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Debinder S. Pabla; Steve J. Elston

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Optical studies of dynamic director configurations in ferroelectric liquid crystal devices

DEBINDER S. PABLA and STEVE J. ELSTON*
Department of Engineering Science, University of Oxford, Parks Road, Oxford OX1 3PJ, United Kingdom

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An investigation into the transmission spectrum of a ferroelectric liquid crystal device is undertaken. This is done both for an initial static state and during a switching process. Comparisons are made between experimental data and theoretical predictions. The dynamic internal director configurations in the device is shown to be consistent with a simple model during both monopolar and bipolar addressing pulses.

1. Introduction

Developing a full understanding of the switching processes in ferroelectric liquid crystals (FLCs) is essential to the further development of technology based on these materials. To this end a number of models have been put forward in order to understand the dynamic behaviour of these materials when switched with simple and complex pulses.

In this paper we use a one dimensional model with strong surface and interface anchoring to predict the director profiles for monopolar and bipolar pulses when switching a sample. These are then compared with experimental results for devices containing the ferroelectric liquid crystal material SCE8.

The technique described in this paper uses optical measurements of the visibile transmission variation with wavelength for a device placed between crossed polarizers. Such results allow direct comparisons with generated spectra for predicted dynamic director profiles. A similar approach has been used before to investigate the dynamics of related structures [1], and it is closely related to that used by Anderson *et al.* to study the director profiles in liquid crystal devices [2]. A detailed study of the spectral response for dynamic profiles is therefore undertaken, by comparing experimental data with simulations for both monopolar and bipolar pulses in both low and high voltage regimes.

We begin in §2 by discussing the approach to modelling the dynamic director profiles during switching. In §3 we describe the experimental arrangement used, and in §4 we describe the simulation of the spectra from the initial director profile. In §5 we make comparisons between the experimental and theoretical results for dynamic switching processes, followed by concluding comments in §6.

*Author for correspondence; e-mail: Elston@eng.ox.ac.uk

2. Modelling dynamic profiles in C2 structures

We will consider the structure and reorientation of the ferroelectric liquid crystal director within an ideal C2 structure [3]. In this case the smectic layers form a chevron structure with a tilt angle δ relative to the cell surface normal. The surface pre-tilt is then assumed to be such that the director at the surface is in the alignment (or rubbing) direction and the azimuthal angle ϕ at the upper and lower surfaces is set to 90° and $-90°$, respectively. These are used as boundary conditions in the solutions below. The static director profile is then made to vary at a constant rate through the device from the surfaces to the fixed azimuthal angle ϕ_{IN} at the chevron interface, to form the so called Triangular Director Profile (TDP) [2]. ϕ_{IN} is taken as the boundary condition at the chevron interface and is given by

$$\phi_{IN} = \sin^{-1}\left(\frac{\tan\delta}{\tan\theta}\right) \tag{1}$$

where θ is the cone angle and δ is the layer tilt. Furthermore, in the co-ordinates of the device, the director can be expressed as

$$\mathbf{n}(X, Y, Z) = \begin{pmatrix} \sin\theta\cos\phi \\ \sin\theta\sin\phi\cos\delta - \cos\theta\sin\delta \\ \sin\theta\sin\phi\sin\delta + \cos\theta\cos\delta \end{pmatrix} \tag{2}$$

where Z is in the alignment direction and Y is perpendicular to the cell surfaces. Thus, the twist angle ψ may

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be expressed as

$$\psi = \tan^{-1}\left(\frac{\cos\phi\tan\theta}{\cos\delta + \sin\phi\sin\delta\tan\theta}\right) \quad (3)$$

and the tilt angle ζ is given by

$$\zeta = \sin^{-1}(\sin\phi\cos\delta\sin\theta - \cos\theta\sin\delta) \quad (4)$$

where the twist is the reorientation angle in the plane of the cell surfaces and the tilt is the reorientation angle out of the surface plane; both of these are required when modelling the optics of a given profile, as discussed later. It should be noted that in calculating ψ and ζ the sign of δ is opposite in the two halves of the chevron structure.

