniaxially oriented PDLC films may be quite significant [3].

By virtue of the symmetry of the problem, we can limit consideration of the angle α to the range 0–90° (figures 2, 3 and 4). Values of the angle θ will be taken in the range of 0–45°, which is common in commercially available crystals. We shall also restrict ourselves to the consideration of what is technologically practical and assume the optical anisotropy parameter, $T_{\parallel}/T_{\perp}$, to vary within the limits 0.01–0.5.

When the director in FLC droplets is oriented at the angle $(\alpha + \theta)$ to the light polarization plane, position 1 in figure 4(*b*), the light transmission level T_1 is achieved as determined by the following expression:

$$T_1 = T_{\perp}\left[1 + \left(\frac{T_{\parallel}}{T_{\perp}} - 1\right)\cos^2(\alpha + \theta)\right]. \quad (1)$$

From this it follows that T_1 reaches its maximum, equal to $T_{\perp}$, at $\alpha + \theta = 90°$, i.e. at $\alpha = 90° - \theta$. Dependence (1) is shown in figure 5 as a three-dimensional graph. Calculations have been performed for $\theta = 26°$. We have also used the value $T_{\perp} = 0.58$ in the approximation of its independence of the optical anisotropy. Such an approximation is believed to be valid since the value of $T_{\perp}$ changes insignificantly, varying in the range of 0.58–0.65, in spite of the substantial difference in the optical anisotropy, $T_{\parallel}/T_{\perp}$, of the PDFLC films under study. Note that the T_1 maximum does not depend on the $T_{\parallel}/T_{\perp}$ value and occurs at $\alpha = 64°$.

The light transmission level T_2 corresponds to the angle $(\alpha - \theta)$, position 2 in figure 4(*b*), and is expressed by:

$$T_2 = T_{\perp}\left[1 + \left(\frac{T_{\parallel}}{T_{\perp}} - 1\right)\cos^2(\alpha - \theta)\right]. \quad (2)$$

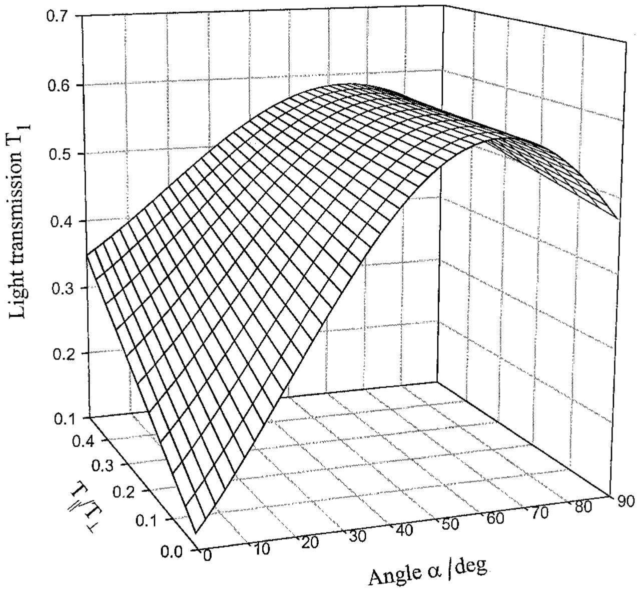

Figure 5. The light transmission T_1 of a single-polarizer PDFLC cell calculated as a function of the angle α and the optical anisotropy $T_\parallel/T_\perp$. The tilt angle $\theta = 26°$, $T_\perp = 0.58$.

