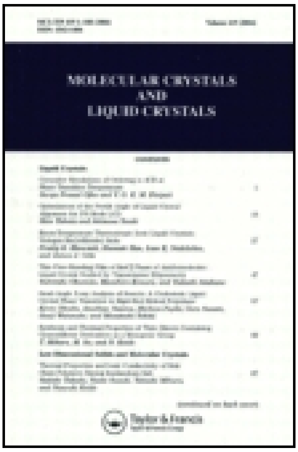

Molecular Crystals and Liquid Crystals Science and Technology. Section A. Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl19

Investigations on Restoring Torques in Bistable SSFLC Cells

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Version of record first published: 23 Sep 2006.

Mol. Cryst. Liq. Cryst. 1995, Vol. 266, pp. 153–162
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INVESTIGATIONS ON RESTORING TORQUES IN BISTABLE SSFLC CELLS

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Abstract The paper is based on accurate measurements of the optical response of SSFLC cells driven by specially designed test waveforms. Switching slopes are measured under different conditions and the balance of elastic, dielectric and ferroelectric torques is experimentally studied. The results are given as functions of a normalized optical transmission and the applied voltage.

INTRODUCTION

Usually, to characterize the switching behaviour of SSFLC cells, only response times are measured and related to the ferroelectric torque, acting on the liquid crystal director in the SmC* phase, and to its rotational viscosity. Recent publications showed the importance of second order torques, mainly of dielectric origin, on the matrix addressing behaviour of SSFLC cells [1]. However, no published experimental data was available for the evaluation of their magnitude and angular dependence.

In the simplest uniform-director models, ferroelectric, dielectric and restoring torques depend on the state of the cell and on the voltage applied to it. In most cases, the state of the cell has a one-to-one correspondence with its optical transmission and does not depend on its history. In order to measure such torques as a function of an optical transmission we devised and performed three new experiments.

In the first and second series of experiments, through computerized data acquisition and filtering, we have been able to measure the slope of the optical response for applied constant voltages, during switching pulses and during oscillations induced by a square wave. Slope measurements can be directly related to the existing torques, but they are very delicate and tend to be noisy, since they require computing of the derivative of the optical transmission being measured. In our third series of experiments we deformed with ac and dc fields the mid-term stable states of an up and down switching cell and measured for the first time their amplitudes in the deformed equilibrium.

EXPERIMENTAL CONDITIONS

In our experimental setup, the white light optical response of the liquid crystal cell between crossed polarizers was collected by a photomultiplier through an optical fibre bundle, while monitoring the cell in a microscope. Care was taken to have a uniform field without microdomains or alignment defects, and to avoid charge accumulation phenomena. For this reason we used dc balanced waveform segments and symmetrical up and down switching at a high enough rate (field times smaller than 15 ms). The cells were oriented to obtain the maximum peak to peak amplitude in the optical signal. The optical response was measured in arbitrary units ranging from 0 for the minimum transmission to 1 for the maximum, to easily relate the value to the intermediate state of the cell. In such a way symmetrical curves were obtained for up and down switching.

We made use of a LeCroy 9310L digital oscilloscope for data acquisition and display. The average of one thousand traces (one thousand points each) was downloaded to a computer and processed by the software specially developed for this purpose. We measured a delay of approximately 1.2 μs of the maxima and minima in the response of the cells to square waves and we attributed it to the RC response of our photomultiplier output circuit. This was partially corrected in data processing by a 1.2 μs time shift. The temperature of the liquid crystal cell was stabilized at 26°C by air flow.

The experiments have been carried out using a dedicated LCD Waveform Generator of new design that has been described elsewhere [2]. This generator has eight channels capable of pulse amplitudes up to ±100 V at slew rate of 350 V/μs. It is controlled by a Macintosh computer taking advantage of its graphical interface. The software automatically assures an overall dc-compensation and allows for defining the functional behaviour or the pulses within the generated waveforms, so that a desired, complex change can be accomplished by a single command. The software can also provide the on-line simulation of the optical response of an SSFLC cell based on the electrooptic model proposed by Maltese *et* al. [1].

We present here results obtained from long and medium term bistable SSFLC cells fabricated by GEC (UK), which have polymer alignment layers and are filled with Merck low spontaneous polarization mixtures. Most results are from a ZLI 4655/000 cell that already gave very interesting matrix addressing performances [3,4]. Some results correspond to a cell filled with SCE8, which exhibits higher dielectric anisotropy.