In addition, we require the governing equation to calculate dynamic director profiles in one dimension through the device. In a one constant approximation this is taken to be

$$\eta\frac{\partial\phi}{\partial t} = \mathbf{PE}\sin\phi\cos\delta + K\frac{\partial^2\phi}{\partial y^2} + \partial\varepsilon\varepsilon_0\mathbf{E}^2\sin^2\theta\sin\phi\cos\phi\cos^2\delta \quad (5)$$

where η is the material viscosity, $\mathbf{P}$ is the polarization, $\mathbf{E}$ is the applied electric field, K is an elastic constant and $\partial\varepsilon$ is the dielectric biaxiality.

Numerical solutions to this equation, with the boundary conditions discussed above and initial condition taken to be the TDP, allow one to generate director profiles as a function of time when a field is applied. Now that the director profile, twist and tilt angles can be modelled, this information can be used to determine the corresponding device optics. We wish to determine the device transmission as a function of the optical wavelength, the spectrum of the transmitted light being a probe of the molecular/director orientation. As such we need to translate the dynamic profiles created by the proposed model into an optical response for a particular wavelength.

An accurate method to determine the influence of a liquid crystal on polarized light is adopted. The so called '4×4 matrix technique' allows calculation of reflection and transmission for anisotropic multilayered structures [4]. The technique results from the systematic reduction of Maxwell's equations for stratified media and permits the calculation of the optical properties of oblique incidence, as well as accounting for multiple reflections at the interfaces. If the entire medium is piecewise homogeneous, exact expressions of the output quantities can be calculated. For inhomogeneous media, such as in SSFLC devices, for which the optic axis varies continuously with the position normal to the plane of stratification, the media can be approximated by a large number of thin homogeneous slabs (normally $\ll\lambda$ thick). Each slab is then represented by a 4×4 matrix, and the characteristic matrix of the whole medium is the product of the 4×4 matrices of all the individual slabs. The boundary conditions at the entrance and at the exit of the medium together with the characteristic matrix yield a set of four equations, which must be solved in order to obtain the reflection and transmission coefficient for a particular combination of input and output polarisations. Calculating the transmission coefficient as a function of wavelength for a device between crossed polarizers then gives the required spectrum.

3. Experimental arrangement

The experimental arrangement used is illustrated in figure 1. A general purpose monochromator illuminated with light from a halogen lamp and using a 1200 line mm^{-1} diffraction grating provides the light source. The monochromator is under computer control, allowing wavelength scanning to be automated. The output light was passed through a fibre bundle and focused by a pair of lenses, both with a focal length of 5 cm, onto a defect free area of the device measuring approximately 4 mm^2.

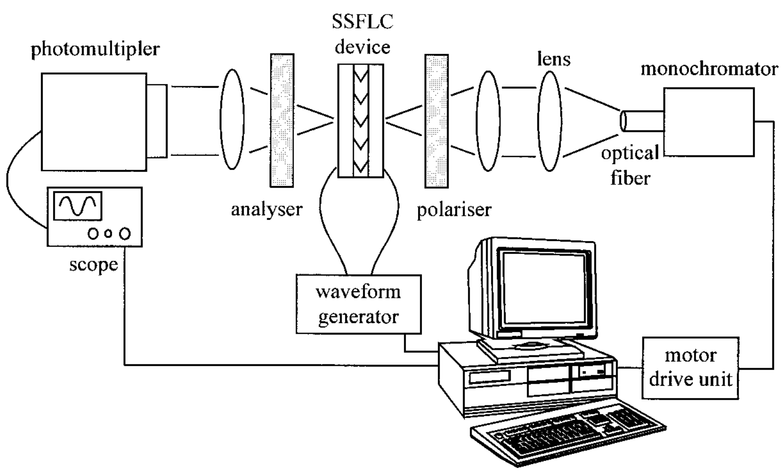

Figure 1. Schematic diagram of the experimental arrangement used to collect spectral data from a device between crossed polarizers. The monochromator is a diffraction grating based instrument. The computer controls the change in wavelength from the monochromator, the addressing waveform to be sent and the collection of data at a given point in an addressing waveform cycle.

