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Effect of combined action of electric field and light on gliding of the easy axis in nematic liquid crystals

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A new effect is described of the combined action of an electric field and light on the slow surface dynamics in a layer of nematic liquid crystal (NLC) contacted with a layer of dye pre-treated by UV irradiation. Simultaneous application of a relatively weak “in-plane” electric field and polarised light resulted in slow variation of the boundary orientation of the sample transmitted to the bulk of the layer. At the same time, the separate action of the two factors mentioned above did not produce any visible changes in the LC layer at the same intensity and time of application. After turning off both the electric field and light, extremely slow relaxation of the system to the initial state was observed. This effect depends on a number of control parameters (applied voltage, intensity of light, time of application, dose of a preliminary UV irradiation). The critical slowing down of this process (up to some weeks) via a proper choice of control parameters was established. The physical processes responsible for the combined effect were considered and applied to modify a previously proposed phenomenological model for the electrically induced slow azimuthal rotation of the easy axis of an NLC. The modified model was found to be in a qualitative agreement with the main experimental results.

Keywords: nematic liquid crystal; easy axis gliding; photo-alignment

1. Introduction

The surface anchoring of a liquid crystal (LC) on solids and polymer films, which can be considered as a primary problem in the physics of LCs, is also of significant practical importance (1, 2). Progress in surface treatment technology during recent decades allows some new types of controlled surfaces to be obtained that are of interest for application in LC devices (3–6). Among them, the photo-alignment (PA) technique seems to be the most promising since it provides surfaces with well-controlled anchoring properties via use of visible or UV light irradiation, which can easily be compatible with the *technological* processes applied in the modern display industry (3, 4). It is important that the final outcome of the action of a PA-treated surface on the structure of LC layers is determined by a number of *physical* processes, referred to essentially different time and space scales. Such processes, connected with both individual and collective molecular transformations in the surface light-sensitive solid (polymer) layer and in the adjacent LC layer, can occur both *before* and *after* the direct contact of a liquid crystal with a PA-treated surface (7–11). Although the particular stages of photo-induced orientation can be considered in the framework of reasonable physical models (9, 11–14), the total picture is far from being understood. That is

why the nature of the physical phenomena responsible for photo-induced surface anchoring is a hot topic of research.

In particular, it has been found (7, 14) that an extremely slow surface process resulting in overall change of preferred orientation \mathbf{n}_b in bulk of LC layer can be produced by strong electric (magnetic) field applied in the direction approximately orthogonal to the initial one imposed by preliminary UV treatment of a photosensitive polymer coating of an LC cell. Such phenomena are usually described in terms of slow “gliding” of an easy axis \mathbf{n}_e referred to the mean orientation of LC molecules absorbed by a surface. It was found that after turning off field the easy axis relaxes to the initial state after an extremely long time (several hours, for example). Further investigation (15) showed that such a slow process may also take place in an LC layer contacted with a sensitive surface layer of a sulfuric azo-dye (SD-1). In the latter case, the mechanism of polymeric chain reorientation proposed to describe gliding phenomena at a polymer coating (16) can be excluded *a priori*. A number of experimental studies of gliding imposed by both electric and magnetic fields (7, 14–19) have shown that this phenomenon is a general property of surfaces of different types, including those with relatively strong anchoring (rubbed

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polyimide film, for example). It takes place for a slow reorientation of absorbed molecules both in the plane of the LC layer [azimuthal gliding (19)] and out of plane of a layer [zenithal gliding (18)]. In all cases, the slow surface dynamics show some general features. For example, an increase in both the strength of an applied field and its duration result in an increase of the characteristic times of the relaxation of the system to the initial state after turning off the field. So the usage of phenomenological models (13, 15, 18) to describe the slow surface dynamics seems to be reasonable. At the same time, the physical background of such models has to be based on a clear understanding of molecular processes leading to the observed phenomena. One of the ways to reach this understanding is the experimental determination of control parameters responsible for the processes under consideration.

In this paper, the first results are presented of an experimental study of slow dynamical processes induced by the combined action of an electric field and light in the layer of a nematic contacted with a UV-treated layer of azo-dye SD-1. This case differs essentially from the combined effect observed by action of non-polarised light on the photopolymer surface preliminary poled by an electric field (10). Modifications are discussed that have to be introduced to the previously proposed phenomenological model to describe the complicated phenomena observed in experiments.