EXPERIMENT I

In the first series of experiments, the up-going and down-going switching slopes were measured during positive and negative switching pulses of amplitudes ranging from 20 to 70 volts and duration just enough to obtain clean switching (without mixed domains). The switching pulse was preceded by an equal counter pulse to avoid charge storage phenomena. In Figure 1 the results so obtained for the ZLI 4655/000 cell are plotted (in absolute values) versus its optical transmission, which was normalized to span between 0 and 1. Similar results are shown in Figure 3 for the SCE8 cell.

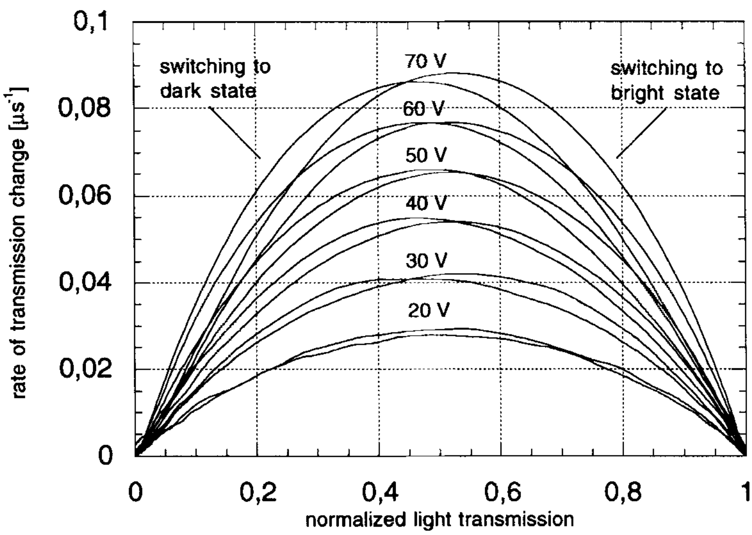


FIGURE 1 The slope of optical response to switching pulses of different amplitudes (ZLI 4655/000 at 26°C). To facilitate comparison, negative slopes are plotted in absolute values.

EXPERIMENT II

In our second series of experiments we applied test waveforms like the one presented in Figure 2a. The three-pulse (compensation, erase and write) dc-balanced switching sequence had a constant amplitude and total length. The width of the central erase pulse was constant and equal to one half of the total length. The parameters were chosen to obtain a clean switching at the central pulse. Its position was shifted within the sequence, altering as a consequence the width (t in Figure 2a) of the last pulse. This allowed to obtain a well-controlled partial switching, which was then completed by the effect of a high-frequency square wave (Figure 2b). We checked if the whole area was switching and disregarded the measurements for the conditions when mixed domains appeared (.30 < normalized light transmission after the third pulse < .70).

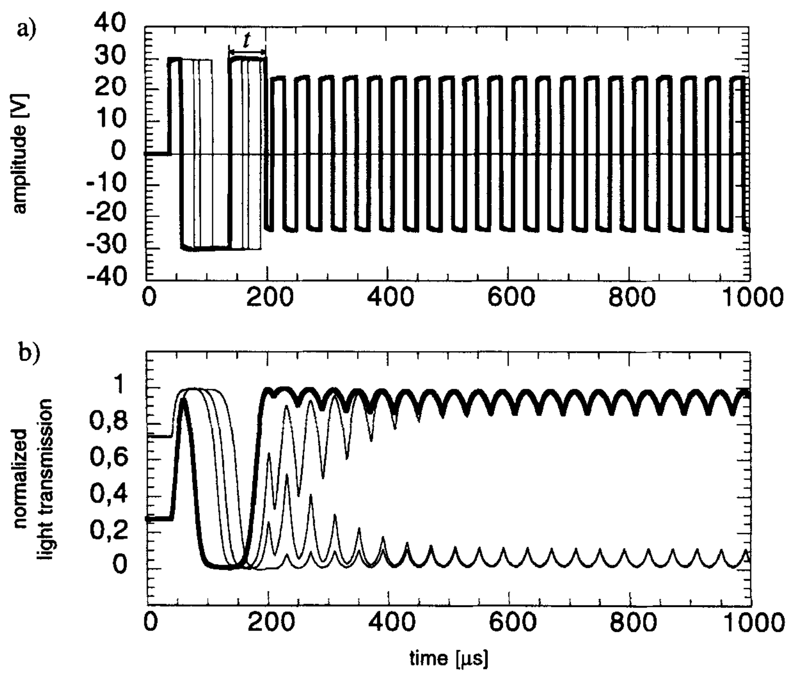


FIGURE 2 a) Example of test waveform used in Experiment II (ZLI 4655/000 cell at 26°C). The thin lines show different positions of the central pulse.
b) Corresponding set of optical responses to the test waveforms (normalized to span between 0 and 1). Partial switching achieved by varying the position of the central pulse.