Because of the low levels of light intensity being transmitted a photomultiplier detector was used. The detected signal was displayed and digitized by an oscilloscope and passed onto the computer for analysis.

The device under investigation was constructed from two ITO-coated glass plates, treated with a rubbed surface alignment layer and assembled face to face with glass balls as spacers. Rubbing directions were aligned parallel and the device was filled with the FLC material SCE8 (Merck Ltd). Before mounting the device in the experiment, it was examined in a polarizing microscope to determine that the area under investigation was in the C2 state and free of zig-zag defect lines [5]. This was crucial, since the C1 and C2 regions (separated by these defect lines) and the lines themselves have their own respective influence on light propagation and so would affect the data which we wished to collect. In order to compare spectral data of the device with the model, one needs to determine carefully how the device is orientated relative to the input polarizer. For normally incident light, although the direction of the chevron is irrelevant (since rotating the device by 180° about the incident beam results in an optically indistinguishable situation), the actual projection of the chevron layer normal onto the glass surfaces is not. It is this, which is taken to be coincident with the rubbing direction, that defines the orientation of a device with reference to the input polarizer. Here, this angle is generally chosen to give maximum contrast between light and dark states, and is found to be 21.0 degrees.

With the device in this configuration, transmission spectra from 450 to 700 nm were collected for the relaxed states, as well as for a range of monopolar and bipolar pulses in low and high voltage regimes, with the device starting in both the dark and light states. The transmission in the dynamic cases could be collected synchronously at various points within the addressing pulses.

Before direct comparisons could be made with the simulations, we needed to ensure that the data corresponded to the spectral response of the liquid crystal alone, and that any effects of the apparatus (spectrum of the illuminating bulb, etc.) were cancelled out. This was achieved by normalizing the data using the formula

$$T = \frac{T_{\mathrm{cwd}} - T_{\mathrm{cwod}}}{T_{\mathrm{pwod}} - T_{\mathrm{cwod}}} \qquad (6)$$

where T is the transmission at a particular wavelength, T_{cwd} is the transmission for the device when between crossed polarizers, T_{cwod} is the transmission with the polarizers crossed and with the device removed, and T_{pwod} is the transmission without the device with the polarizers parallel.

4. Simulating spectra of director profiles

The device transmission as a function of the optical wavelength depends not only on the molecular orientation, but also on the device thickness and the refractive index anisotropy of the material. The molecular reorientation can be generated with the proposed switching model and the device thickness can be determined optically or approximated from the birefringence colours observed under a polarizing microscope. All that remains before comparisons with experiment can be made is for a method of determining the refractive index dispersion to be developed.

For this we follow the approach to FLCs by Jones *et al.* [6] which utilises a truncated version of the Cauchy formula

$$n = a + \frac{b}{\lambda^2} \qquad (7)$$

where a and b are constants and n is either n_e or n_o, the extraordinary and ordinary refractive indices, respectively. The values of n_e and n_o were chosen so that they followed those given by Jones *et al.* [6] of

$$n_e = 1.598 + \frac{19439}{\lambda^2} \qquad (8)$$

$$n_o = 1.467 + \frac{7582}{\lambda^2} \qquad (9)$$

where λ is in nanometres.

Initially, we attempted to model the static spectral response for the device in the relaxed light state. This allowed us to check that the initial state is the TDP and also allowed the values of a number of parameters to be