2. Experimental

The LC cell (18 μm thick) used is shown in Figure 1. It consisted of two glass plates treated to provide strong (rubbed polyimide film) and weak planar surface anchoring (a film of SD1 illuminated by polarised UV light). A substrate with azo-dye SD-1 was preliminary irradiated by UV light ($\lambda=365\text{ nm}$) in a special way to obtain zones with different exposure energetic doses, D_p , of UV irradiation, and thus with different anchoring strength. It was impossible to obtain a perfect planar orientation in the absence of a preliminary UV treatment ($D_p=0$), as can be seen in Figure 1.

A similar construction was used previously (15) to study the field-induced gliding of an easy axis. The LC cells were filled with nematic mixtures ZhK 616 and ZhK 1289 (produced by NIOPIK), both of which have a positive dielectric anisotropy ($\Delta\epsilon=3.4$ for ZhK 616; $\Delta\epsilon=10.7$ for ZhK 1289) and were synthesised previously for practical applications. Most experimental data presented below (excluding those shown in Figure 5(c)) correspond to the first nematic

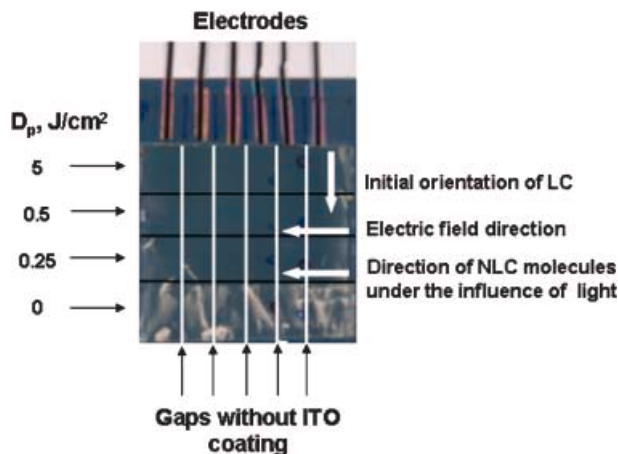


Figure 1. General scheme of the LC cell.

mixture ZhK 616. An “in-plane” ac electric field ($f=3\text{ kHz}$) was produced by the application of an electric voltage, U , to the gap (50 μm) between transparent SnO_2 (ITO) electrodes on the UV-treated substrate. It induced a rotation of the director, as detected using polarised light via an optical microscope and a digital camera (see Figure 2).

Polarised light from the halogen lamp (HLWS4, Narva) of a microscope was used as an additional factor that acted on the cells. This light illuminated the bottom substrate of the cells coated with a dye layer. The intensity of the light (I_2) in UV region (350–400 nm) was controlled by a radiometer. In our experiments, the electric field and light were applied simultaneously during the same exposure time, t_{exp} . After turning off both the field and light, the initial dark image of the gap was restored after some characteristic time strongly dependent on the controlled parameters of the experiment (the exposure dose of the preliminary UV irradiation, D_p , the intensity of light, I_2 , the applied voltage, U , and the exposure time, t_{exp}). Examples of the corresponding snapshots are presented in Figure 3.

An image processing procedure was used to obtain the time dependence of the brightness, R , of images inside the gap, which is considered as being proportional to the local intensity of light $I(t)$ passing through the cell and crossed polarisers.

3. Results and discussion

It was found that without the additional action of light, after turning off the electric field the initial planar orientation was restored rather quickly (1–60 s) in the voltage range 10–100 V applied for a rather long excitation time (from 20 min to 80 min). This behaviour was drastically changed when the cell