In the optical response we identified minima and maxima corresponding to the period of the applied hf square wave. We calculated the slope for the central values of transmission between minimum and maximum levels as the ratio between their difference and the corresponding time interval.

Figure 3 presents the absolute values of the slopes calculated as described from the optical response of a cell (SCE8) subjected to the hf part of our test waveforms. The corresponding slopes for switching pulses of the same amplitudes (experiment I) are also plotted here for reference.

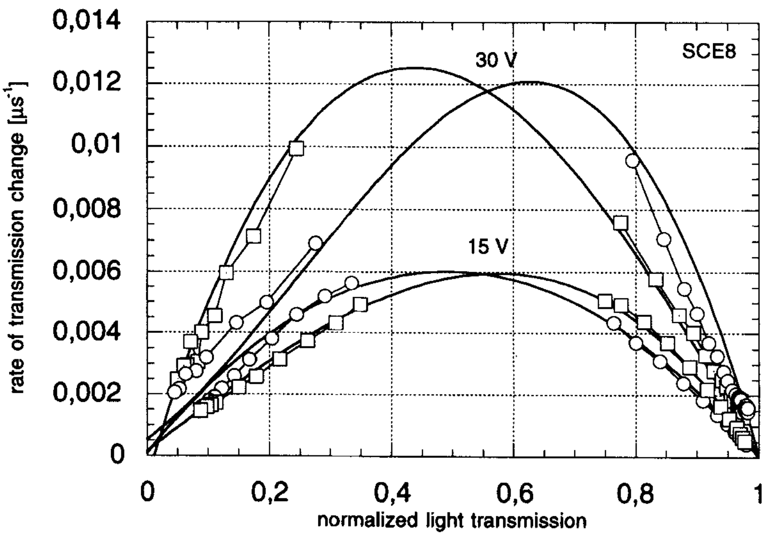


FIGURE 3 The absolute values of the slopes for oscillations during the application of hf square waves (measured points, 30 V, $t/2 = 20\ \mu s$ and 15 V, $t/2 = 40\ \mu s$) and for switching pulses of the same amplitudes (solid lines), for an SCE 8 cell at 26°C.

For the faster ZLI4655/000 cell, the average slopes calculated in this way were found incorrect. This was due to the reduction in amplitude of the optical signal by the previously mentioned time constant of the photomultiplier circuit, because half waves of 13 µs and shorter were applied. In order to get useful results, we calculated the slope as a smoothed time derivative of the optical response data collected from the oscilloscope. This slope is plotted (in amplitude and sign) in Figure 4 versus the corresponding optical transmission in proximity of its extremes during the oscillations. As can be seen, its envelope fits well the curves representing the slopes during switching pulses of the same amplitude.

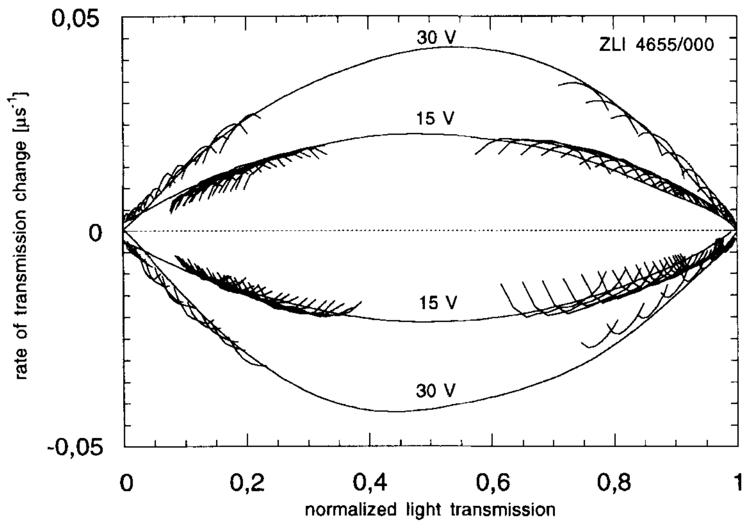


FIGURE 4 The extremes in the time derivative of the optical response during oscillations caused by hf square waves (30 V, 6.5 μs and 15 V, 13 μs, respectively) compared with the switching slopes (in amplitude and sign) for pulses of the same amplitudes. ZLI 4655/000 cell at 26°C.