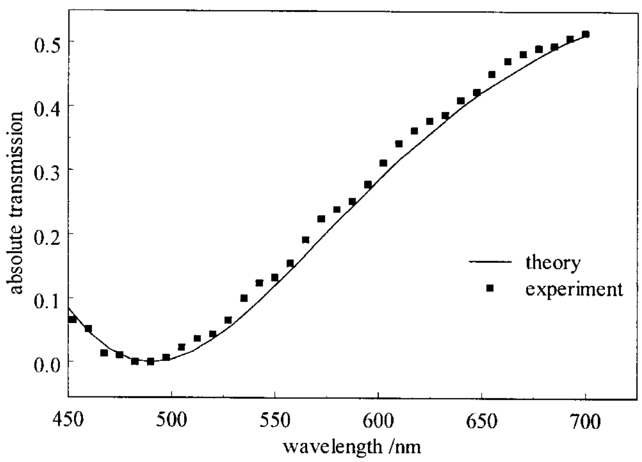

Figure 2. The wavelength dependence of the transmission for a ferroelectric liquid crystal device in the relaxed light state. This is fitted numerically to a triangular director profile using the corresponding twist and tilt angles.

fixed, this being a subset of the total set of parameters for which values must be chosen in order to model the dynamic spectra.

We fixed the cone angle at the manufacturers quoted value of $\theta = 19.5°$. The remaining parameter values needed to determine the static spectra were the smectic layer tilt angle δ and the thickness d; these were then chosen so as to achieve the best possible fits to the experimental data (transmission spectra). This was accomplished by segmenting the interior of the device into one hundred individual layers of material with the individual twists and tilts calculated as outlined above. The optical behaviour could then be calculated using the 4×4 matrix approach. The smectic layer tilt angle was found to be 17°, and the thickness value was found to be 2.9 μm. This value was, not surprisingly, in close agreement with the estimated value, determined from the appearance of the birefringence colours of navy blue and yellow (which represented the dark and light states, respectively), when viewing the sample in a polarizing microscope. The set of parameters used to model (and determined from) the relaxed state TDP are shown in table 1, and an example fit between a TDP spectrum and the theory is shown in figure 2. It should be noted that this was checked for a number of device orientations, and therefore this is equivalent to the approach used by Anderson *et al.*, where the extinction angle as a function of wavelength was extracted from transmission data [2]. Thus having assigned values for those parameters which determine the static spectrum, the remaining parameter values required to determine the dynamic spectra need to be set.

Table 1. Parameter values used in determining the static (relaxed state) spectral response.

Parameter	Value
Cone angle θ	19.5°
Layer tilt δ	17.0°
Thickness d	2.9×10^{-6} m
Extraordinary refractive index n_e	$1.598 + \frac{19439}{\lambda^2}$
Ordinary refractive index n_o	$1.467 + \frac{7582}{\lambda^2}$

