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Write and erase mechanism of surface controlled bistable nematic pixel

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Abstract. Recently a new nematic bistable pixel, using simple monostable planar anchorings, has been proposed [4–6]. This pixel can be switched between two textures, having the same boundary conditions but different optical properties: one texture (U) is undistorted, whereas the other one (T) is characterized by the presence of a half-turn twist. The $U \to T$ switching was obtained by abruptly dropping the driving electric field. A slow decrease of the driving electric field favors the $T \to U$ transition. The electric field fall rate discriminates the kind of coupling between the boundary surfaces, hydrodynamic or elastic. Here we show the same behavior of this system by using square electric field pulses. We present experimental results concerning the critical values (amplitude and duration) of the driving signals, for which the elastic and the hydrodynamic effects are balanced and we measure their optimized values. Our results are in reasonable agreement with the theoretical predictions obtained by a simplified model.

PACS. 42.79.-e Optical elements, devices, and systems – 61.30.-v Liquid crystals – 61.30.Eb Experimental determinations of smectic, nematic, cholesteric, and other structures

Nematic liquid crystal bistability is more and more of interest for applications, as it would allow to realize electro-optical devices characterized by infinite multiplexing capability. Such devices were already proposed, based on complex substrates showing two different surface easy directions [1–3]. In recent papers [4–6] a simpler bistable nematic pixel, using usual planar anchoring surfaces, has been presented. One of the two cell plates is treated to give a weak planar anchoring. The other plate is treated to give a strong planar or oblique anchoring.

In the past it was experimentally shown [4–6] that:

1. the rapid switch off of the electric field favors a final half-turn twisted state of the pixel;
2. the slow decrease of the field switches back the pixel to its initial planar texture.

At that time a qualitative explanation was proposed of this two-ways switching through the balance between the dynamic and the static couplings of the surface director reorientations on the two plates. Here we show the same behavior of the system using square electric field pulses, easier to achieve in practice. Experimentally, we observe the critical pulse amplitude and duration for which the two effects are balanced and we measure their optimized values, in reasonable agreement with the model predictions.

The model

Let us consider a nematic cell in the U texture shown in Figure 1a. The upper anchoring is assumed to have infinite strength and hence to be electric field independent. The anchoring easy direction is oblique at an angle $\vartheta_0 \sim \pi/2$ with respect to the surface normal. The lower anchoring is a weak planar one ($\vartheta_S = \pi/2$). Under the application of an electric field E, ϑ_S varies between $\pi/2$ and 0. For $E = 0$, $\vartheta_S = \pi/2$ is almost uniform, only a weak splay distortion is present in the cell. The boundary surfaces, parallel to the x-y plane, constitute transparent electrodes. The z axis is perpendicular to them. Figure 1b shows a twisted texture T. The T-state satisfies the same boundary conditions as the U-state. In the following we will call *writing* the $U \to T$ transition and *erasing* the $T \to U$ transition.

It is easy to see that, because of the T and the U textures topology, a $T \to U$ or a $U \to T$ transition is possible only through the anchoring breaking on one of

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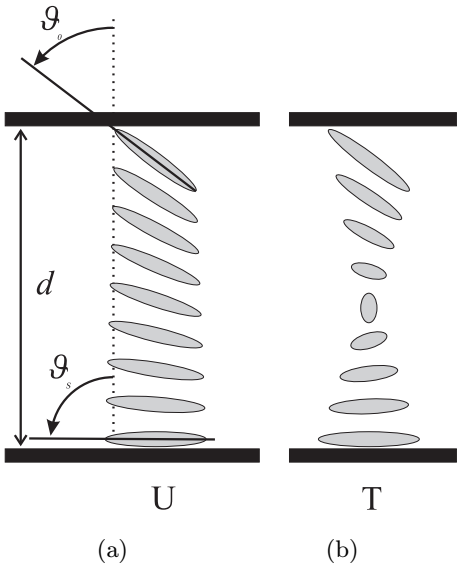

Fig. 1. Cell geometry used in our experiments: both plates are SiO coated. The upper one is treated to give an oblique strong anchoring (82.5°, 107 nm), whereas the lower one is treated to give a planar weak anchoring (75°, 10 nm). d is the cell thickness, ϑ_0 and ϑ_S are the zenithal angles of the oblique and the planar surface easy axes respectively. U and T represent the two stable textures compatibles with the same boundary conditions.

the boundary surfaces. This is done on the lower plate, where the anchoring is weak, by applying an electric field of suitable amplitude and duration [7].