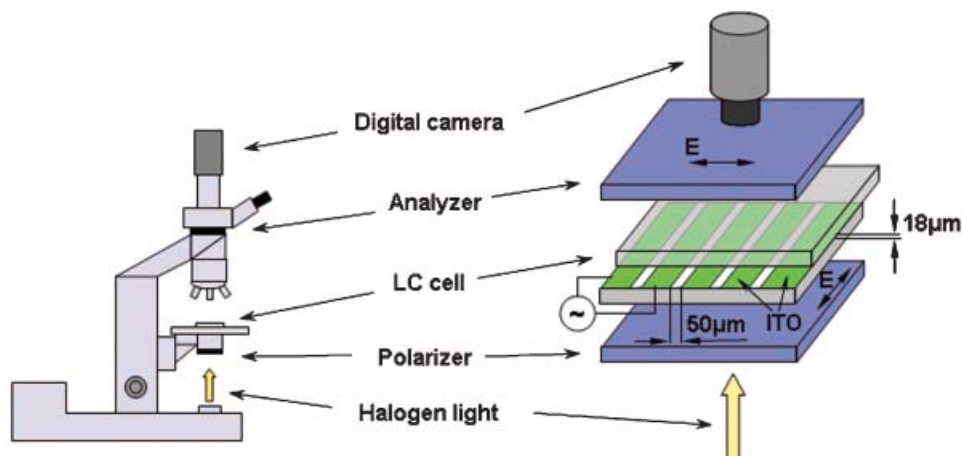


Figure 2. Experimental set-up and geometry of the experiment.

was illuminated by polarised light (in the direction of an initial planar orientation) from a halogen lamp at the same time as applying the electric field.

The light intensity I_2 was considered as the *first control parameter* that plays an important role in the

combined effect under consideration. *In the absence of light*, an electric field of moderate strength (about $1 \text{ V } \mu\text{m}^{-1}$) was unable to produce pronounced gliding-like behaviour after being turned off (Figure 4(a)). For low values of the exposure intensity, I_2 , of light acting simultaneously with the field, a rather rapid (several minutes) relaxation of the brightness of images to the initial state was observed. The corresponding $I(t)$ dependence presented in Figure 4(a) could be hardly referred to the usual bulk relaxation induced by boundaries (with a characteristic time about some seconds). The slow relaxation became most pronounced (see Figure 4a) at a moderate value (74 mW m^{-2}) of light intensity I_2 , which did not produce a visible action *in the absence of an electric field* at the conditions of our experiment. So, such an intensity was used in all experiments described below.

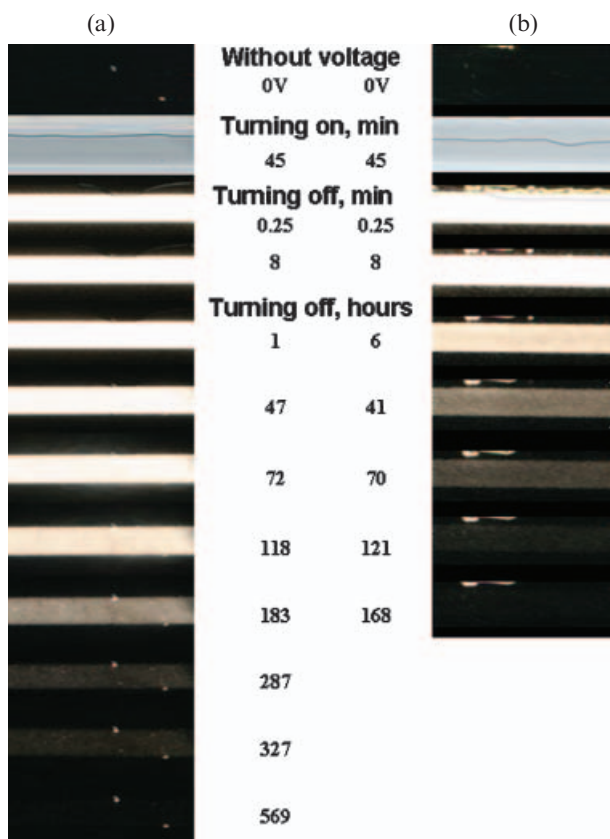


Figure 3. Microscopic images of the gap: before applying, after turning on strong electric field ($U=100 \text{ V}$, $t_{\text{exp}}=80 \text{ min}$) and light ($I_2=74 \text{ mW m}^{-2}$) and after turning off electric field and light at different doses (a) $D_p=0.25 \text{ J cm}^{-2}$ and (b) $D_p=5 \text{ J cm}^{-2}$ of the preliminary UV irradiation.

We established that under the additional action of light of moderate intensity the electrically induced gliding could be registered at extremely weak fields (about $0.2 \text{ V } \mu\text{m}^{-1}$), which was quite insufficient to induce such an effect in the absence of light (Figure 4(b)). The strength of electric fields used in display technology and other LC devices is comparable with this value, so this fact has to be taken into account for practical usage of the PA technique. It is worth noting that two relaxation times seem to be sufficient for an approximation of the experimental time dependences of the light intensity $I(t)$. This is a general result of our experiments, as discussed below. The slowest process has to correspond to the small deviations of the system from the initial state. So, linear approximations (15) can be used for a theoretical description of this stage.