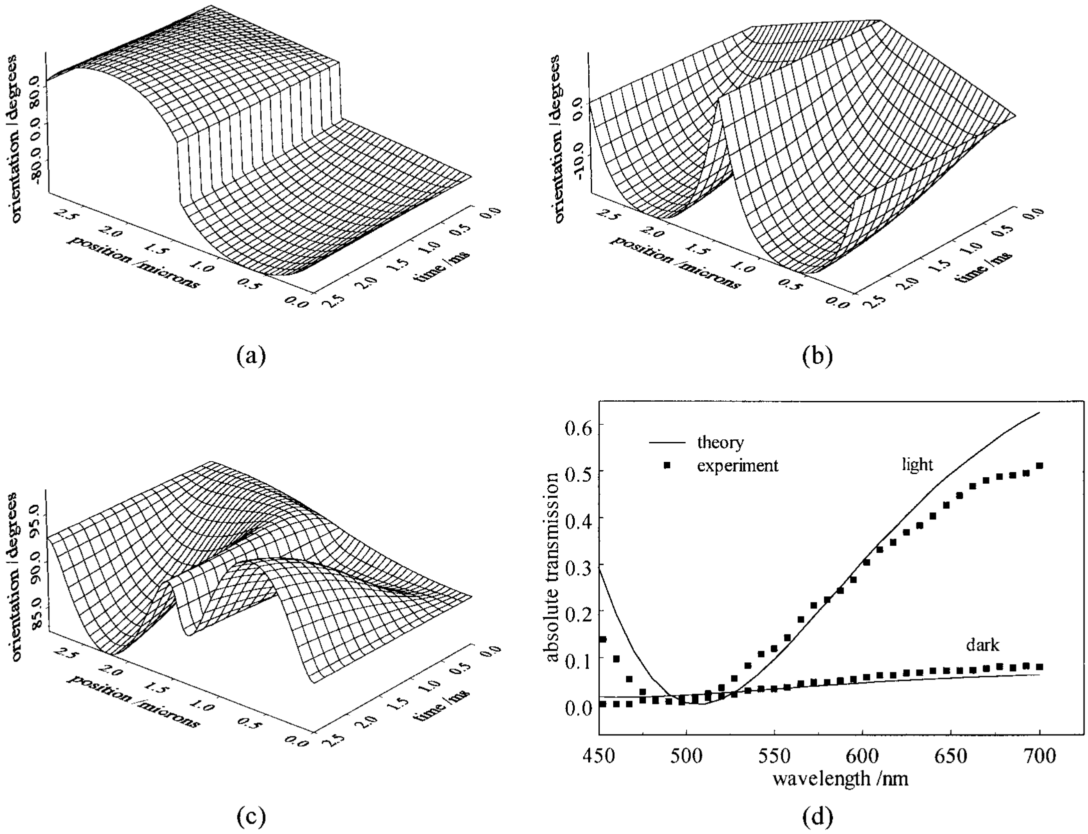

Figure 3. Simulations of the (*a*) azimuthal angle, (*b*) twist angle and (*c*) tilt angle when addressing with a 2.0 V, 2.5 ms monopolar pulse. (*d*) Theoretical and experimental comparisons of the transmission spectra for a device between crossed polarizers. The spectral plots correspond to the stressed switching response towards both the dark and light states at the end of the monopolar addressing pulse.

5. Modelling spectra for dynamic director profiles

Fitting to multiple sets of data is a non-trivial task because, although one set of parameters may fit one particular data set well, the same parameters may prove to be totally unacceptable for another data set. In view of this constraint, a set of values for the remaining parameters was chosen such that the fits between data and theory were satisfactory in all cases. Indeed as we shall see, the fact that satisfactory fits are achieved for both monopolar and bipolar data suggests that the chosen parameters and the model itself do predict the actual state of the device well.

The value of the birefringence is $0.15 < \Delta n < 0.19$ over the 450–700 nm range considered here, and the values of the cone angle θ, layer tilt δ and thickness d have been determined above using the static spectral response. The remaining parameter values chosen in determining the dynamic director profiles from which the dynamic optical spectra may be found are shown in table 2. Figures 3 to 6 each show the sequence of plots, azimuthal angle, twist angle and tilt angle, as well as the respective comparisons of the spectra at the end of the addressing pulse. It is important to note that in all but the high voltage monopolar case, this clearly corresponds to a dynamic situation. In all the spectral simulations, one hundred numerical strata were again created within the thickness of 2.9 μm. Figures 3 and 4 show the simulations and spectral comparisons for low and high voltage monopolar pulses. Likewise, figures 5 and 6 show plots for low and high voltage bipolar pulses, respectively. Looking at the stressed azimuthal angle in figures 3(*a*) and 4(*a*), we see that the directors rotate around their respective 'cones' to a lesser extent in the former case than in the latter case, as is to be expected. The degree

Table 2. Parameters used in the generation of dynamic director profiles.

Parameters	Value
$\partial\varepsilon\varepsilon_0$	5.275×10^{-12} F/m
η	77.0×10^{-3} Nm
K	1.0×10^{-11} N
P	6.9 nC cm^{-2}