We first recall shortly the static anchoring breaking mechanism. When an electric field E is applied across the cell, it tends to align the molecules along $\mathbf{z}$, *i.e.* with $\vartheta(z) = 0$. Any tilt perturbation will relax in the bulk along the electric screening length ξ defined by [8]

$$\frac{K}{\xi^2} = \frac{\varepsilon_a E^2}{4\pi}, \tag{1}$$

where ε_a is the positive dielectric anisotropy, and K a bulk elastic constant. When the bulk molecules align along $\mathbf{z}$, the texture creates a surface torque on each plate, which tends to rotate the surface director away from its easy direction. In the one elastic constant limit, the sum of the dielectric torque acting on the planar surface is [9]

$$\frac{1}{2}\frac{K}{\xi}\sin(2\vartheta_S), \ i.e. \ \frac{K}{\xi}\vartheta_S \text{ for small } \vartheta_S. \tag{2}$$

In the same limit, the elastic surface energy in the Rapini-Papoular approximation can be written as [10]

$$\frac{1}{2}\frac{K}{L}\cos^2\vartheta_S, \tag{3}$$

where $L \sim 1000$ Å is the usual extrapolation length of the surface anchoring. The elastic surface torque is then $-(K/L)\vartheta_S$ for small surface angle.

The static surface "breaking" is given by the zero surface torque condition:

$$K\left(\frac{1}{\xi} - \frac{1}{L}\right)\vartheta_S = 0, \tag{4}$$

i.e. for the finite electric field defined by $\xi = L$ [7] for which the surface elastic torque is just balanced by the field induced bulk torque, at zero tilt ϑ.

In the small angle limit, the surface breaking dynamics can be roughly described by the following equation

$$K\left(\frac{1}{\xi} - \frac{1}{L}\right)\vartheta_S + \gamma_S\dot{\vartheta}_S = 0. \tag{5}$$

The first term describes the competition between the dielectric torque and the elastic surface torque, which results in the surface anchoring breaking. The second term is a dissipative term, taking into account the surface viscosity [11,12]. From dimensional reasons, it can be calibrated *versus* an effective bulk viscosity γ assuming $\gamma_S = \gamma l$. Here l is a characteristic length of the surface dissipation, expected to be in the $100 \div 1000$ Å range [13]. In a earlier study [7], because the only length associated with the surface anchoring was the extrapolation length L, it was arbitrarily assumed $l \sim L$. This gave a surface relaxation time $\tau_S \approx \gamma L^2/K$, quadratic in the inverse anchoring strength. In fact, in a very recent model [14] it has been shown that the dissipation length l can be quite independent of L. In the case of pure hydrodynamic relaxation, without any other sources of dissipation, l is defined by the bulk extent of the substrate-liquid crystal interactions. With this new model the surface relaxation time becomes $\tau_S \approx \gamma L l/K$, linear in the inverse anchoring strength. In practice, the surface dissipation could depend on other mechanisms (surface roughness, order parameter variation, *etc.*). Then l would increase, but should remain independent of L.

When one turns off the field, the system will tend to go back to its equilibrium angle $\vartheta_S = \pi/2$, obeying for small ϑ the equation

$$-\frac{K}{L}\vartheta_S + \gamma l\dot{\vartheta}_S = 0. \tag{6}$$

In general, γ depends on ϑ_S and can be expressed [14] as a special combination of the Leslie coefficients. For small ϑ_S, γ can be written as a constant effective bulk viscosity.

The solution of equation (6) is $\vartheta_S(t) = \vartheta_{S1}\exp(t/\tau_S)$ where ϑ_{S1} is an eventual tilt fluctuation and $1/\tau_S = K/\gamma L l$ is the exponential growth rate of the tilt angle. In the opposite limit, when ϑ_S gets closer to $\pi/2$, by changing $\vartheta_S \to \psi_S = \pi/2 - \vartheta_S$ one can write a similar equation for ψ_S. Now ψ_S tends toward zero exponentially, with comparable relaxation time $\sim \tau_S$. Note that τ_S is also the response time of the bulk curvature mode of wavelength $\sqrt{Ll}$. By assuming $l \sim 1000$ Å, $L \sim 500$ Å, $K \sim 10^{-6}$ erg/cm and $\gamma \sim 0.1p$, we estimate $\tau_S \sim 10^{-5}$ s.