The exposure time t_{exp} was considered as the *second control parameter* that defines the combined

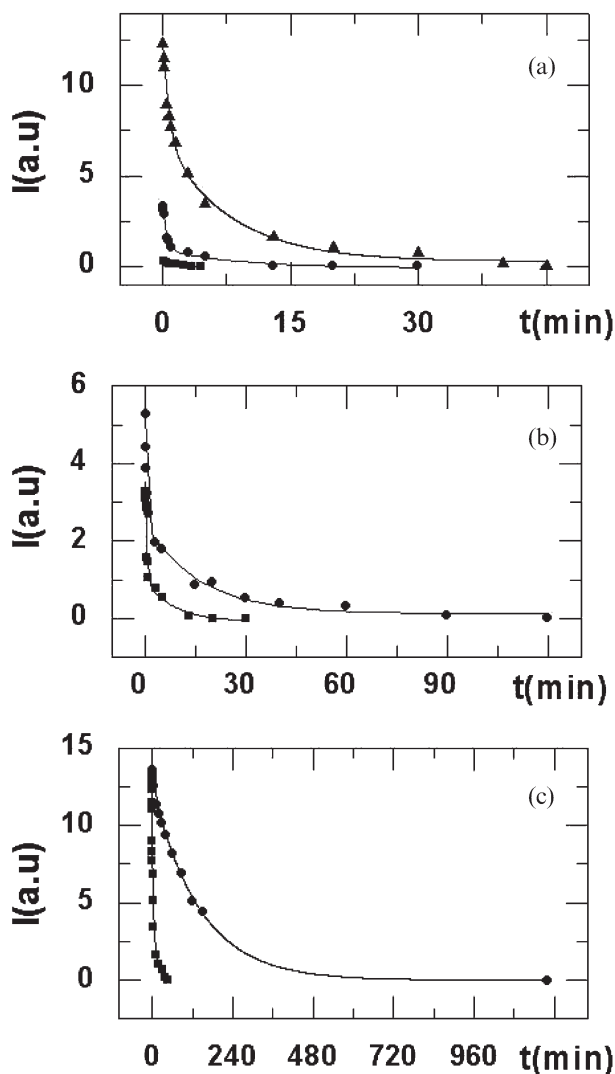


Figure 4. Time dependences of light intensity $I(t)$ after turning off electric voltage (U) and light (I_2) at the unique value of a dose of preliminary irradiation ($D_p=0.25 \text{ J cm}^{-2}$) and fixed values of exposure time (a), voltage and light intensity (b, c); solid lines show the approximation in accordance with the two-exponential law, $I(t)=I_0+A_1\exp(-t/\tau_1)+A_2\exp(-t/\tau_2)$. (a) $t_{\text{exp}}=20 \text{ min}$: \blacktriangle $U=50 \text{ V}$, $I_2=0$; \bullet $U=50 \text{ V}$, $I_2=30 \text{ mW m}^{-2}$; \blacksquare $U=50 \text{ V}$, $I_2=74 \text{ mW m}^{-2}$. (b) $U=10 \text{ V}$, $I_2=74 \text{ mW m}^{-2}$: \blacksquare $t_{\text{exp}}=20 \text{ min}$, \bullet $t_{\text{exp}}=80 \text{ min}$. (c) $U=50 \text{ V}$, $I_2=74 \text{ mW m}^{-2}$: \blacksquare $t_{\text{exp}}=20 \text{ min}$, \bullet $t_{\text{exp}}=80 \text{ min}$.

effect. The relaxation processes are significantly slowed down as this time increases (Figures 4(b) and 4(c)), which corresponds to the case of an electrically induced gliding. This was also true for the influence of the electric voltage (the *third control parameter*) on the time dependences of the light intensity (Figure 5(a)). So, one can hope to adopt previously proposed model of electrically induced gliding (15) to the more complicated effect under consideration.