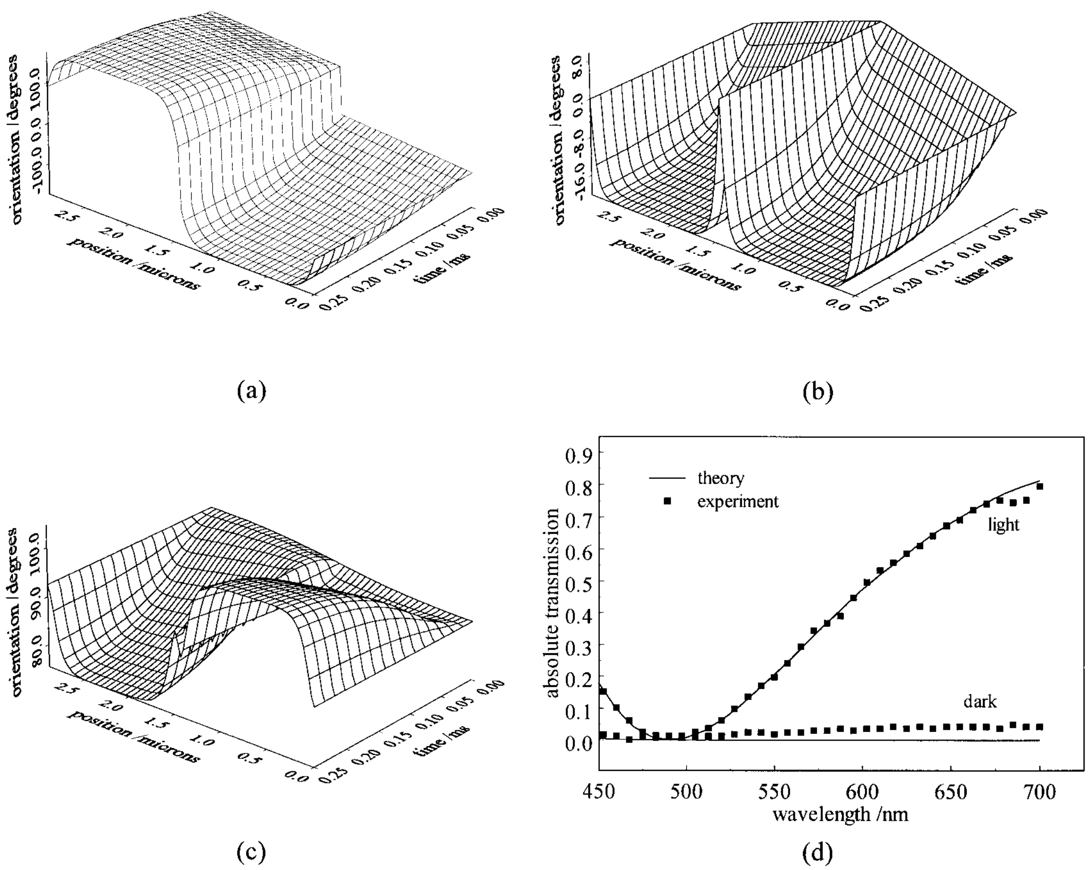

Figure 4. Simulations of the (*a*) azimuthal angle, (*b*) twist angle and (*c*) tilt angle when addressing with a 13.5 V, 0.25 ms monopolar pulse. (*d*) Theoretical and experimental comparisons of the transmission spectra for a device between crossed polarizers. The spectral plots correspond to the stressed switching response towards the dark and light states at the end of the monopolar addressing pulse.