EXPERIMENT III

We investigated here the deformations of the mid-term (2-100 ms) stable states of the cell by balancing with dc voltages the equilibrium restoring torques and the stabilizing torques, appearing when a hf voltage is applied. These torques are currently attributed to the dielectric anisotropy and the dielectric biaxiality of the liquid crystal.

The cell was first switched up and down between the two stable states by a dc-compensated double pulse. After ten times the duration of the switching pulse (a delay large enough to allow full relaxation into a mid-term stable, zero-voltage equilibrium state), the liquid crystal was forced out of the relaxed state by means of a small dc voltage. It was maintained in this deformed state, in spite of the equilibrium restoring torques and of hf voltages, by a second, immediately following, torque balancing dc voltage. The latter was measured as a function of the transmission corresponding to the deformed state and of the hf voltage applied. Thereafter, a square wave was superimposed during this period and again balanced by an additional dc voltage. By measuring the value of such additional voltage we estimate the stabilizing action of the applied hf voltage.

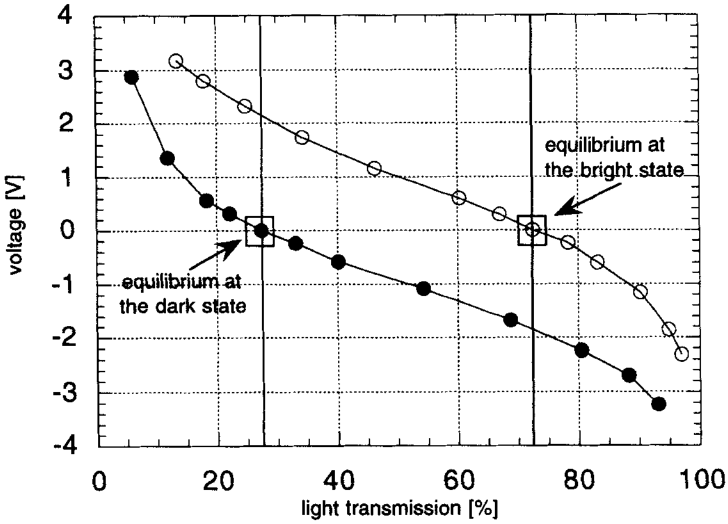
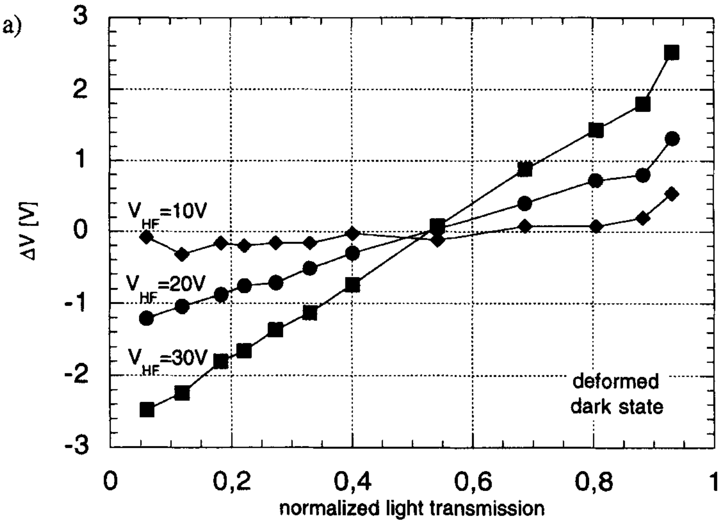


FIGURE 5 DC voltages required to balance equilibrium restoring torques for deformed mid-term (2-100 ms) stable states. ZLI 4655/000 cell at 26°C.

The measurements were performed using a test waveform composed by a bipolar switching pulse (40V, 2x250μs), a 2.5 ms pause, a 250 μs equilibrium deformation step, during which a first constant voltage was applied, and a 500 μs deformed-state balancing step, followed by dc compensation steps and another 2.5 ms pause. During the balancing step, a dc voltage and a hf square wave burst of an amplitude in the range of 0÷30 V were superposed. Such hf sequence consisted of ten full periods and had a half length pulse at the beginning and at the end. When a non-zero hf voltage was applied, an additional dc voltage had to be the superposed to counteract hf stabilizing effect, so that the light transmission at the end of the balancing step was equal to the initial value. The waveform segment, described above, was then repeated with inverted polarity.