Close to the surface breaking threshold, in presence of the electric field, the planar plate surface relaxation time

is much longer than τ_S. From (5), we find

$$\tau'_S = \frac{\gamma l}{K}\left(\frac{1}{\xi} - \frac{1}{L}\right)^{-1} = \tau_S\left(\frac{\xi}{L-\xi}\right). \qquad (7)$$

τ'_S goes to infinity at the surface anchoring threshold, when the electric coherence length ξ is equal to the surface extrapolation length L. We are going to use these properties to define the time shape of the "writing" and "erasing" electric signals.

The writing mechanism has been explained in references [4–6]. We start with the U-state. The electric field has a square pulse shape, of amplitude E_1 and duration τ_1. E_1 is larger than the dynamical threshold to break completely the anchoring of the lower plate. At $t = \tau_1$, $E = 0$, the lower surface angle goes to $\vartheta_S = \pi/2$ with the time $\tau_S = \gamma L l/K$. Close to the upper surface, the bulk molecules were strongly bent on the length ξ_1. They relax rapidly toward a less bent state, inducing a transient flow in the cell, during the time $\gamma\xi_1^2/K < \gamma L l/K$. In other words, the upper surface relaxes more rapidly than the lower one. This flow propagates across the cell in a very short time $\tau_d \approx \rho d^2/\gamma = 10^{-8}$ s, at least two orders of magnitude shorter than the surface relaxation time, and forces the lower plate surface director to relax towards $\pi/2$ in the opposite direction with respect to the upper plate surface director. As result, one gets a π bend from its U-state. Because the liquid crystal elastic anisotropy, the π bend distortion relaxes in the π twisted state T having a lower elastic energy.

In principle, to erase the T-state, *i.e.* to induce the $T \to U$ transition one has only to decrease E_1 slowly enough to suppress the transient hydrodynamic coupling. In that case, the elastic coupling between the two plates should lead to the lower elastic energy U-state. Experimentally [15], this works with a field exponential decay of ~ 1 ms. We would like to erase more rapidly. To induce the U-state, we cannot simply drop E_1, down to zero, since we would rewrite the T state. A way to erase rapidly is still to apply the pulse (E_1, τ_1) and to place just after its end a second pulse (E_2, τ_2) (see Fig. 2). At $t = \tau_1$ the cell is in the same state as when the initial state was U; all memory of the previous state, T or U, is forgotten. E_2 should be chosen close to the static threshold of the lower plate anchoring breaking. In that case, the surface response time τ'_S is as large as we like. Provided that, after turning down E_2 at time $t = \tau_1 + \tau_2$, the last hydrodynamic effect is negligible (E_2 is lower than the dynamic writing threshold), the final texture should always be U, whatever may be the initial T or U textures. We want to check these ideas and to measure the smallest τ_2 necessary to achieve the erasing.

The experiment

In order to check this idea, we prepared several cells of thickness d in the range $0.8 \div 1.6$ μm. We use ITO transparent electrodes coated glass plates. As surface treatment we use oblique evaporation of SiO. To produce the tilted orientation with strong anchoring for the upper plate, we evaporate an SiO layer 107 nm thick (measured perpendicularly to the SiO source) at 82.5° incidence with respect to the surface normal. The weak planar anchoring is also produced by SiO evaporation, with thickness 10 nm at 75°. The cells are filled with pentyl-cyano-bifenyl liquid crystal (5CB), nematic at room temperature. The observations are made under a Leitz Orthoplan polarizing microscope, in transmission mode, between crossed polarizers. We orient the cell optical axis (U-state) at 45° with respect to the polarizers. Under these conditions the U-state appears bright whereas the T-state appears dark.

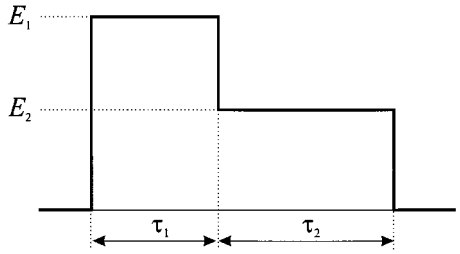

Fig. 2. The signal shape we use to drive the $T \to U$ transition. It consists of two parts: the first one is characterized by a length τ_1 and an amplitude $E_1 = V_1/d$, larger than the lower planar plate anchoring breaking threshold, in order to erase any memory of the previous state. The second part has an amplitude $E_2 = V_2/d$, comparable with the lower plate anchoring breaking static threshold. Its length τ_2 has to be chosen in order to allow the damping of the hydrodynamical perturbation due to the $E_1 \to E_2$ electric field drop.