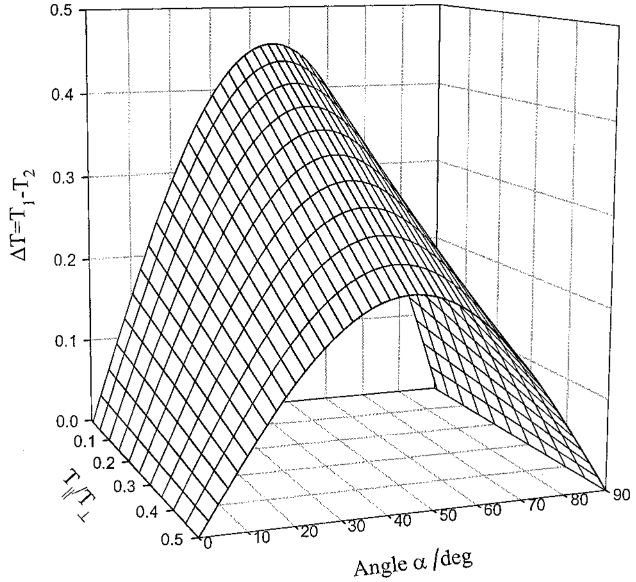

Figure 6. The amplitude of light transmission modulation ΔT of a single-polarizer PDFLC cell calculated as a function of the angle α and the optical anisotropy $T_\parallel/T_\perp$. The tilt angle $\theta = 26°$, $T_\perp = 0.58$.

The minimum values of T_2, equal to $T_\parallel$, are observed at $\alpha = \theta$.

From expressions (1) and (2), after proper trigonometric transformation, one obtains:

$$\Delta T = T_1 - T_2 = T_\perp \left(1 - \frac{T_\parallel}{T_\perp}\right) \sin 2\alpha \sin 2\theta. \quad (3)$$

From the above it follows that the position of the maximum on the $\Delta T(\alpha)$ curve is dependent neither on the angle θ nor on the optical anisotropy $T_\parallel/T_\perp$ and is always observed at $\alpha = 45°$. The three-dimensional graph in figure 6 is a good illustration of the indicated feature of dependence (3). This estimation again has been carried out in the assumption of the value of $T_\perp = 0.58$ being independent of the optical anisotropy. It should be mentioned that for the purpose of light modulators, it is not at all necessary to have a PDFLC film with high optical anisotropy (small $T_\parallel/T_\perp$ ratio). It is obvious that for the FLC under study, even with the component ratio $T_\parallel/T_\perp = 0.5$ it is possible to obtain a light transmission modulation amplitude as high as $\Delta T > 20\%$.

The contrast ratio dependence on the angular and material parameters appears to be more involved:

$$C = \frac{T_1}{T_2} = \frac{1 + \left(\frac{T_\parallel}{T_\perp} - 1\right)\cos^2(\alpha + \theta)}{1 + \left(\frac{T_\parallel}{T_\perp} - 1\right)\cos^2(\alpha - \theta)}. \quad (4)$$

From the above formula, the maximum contrast ratio C is found to take place at the angle α:

$$\alpha_m = \frac{1}{2} \arccos\left(\frac{T_\perp - T_\parallel}{T_\perp + T_\parallel} \cos 2\theta\right). \quad (5)$$

It should be noted that the conditions for obtaining a maximum contrast ratio C and a minimum light transmission T_2 are generally not the same. The angle α_m in equation (5) depends not only on the angle of the molecular tilt θ, but also on the light transmission anisotropy of the PDFLC film. The complex behaviour of the contrast ratio curve (4) as a function of the film optical anisotropy and angle α is conveniently analysed with the help of the 3D graph represented in figure 7. One can see that the position of maximum contrast is strongly dependent on the $T_\parallel/T_\perp$ value. For example, at $T_\parallel/T_\perp = 0.5$ the angle $\alpha_m = 39.1°$, which considerably exceeds the value of the angle θ in the FLC under study. Even with smaller values of $T_\parallel/T_\perp$ it should be taken into account that $\alpha_m > \theta$. For instance, if $T_\parallel/T_\perp = 0.1$, the contrast ratio maximizes at $\alpha_m = 29.9°$ and is equal to $C_m = 6.9$; if $T_\parallel/T_\perp = 0.05$, then $C_m = 13.1$ at $\alpha_m = 28.1°$. However if the $T_\parallel/T_\perp$ ratio is fairly small, one can safely assume

$$\alpha_m \cong \theta. \quad (6)$$

For example, if $T_\parallel/T_\perp = 0.01$, then $C_m = 62.8$ occurs at $\alpha_m = 26.4°$. From equation (4) it follows that for such samples the maximum contrast ratio can be estimated