Figure 5 presents the amplitudes of the balancing voltage required to maintain the deformed states, at the transmission levels given in the horizontal scale, when no hf voltage is applied. They correspond to the balance between the equilibrium restoring torque and the ferroelectric torque, since the dielectric torque should be negligible at these voltage levels. The upper curve was measured for the deformations of the equilibrium bright state, and the lower one for the deformations of the equilibrium dark state. It is interesting to note a)



b)

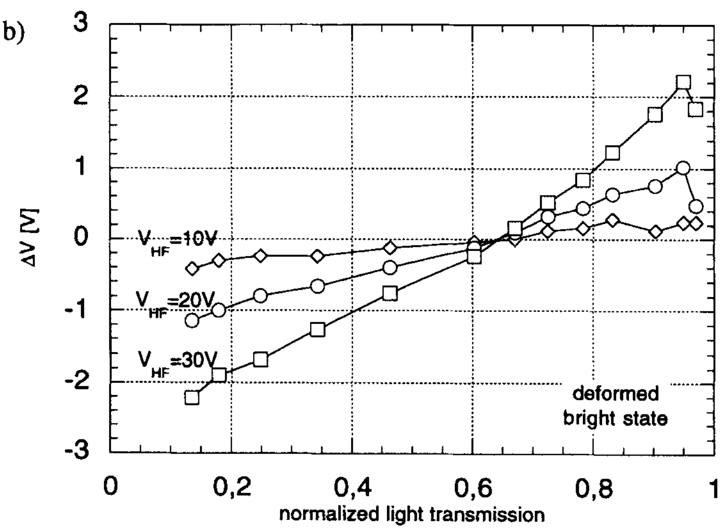


FIGURE 6 Additional dc voltages required to balance the (dielectric) torques from the application of hf square wave trains of different amplitudes (ZLI 4655/000 cell at 26°C): a) for deformations of the dark state; b) for deformations of the bright state.

that the liquid crystal can be deformed well past the opposite equilibrium state without causing a state change.

Figures 6a and 6b present, respectively for the two initial equilibrium states, the values of the additional dc voltage, required to counteract the effect of superposed hf square wave, as functions of the light transmission and the amplitude of the hf burst.

DISCUSSION

Three new measurement techniques to study the real torques existing in bistable SSFLC cells during switching and when the stable states are deformed have been introduced together with our first results from their use. To our knowledge this is the first time that similar measurements are reported.

It is clear that a careful analysis of the data in comparison with cell models is necessary to derive all their implications and that better measurements at different temperatures and for a wider range of cells are requested. Only a preliminary discussion of our results can be presented here.

The asymmetries in Figures 1 and 3 between the initial and final part of switching, larger for higher voltages, can easily be attributed to the increasing influence of dielectric torques. Their quadratic voltage dependence is in agreement with the data in Figure 3 and in Figure 6. The fits in Figures 3 and 4 between the slopes measured during switching pulses with those measured during oscillations in proximity of the stable states suggest pure viscosity torques counteracting switching (no backflow effects) and suggest cell states at the beginning and at the end of the switching process very similar to the stable ones. The data in Figure 5 are our most important result since the nature of the bistability itself is hidden behind them. These data and, to a minor extent, the difference between the data in Figures 6a and 6b, show that each stable state is very different from the other state that has been temporarily deformed to give the same optical transmission as the first one. We argue that this difference develops itself during the central part of the switching process. It could be due to a non-uniform director in the low voltage deformed states and to switching charges at the liquid crystal interfaces.

We do not find in Figure 1 neither the expected exact proportionality of the maximum slope to the voltage, nor the expected voltage-square dependence of the asymmetries. Such deviations can be attributed in part to the insufficient bandwidth of the optical detection circuit used, limiting the maximum slope being measured.

ACKNOWLEDGEMENTS

We thankfully acknowledge the use of experimental cells fabricated and supplied by GEC (UK) during our previous activity under the European Community ESPRIT FELICITA project. The present work has been performed at the University of Rome La Sapienza under funding by the Swedish Academy of Science, in the frame of a Scientific Network in the European Community programme Human Capital and Mobility.

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