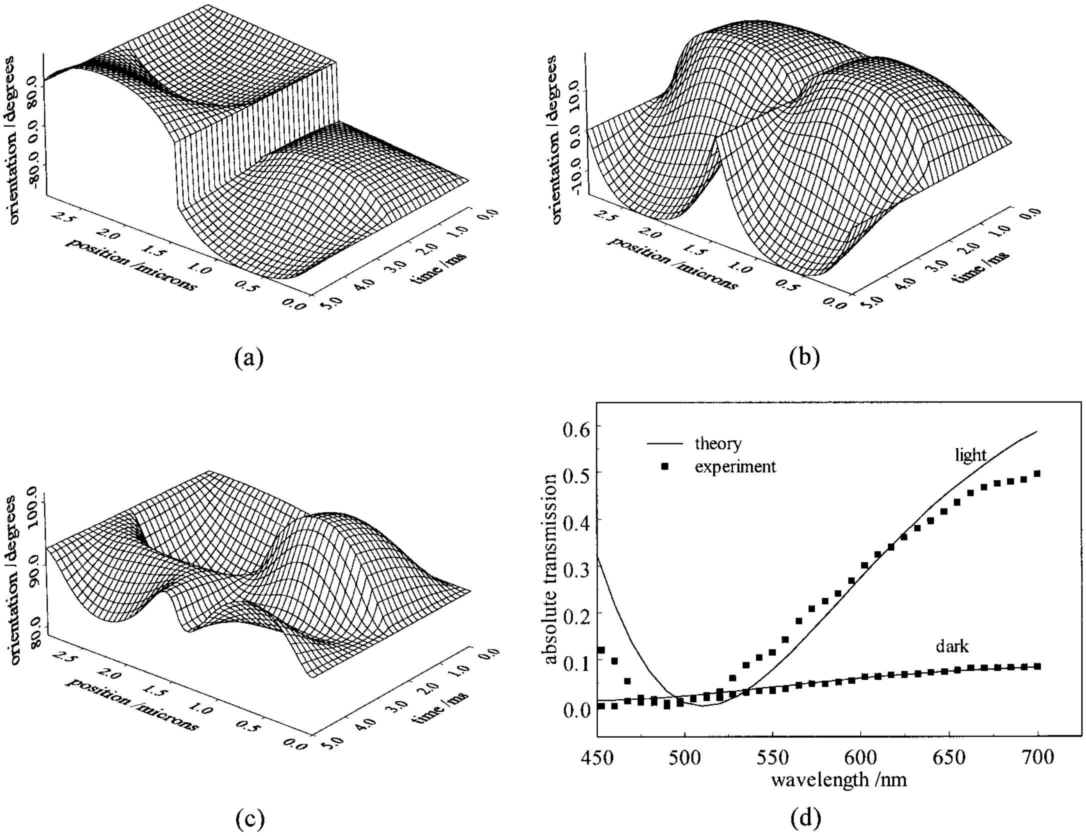

Figure 5. Simulations of the (*a*) azimuthal angle, (*b*) twist angle and (*c*) tilt angle when addressing with a 2.24 V, 5.0 ms bipolar pulse. (*d*) Theoretical and experimental comparisons of the transmission spectra for a device between crossed polarizers. The spectral plots correspond to the stressed switching responses towards the dark and light states at the end of the bipolar addressing pulse.

of stressing is the only difference in the two profiles at the end of the pulse. The spectrum compares well with the theory in both monopolar cases, particularly in the high voltage case. This is as we might expect, because at the end of the high voltage monopolar pulse, the director structure appears to have reached an equilibrium orientation (figure 4), and therefore fitting returns to what is in effect the static situation. However, in the low voltage pulse case (figure 3), the structure is still evolving, and therefore the results correspond to what is truly a dynamic situation, which is more difficult to simulate correctly.

The simulations of low and high voltage bipolar responses are given in figures 5 and 6, respectively. In the low voltage bipolar case, the azimuthal profile at the end of the addressing pulse is very similar to the monopolar low voltage azimuthal profile. This fact is further exemplified by the spectrum which has a very close resemblance to figure 3 (*d*). Again the spectral fits for the dark and light states are reasonably accurate for this case, where the structure is in the process of dynamic evolution.

In the high voltage case, the profile has evolved so as to be fundamentally different from all the previous cases. Here the azimuthal angle near the surface and interface regions leads the bulk in the degree of reorientation achieved when switching towards the opposite state. This is opposite to all the other cases considered. However, our simulations compare very well with the spectral response for this example, as illustrated in figure 5 (*d*). As can be seen, the transmission levels when switching towards the dark state are greater than when switching towards the light state. This is complementary to the other spectra shown here. The fact that the high voltage bipolar data are so different from all the other cases, and that they are accurately modelled indicates that reorientation near the sufaces does lead the bulk at high voltages. Such subtle effects are difficult to demonstrate when making a simple transmission measurement at a single wavelength. The extra information is present when spectra are studied because the influence of a given structure varies critically with wavelength when the scale of the structure is of the order of the wavelength of light in size.