The *fourth control parameter*, i.e. the exposure dose of the preliminary UV irradiation, D_p , defines the azimuthal anchoring strength, W_0 [at low values of this dose $W_0 \sim D_p$ (9)]. The images presented in Figure 3 clearly demonstrate that *strong anchoring suppresses the slow surface dynamics*. It opened ways for the additional control of the long-term effects observed in our experiments. For a proper choice of the control parameters, the total storage time of memorised images can reach up to several weeks (Figures 3 and 5(b)).

Nevertheless, in any case *the optical images returned to the initial dark state without visible permanent memory*. So, this means that this effect is very useful for temporary memory devices. The numerical data on relaxation times for various values of the control parameters, which are useful for a comparison with the theoretical results, are summarised in Tables 1 and 2. The data in Table 2 correspond to the extremely slow relaxation process, which is reminiscent of the critical slowing down of the fluctuations at a second-order phase transitions. So, it is of interest if such transition really takes place in our case.

The molecular nature of the phenomena under consideration is not quite clear. Previously, it was found that in a photochromic NLC the similar combined action of UV irradiation and an electric field stimulates a planar-to-homeotropic transition (20). It was ascribed to the light-induced trans-cis isomerisation of LC molecules, which leads to lowering of the threshold for a Fredericks transition via an increase of the number of cis-isomers absorbed by a surface. Such a mechanism cannot be excluded *a priori* for the nematic mixture ZhK 616, based on a binary mixture ZhK 440. The latter contains both cis and trans isomers of azoxy compounds (two-thirds of *p-n*-butyl-*p*-methoxyazoxybenzene and one-third of *p-n*-butyl-*p*-heptanoylazoxybenzene) effectively absorbing light (21). So, we carried out some analogous experiments with a colourless nematic mixture ZhK 1289 of quite different chemical structure, which does not contain azoxy compounds. The results obtained were found to be in qualitative agreement with those reported above for ZhK 616. As an example, Figure 5(c) shows the time dependence of the light intensity described by the same law as in the case of ZhK 616. The ZhK 1289 LC mixture does not exhibit trans-cis isomerisation processes under UV light illumination. So, the main origin of the phenomena under consideration is presumably connected with the processes in the layer of the photosensitive azo-dye film and in the near-surface LC layers.

One of the interesting questions arising in our experiments is related to *the possibility of a variation*