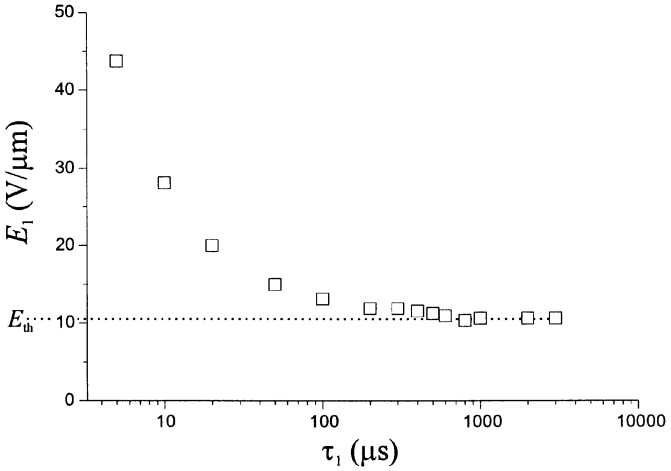

Fig. 3. Typical values for the (E_1, τ_1) pairs to induce the $U \to T$ transition. In the limit of large τ_1, E_1 tends toward the typical value $E_{th} \sim 10$ V/μm for the static anchoring breaking threshold.

The $U \to T$ transition is obtained by applying a square electric pulse (typically $E_1 \sim 15 \div 20$ V/μm for a pulse of $\tau_1 \sim 100$ μs length). In Figure 3 are reported typical writing curves.

Once the cell has been written, the T-state decays spontaneously toward the U-state *via* a defect nucleation process. This is due to the difference in the elastic energy between the U-state and the T-state. This difference,

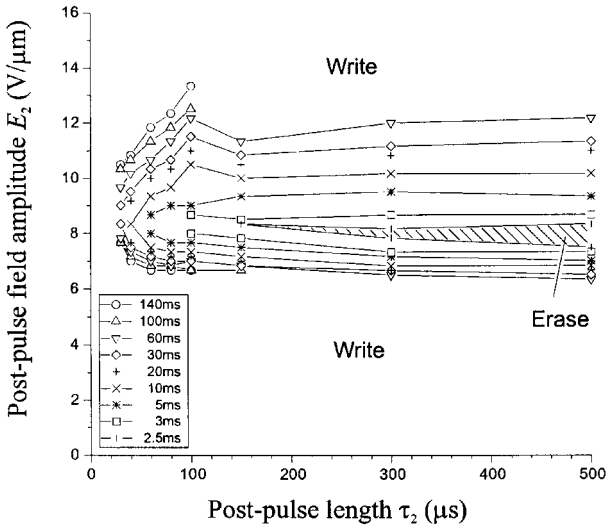

Fig. 4. Equal erasing time curves for a sample 1.2 μm thick. These curves have been obtained by measuring the erasing optical response time (see the text) Vs. The post-pulse parameters $\tau_2, E_2 = V_2/d$, the inner region around $E_2 = 8$ V/μm corresponds to the natural optical relaxation time $\tau_c = \gamma d^2/K$ of the cell, necessary for the bulk molecules to go towards the U texture. Outside this region the erasing occurs via a defect-mediated relaxation. Note that the $E_2 = 8$ V/μm compares well with the static threshold $E_{th} \sim 10$ V/μm shown in Figure 3, in the limit of largest time τ_1. The minimum τ_2 is in the range 50 μs $< \tau_2 <$ 100 μs for this particular case.

which depends on the cell thickness, can be made as small as one wants by suitably doping the 5CB by a chiral compound. By this method, we have been able to get practically infinite lifetimes. For this simple experiment, in absence of chiral compensation, we observe a lifetime of the T-state of the order of 10^1–10^2 milliseconds, depending on the cell thickness. We define the lifetime as the time necessary to reach the 50% of the transmitted light maximum intensity.