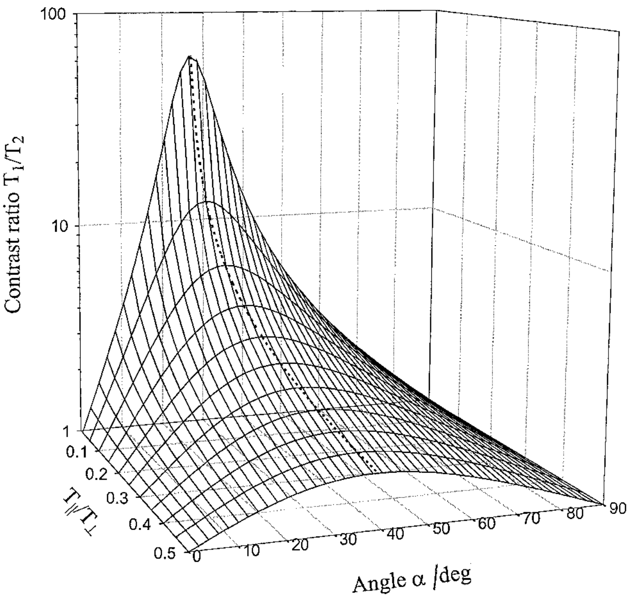

Figure 7. The contrast ratio C of a single-polarizer PDFLC cell calculated as a function of the angle α and the optical anisotropy $T_\parallel/T_\perp$. The tilt angle $\theta=26°$. Maximum contrast ratio values C_m are shown by the dashed line.

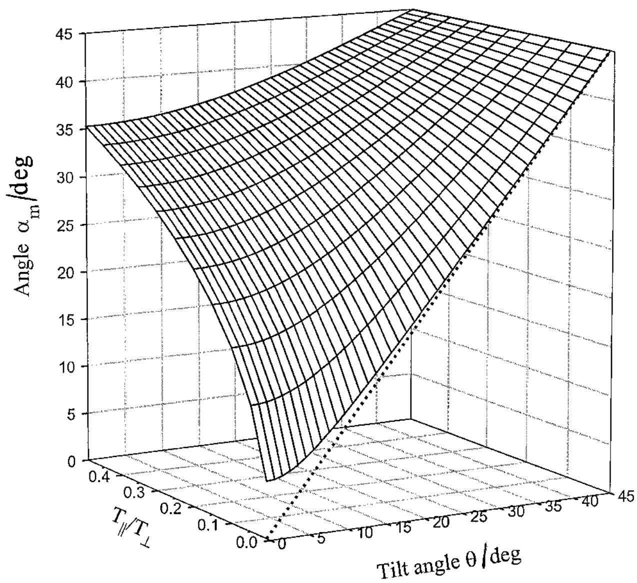

Figure 8. The angle α_m, corresponding to maximum contrast values, versus the PDFLC film optical anisotropy $T_\parallel/T_\perp$ and the molecular tilt angle θ as calculated by formula (5). The dashed line shows approximation (6) for $T_\parallel/T_\perp = 0.01$.

by using the approximate expression:

$$C_m \cong 1 + \left(\frac{T_\perp}{T_\parallel} - 1\right)\sin^2 2\theta \cong \frac{T_\perp}{T_\parallel}\sin^2 2\theta. \qquad (7)$$

To determine the range of applicability of approximation (6), let us analyse the dependence (5) of the angle α_m on the molecular tilt angle θ for various values of $T_\parallel/T_\perp$ (see figure 8). It is obvious that formula (6) is only valid for a PDFLC with high optical anisotropy (i.e. for small $T_\parallel/T_\perp$) and only provided $\theta > 20°$ at that.