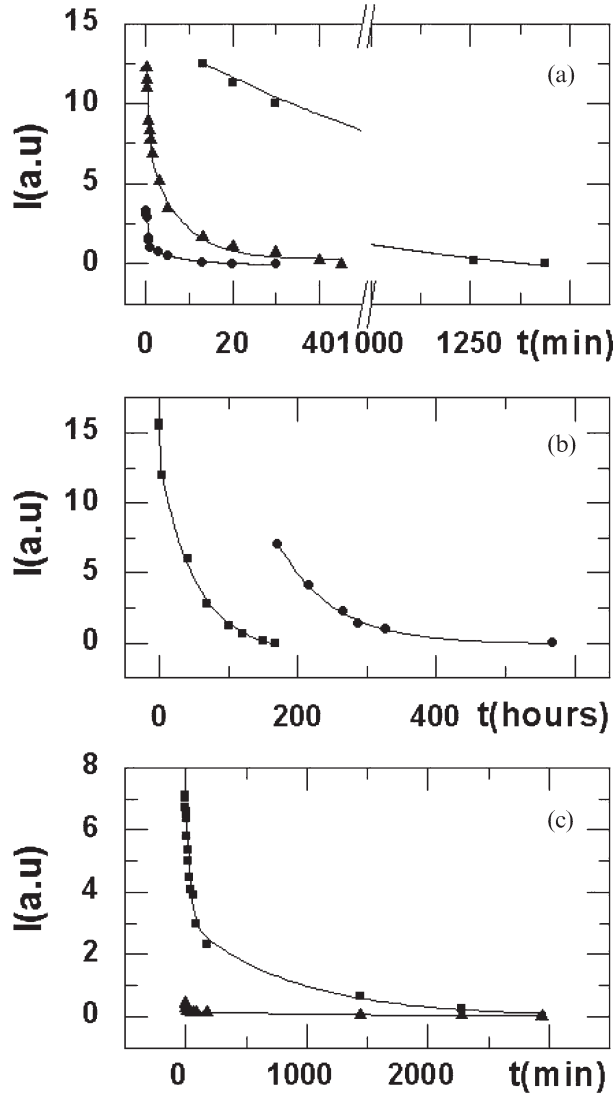


Figure 5. Time dependences of light intensity $I(t)$ after turning off light I_2 and electric field at different voltages (a), doses of preliminary irradiation (b) and for non-absorbing LC - ZhK 1289 (c); solid lines show the approximations in accordance with the two- (a, c) and simple (b) exponential laws. (a) $I_2 = 74 \text{ mW m}^{-2}$, $t_{\text{exp}} = 20$ min: \blacksquare $U = 100$ V, \blacktriangle $U = 50$ V, \bullet $U = 10$ V. (b) $U = 100$ V, $t_{\text{exp}} = 80$ min, $I_2 = 74 \text{ mW m}^{-2}$: \bullet $D_0 = 0.25 \text{ J cm}^{-2}$, \blacksquare $D_0 = 5 \text{ J cm}^{-2}$. (c) $U = 100$ V, $t_{\text{exp}} = 20$ min, ZhK 1289: \blacktriangle $I_2 = 0$; \blacksquare $I_2 = 30 \text{ mW m}^{-2}$.

of the physical state of the system that is not detected by the optical scheme used. Indeed, it is clear that the surfaces with the same direction of an easy axis, but of different anchoring strengths have to show the same dark image in crossed polarisers. To answer this question, we performed additional experiments that showed the changes in anchoring properties of a surface under some cycles of experiments described above. The detailed information on these results will be presented elsewhere.

Table 1. Relaxation times τ_1 and τ_2 for various control parameters in the comparison with theoretical values τ_e^0 calculated in accordance with equation (29).

$D_p/\text{J cm}^{-2}$	0.25	0.25	0.25	0.25	0.25
U/V	10	10	50	50	100
$t_{\text{exp}}/\text{min}$	20	80	20	80	20
τ_1/min	0.44	0.41	0.81	2.97	35
τ_2/min	6.91	21	10.2	141	525
$\tau_e^0/2/\text{min}$	8.62	17.9	9.61	136	

Table 2. Extremely slow relaxation time, τ , corresponding to the simple exponential law at high values of voltage and exposure time.

$D_p/\text{J cm}^{-2}$	0.25	5
U/V	100	100
$t_{\text{exp}}/\text{min}$	80	80
τ/h	78	41

4. Theoretical model

Model of electrically induced gliding

Below we present some results (important for better understanding) of the phenomenological model proposed previously (15) to describe electrically induced azimuthal gliding of an easy axis. The model (see Figure 6) incorporates LC directors of the preferred surface orientation \mathbf{n}_0 , provided by surface treatment, the preferred orientation of absorbed LC molecules (an easy axis \mathbf{n}_e), the mean orientation of molecules inside the near-surface layer (a surface director \mathbf{n}_s) and the orientation of LC into a bulk of the layer (a bulk director \mathbf{n}_b). A strong electric field produces a twist-like deformation of the bulk director, with a torque, Γ_b , transmitted via the near-surface layer from bulk to the surface. This results in slow azimuthal rotation (gliding) of the easy axes.

After turning off the field, the system relaxes to the initial state. These processes are described by the two coupled torque balance Equations

$$\begin{aligned} \Gamma_b + \Gamma_s + \Gamma_{vs} &= K_{22}[(\pi/2) - \varphi_s]/(\xi - h) \\ &\quad - (K_{22}/2L_s)\sin 2(\varphi_s - \varphi_e) - \gamma_s(\partial\varphi_s/\partial t) \quad (1) \\ &= 0, \end{aligned}$$

$$\begin{aligned} \Gamma_b + \Gamma_{ve} &= K_{22}[(\pi/2) - \varphi_s]/(\xi - h) \\ &\quad - (K_{22}/2L_e)\sin 2\varphi_e - \gamma_e(\partial\varphi_e/\partial t) = 0, \quad (2) \end{aligned}$$