To erase the T-texture, we use the electric signal shape described in the previous section, E_1, τ_1, E_2, τ_2 (see Fig. 2). We chose the following parameters: $V_1 = 25$ V, $\tau_1 = 100$ μs. The post-pulse amplitudes V_2 are in the range $7 \div 15$ V. The cell thickness is $d = 1.2$ μm.

We measure the "optical erasing time" as function of the post-pulse parameters τ_2 and V_2. The erasing time is defined, in analogy with the spontaneous decay time, as the time necessary to the system to reach the 50% of the maximum transmitted light intensity. The obtained data are reported as "iso-time erasing" curves $E_2(\tau_2)$ shown in Figure 4. The upper and the lower curves correspond to a defect-mediated time relaxation of 140 ms. This time is the same as the one we observe for $E_2 = 0$. It is the spontaneous relaxation of the twisted state through defect motion. We can say that outside this curve, we still write the T-state.

On the contrary, the inner curve around $E_2 = 8$ V/μm in Figure 4 corresponds to a relaxation time $\tau = 2.5$ ms. This is the elastic curvature relaxation time $\tau_c = \gamma d^2/K$ of the cell, necessary for the molecules in the bulk to go from the field aligned texture towards the U texture. This region of Figure 4 corresponds to the erasing process. The intermediate curves show that the defect mediated relaxation is progressively enhanced by the field effect. The two values of interest we extract from Figure 4 are the value of $E_2 = 8$ V/μm corresponding to the erasing process, and the range of shortest possible erasing times τ_2. E_2 compares well with the static threshold $E_{th} \sim 10$ V/μm shown in Figure 3, in the limit of largest time τ_1, as expected. The minimum τ_2 is in the range 50 μs $< \tau_2 <$ 100 μs for this particular case. τ_2 is typically an order of magnitude larger than the estimated $\tau_S \sim 10$ μs.

To conclude, we have achieved the control – write and erase – of a surface controlled bistable nematic display. Instead of using a slowly decaying field shape we have shown that a double square electric pulse can work. The optimum signal corresponds to a second pulse field amplitude comparable with the static threshold. The shortest erasing time is an order of magnitude larger than the surface relaxation time but much smaller than the previously used decay time ($\sim$ 1 ms). These results should be reproduced on a chiralized material to check that the present conclusion has a general value.

A general physical description of the surface dynamics remains to be done.

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References

1. R. Barberi, G. Durand, Appl. Phys. Lett. **58**, 2907 (1991).
2. R. Barberi, M. Giocondo, G. Durand, Appl. Phys. Lett. **60**, 1085 (1992).
3. R. Barberi, M. Giocondo, Ph. Martinot-Lagarde, G. Durand, J. Appl. Phys. **62**, 3270 (1993).
4. I. Dozov, M. Nobili, G. Durand, Appl. Phys. Lett. **70**, 1179 (1997).
5. Ph. Martinot-Lagarde, I. Dozov, E. Polossat, M. Giocondo, I. Lelidis, G. Durand, *Proceedings of Society for Information Display* 97, 1997, p. 41.
6. I. Dozov, Ph. Martinot-Lagarde, E. Polossat, I. Lelidis, M. Giocondo, G. Durand, *Proceedings of Electronic Imaging* 97, Liquid Crystal Materials, Devices, Applications V, February 9-14, 1997, San Jose, USA.
7. A. Gharbi, F.R. Fekih, G. Durand, Liq. Cryst. **3**, 515 (1992).
8. P.-G. de Gennes, *The Physics of Liquid Crystals* (Clarendon Press, 1974).
9. H. Yokoyama, H. van Sprang, J. Appl. Phys. **57**, 4520 (1985); see also M. Nobili, Ph.D. thesis, Pisa, Italy, 1992.
10. A. Rapini, M. Papoular, J. Phys. Colloq. France **30**, C4-54 (1969).
11. S. Pikin, G. Ryschenkow, W. Urbach, J. Phys. France **37**, 241 (1976).
12. A.I. Derzhanski, A.G. Petrov, Acta Phys. Polon. A **55**, 747 (1979).
13. L. Blinov, G. Durand, S. Yablonsky, J. Phys. II France **2**, 1287 (1992).
14. G. Durand, E. Virga, Phys. Rev. E. (submitted, 1998).
15. I Dozov, G. Durand, Liq. Crystals Todays **2**, 1 (1998).