Theoretical estimates of the highest attainable contrast ratio for the PDFLC films with various values of $T_\parallel/T_\perp$ and θ parameters calculated with the use of exact (4) and approximate (7) formulae are represented in figure 9 and figure 10, respectively. By comparing the figures, it is found that approximation (7) is good for small $T_\parallel/T_\perp$ when the molecular tilt angle θ tends to 45°. For fairly small θ angles, approximation (7) may yield a physically meaningless result ($C<0$) even for highly anisotropic PDFLC samples.

The behaviour featured by the optical response of a PDFLC cell at $\alpha=0$ or $\alpha=90°$ (figures 2, 3 and 4) allows us to use an alternative method of control in PDFLC devices. In this case the cell will become transparent under application of an electric field of either polarity, and the optical state switch over will occur between the levels T_0 and $T_1=T_2$. Figure 2 for $\alpha=0$ suggests that in the given geometry, it is possible to achieve a contrast ratio of 23 : 1; however the brightness of the device in that case will be quite low ($T_1=T_2\cong 0.15$).

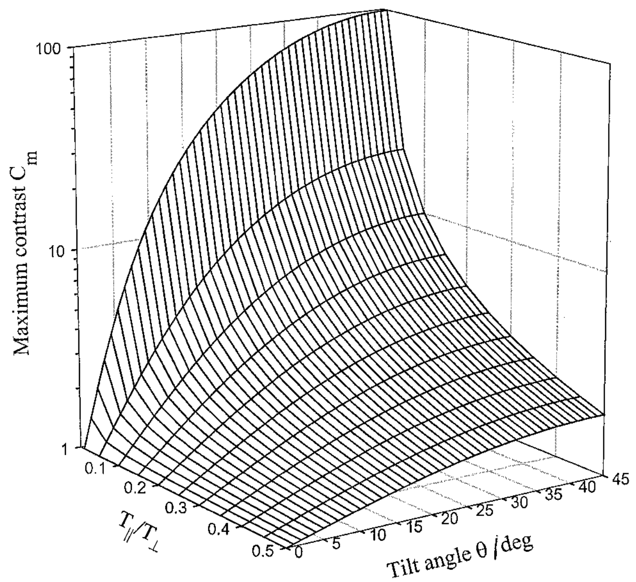

Figure 9. Dependence of the maximum contrast ratio C_m on the PDFLC film optical anisotropy $T_\parallel/T_\perp$ and the molecular tilt angle θ as obtained by the exact formula (4).

5. Experimental results

When measuring characteristics of PDFLC cells the electric field magnitude must fall into the region of saturation of the volt–contrast curves. Lower values of the electric field cannot ensure a complete rotation of the FLC director, in which case a comparison between the theoretical and experimental results would be incorrect. In figures 11 (*a–c*) the optical response behaviour of