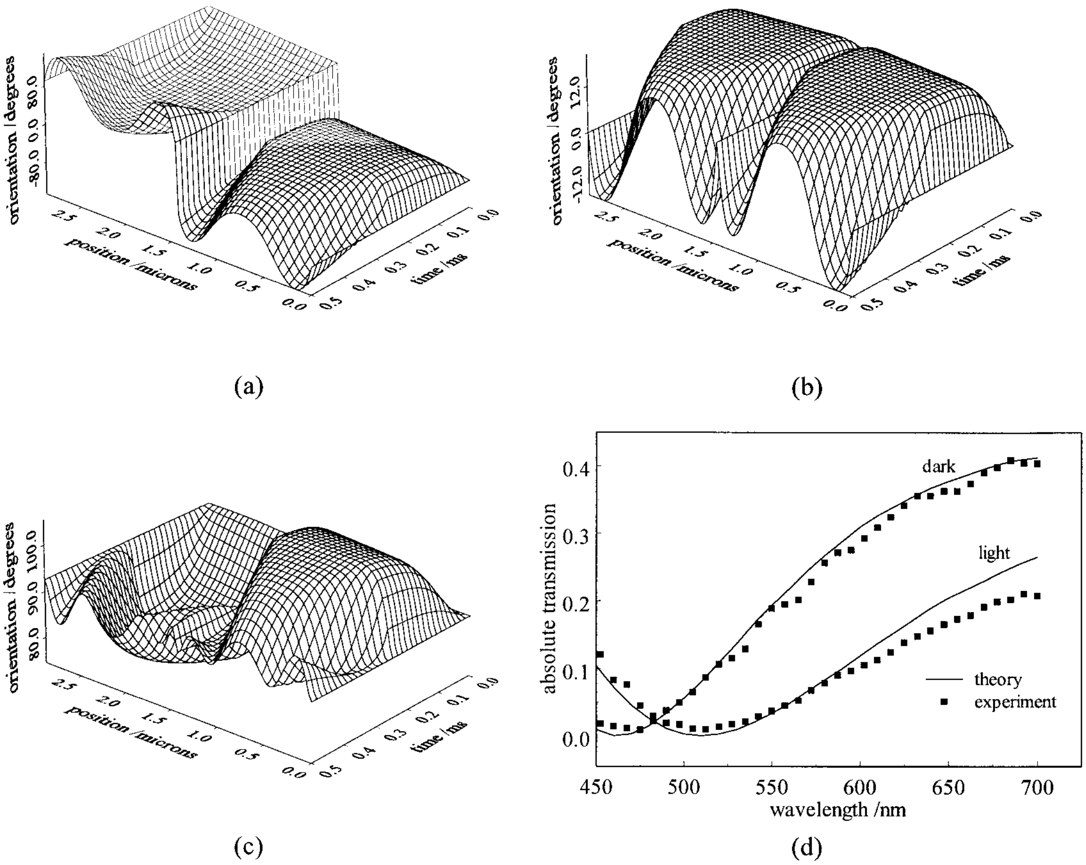

Figure 6. Simulations of the (*a*) azimuthal angle, (*b*) twist angle and (*c*) tilt angle when addressing with a 16.0 V, 0.5 ms bipolar pulse. (*d*) Theoretical and experimental comparisons of the transmission spectra for a device between crossed polarizers. The spectral plots correspond to the stressed switching response at the end of the bipolar addressing pulse; plots of both the dark and light states are shown.

6. Conclusions

In this paper we have discussed the use of the transmission spectrum of a ferroelectric liquid crystal device to study its internal structure. This has been done both for an initial static state, and more importantly during a switching process. Comparisons made between experimental data and theoretical predictions showed that the initial state was consistent with the well established triangular director profile. For the first time we have extended this technique to study the dynamics of director reorientation in a C2 structure during a switching pulse. In this case the internal director configuration in the device was shown to be consistent with a simple one elastic constant model during both monopolar and bipolar addressing pulses. For high voltage bipolar pulses, the structure during switching is complicated by the near surface reorientation leading that in the bulk. Such information is usefully revealed by studying the dynamic transmission spectra.

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