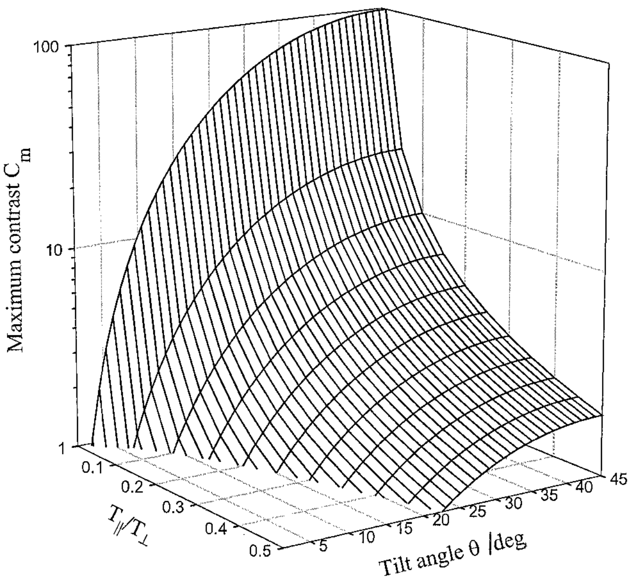

Figure 10. The maximum contrast ratio C_m as a function of the PDFLC film optical anisotropy $T_{\parallel}/T_{\perp}$ and the molecular tilt angle θ estimated by approximate formula (7).

the same sample is shown as a function of the applied voltage for three different values of the angle α. As can be seen, the curves under consideration saturate at $U > 40$ V. By comparing figures 11 (*a*) and 11 (*b*) one can see that both T_1 and T_2 fall as the angle α decreases to 27°. However in the region of VCC saturation, the light transmission T_2 approaches zero, which results in a rapid growth of the contrast ratio C. A further decrease of the angle α, see figure 11 (*c*), complicates the shape of the volt–contrast curve. In this case, as the electric field value grows, the contrast ratio reaches its maximum at $U = 34$ V and then tends to decrease. Such a behaviour is due to the fact that at $\alpha < \theta$—see figure 4 (*b*)—even an incomplete rotation of the FLC director (at $U = 34$ V) proves to be sufficient for its projection onto the film plane to coincide with the light polarization, so ensuring a minimum T_2 and a maximum contrast. In the saturation region, upon a complete rotation of the director, the angle between the director alignment and the light polarization plane becomes $(\theta - \alpha) > 0$, which leads to the increased light transmission T_2 and a dramatic decrease in the contrast ratio.

The results of experimental measurements and the theoretical curves of the contrast ratio C, the T_1 light transmission component and the modulation amplitude ΔT are shown in figures 12 (*a*) and 12 (*b*), respectively, for two PDFLC film samples having different optical anisotropy. The figures indicate good agreement between the experimental and theoretical results. The curves presented provide a good illustration of the difference in the position of the maximuma of the investigated parameters on the α-axis. For the sample with $T_{\parallel}/T_{\perp} = 0.069$, the maximum contrast ratio $C_m = 9.7$ is observed at $\alpha_m = 28.8°$, with the light transmission T_1 being about 0.4. The light transmission T_1 could be increased up to 0.58 by taking $\alpha = 64°$, but then the contrast ratio would drastically drop to 2.3. It should also be noted that the contrast ratio shows a much more critical dependence on the angle α in samples with a higher optical anisotropy.

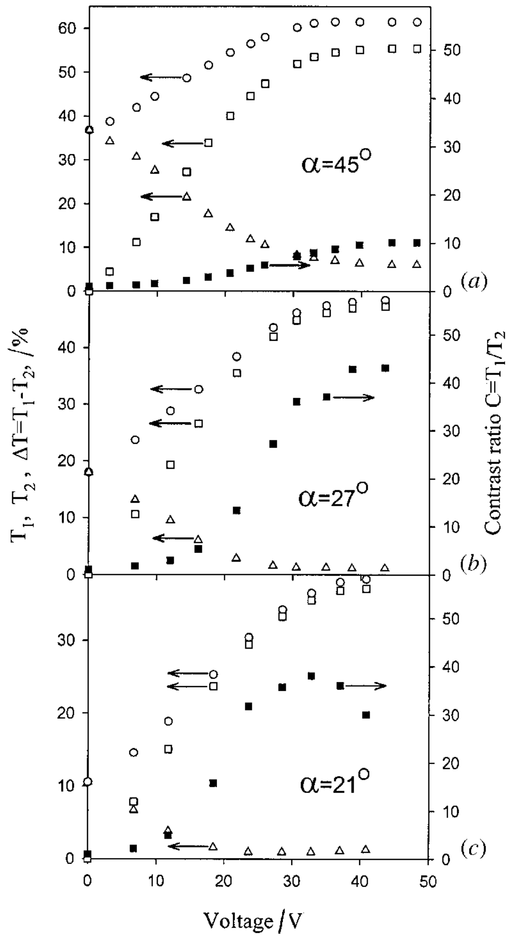

Figure 11. Curves of the light modulation characteristics of a single-polarizer PDFLC cell as a function of the applied voltage obtained experimentally at three different values of the angle α. Contrast ratio C is denoted by (■), amplitude of light transmission modulation ΔT by (□) and light transmission components T_1 by (○) and T_2 by (△).

6. Conclusion

Employment of ferroelectric liquid crystals in composite liquid crystal materials allows improvement of their optical response time by three orders of magnitude compared with similar materials based on the use of nematics and cholesterics. The PDFLC material can find a variety of applications in display and other electro-optical devices where high frequency (up to 1 MHz) light modulation is a requirement. The results of the theoretical analysis

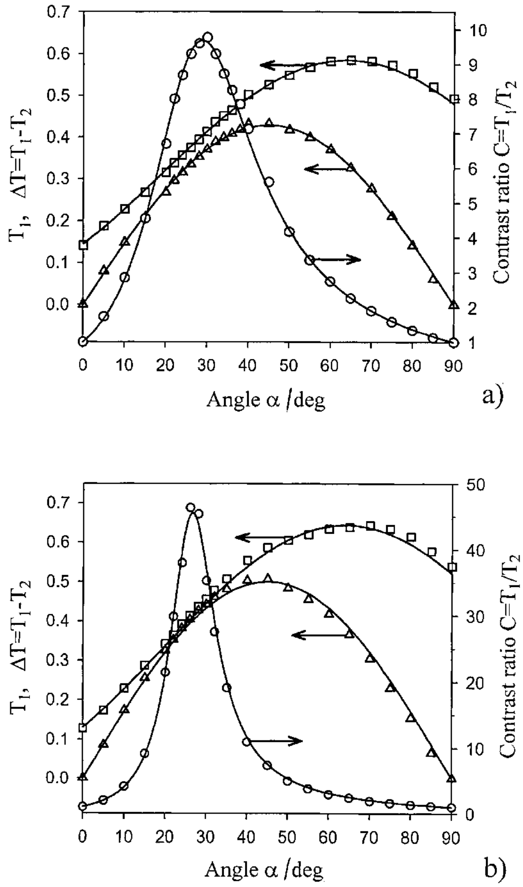

Figure 12. Experimental dependences of the contrast ratio C (○), light transmission T_1 (□) and amplitude of modulation ΔT (△) on the angle α obtained for two PDFLC samples with different optical anisotropies: (*a*) $T_{\parallel}/T_{\perp}=0.069$, $T_{\perp}=0.58$; (*b*) $T_{\parallel}/T_{\perp}=0.014$, $T_{\perp}=0.64$; theoretical curves for these parameters are shown by the solid lines.

and experimental measurements of basic characteristics of the optical response (such as the contrast ratio, maximum light transmission and light transmission modulation amplitude) reported herein, for various designs of the device and different parameters of the material, describe specific features of the application of PDFLC films in single-polarizer modulators operating through the light scattering effect.

From the results obtained, it follows that the requirement for coinciding positions of the maximum values of the contrast ratio, brightness and light transmission modulation amplitude in PDFLC cells can only be satisfied by using liquid crystals with the molecular tilt angle $\theta=45°$ in the geometry $\alpha=45°$. Otherwise, for $0<\theta<45°$, a cell geometry must be chosen to ensure an optimum combination of the light modulation parameters. To that end, expressions (1)–(7) and the graphical analysis data can be used as basic guidelines in choosing components that optimize the technology of uniaxially oriented PDFLC films and the geometry of electro-optical devices.

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