where

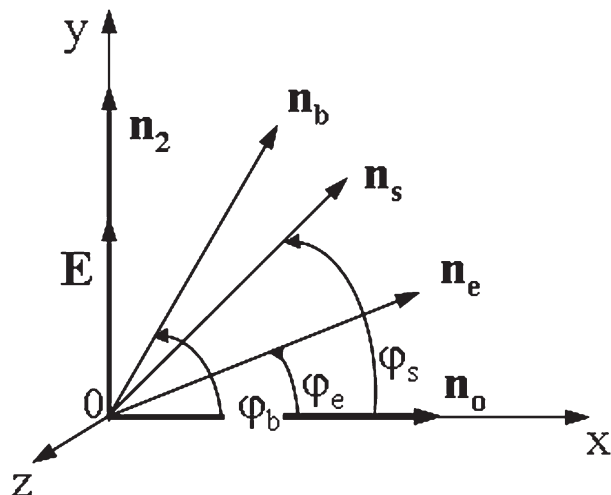


Figure 6. Modified phenomenological model of electrically induced gliding: \mathbf{n}_b =bulk director, \mathbf{n}_s =surface director, \mathbf{n}_e =easy axis, \mathbf{n}_o =unit vector of the initial surface direction produced by preliminary UV treatment, \mathbf{n}_2 =new preferable surface direction, induced by both electric field and polarised light at combined effect under consideration.

$$L_{e(s)} = K_{22}/W_{e(s)}, \quad (3)$$

corresponding to the torques acting on the surface director, Equation(1), and on the easy axes, Equation(2). In these Equations, $\Gamma_{vs}(\Gamma_{ve})$ are viscous-like torques acting on the surface director and the easy axes, Γ_s is the elastic-like torque transmitted from the surface to the surface director, K_{22} is the Frank modulus, $\xi \sim E^{-2}$ is the electric coherence length, which has to be replaced by the layer thickness d for a backward relaxation ($E=0$), γ_s is the surface viscosity describing the phase shift between the surface director and the bulk one (such a shift is essential only for fast processes) and γ_e is the analogous parameter referred to viscous losses at rotation of the easy axes. The characteristic lengths, L_s and L_e , are interrelated with the anchoring strengths W_s and W_e describing non-rigid anisotropic interaction of the near-surface layer with the adsorbed layer of LC molecules and that of LC absorbed layer and the surface [Equation (3)]; h is the effective thickness of the near-surface layer characterised by the surface director \mathbf{n}_s .

It has been shown that the simplest regime of a linear relaxation after turning off the electric field can be described by two relaxation times τ_e^0 and τ_s^0 with considerably different values:

$$\tau_e^0 = (\gamma_e L_e)/K_{22} \gg \tau_s^0 = (\gamma_s L_s)/K_{22}. \quad (4)$$

In the stationary case, nonlinear effects become

important at angles more than 10° . For slow relaxation of an easy axis after turning off the electric field one can obtain (by neglecting the torque transmitted from the bulk LC) the torque balance Equation for an easy axis:

$$(K_{22}/2L_e)\sin 2\varphi_e + \gamma_e(\partial\varphi_e/\partial t) = 0. \quad (5)$$

So, the approximate nonlinear solution in this case can be written as:

$$\tan \varphi_e = \tan \varphi_e^\infty \exp(-t/\tau_e^0), \quad (6)$$

where $\tan \varphi_e^\infty$ is referred to the stationary state of an easy axis before turning off the electric field. So the light intensity, I , passing through the cell placed between crossed polarisers can be expressed as:

$$I = I_0 \sin^2 \varphi_e = I_0 \left\{ \frac{[\tan^2 \varphi_e^\infty \exp(-2t/\tau_e^0)]}{[1 + \tan^2 \varphi_e^\infty \exp(-2t/\tau_e^0)]} \right\}. \quad (7)$$

The modified model of gliding with additional action of light

To explain the main results obtained in our experiments we have to consider the complicated dynamical processes taking place in the vicinity of the LC–solid surface to obtain some physical background for modification of the previously proposed model. At least three molecular systems are involved in the phenomena under consideration.

The first system (B system) consists of LC molecules distributed in the bulk of the layer. It is described by standard continuum Equations (by using a bulk director \mathbf{n}_b) with boundary conditions, corresponding to different surface orientation. The finite anchoring strength in this case is described in terms of the surface director \mathbf{n}_s , which can be varied by strong fields.

The second system (S system) is formed by LC molecules absorbed by a surface. It is characterised by the mean molecular direction (the easy axis \mathbf{n}_e) and by its own surface order parameter. The molecular motions in such systems are slowed due to strong interaction with the molecules of dye.

The system of dye molecules (D system) can also be considered as a statistical ensemble that can be ordered via polarised light illumination, which provides the mean orientation of the dye molecules (\mathbf{n}_o for example) orthogonal to a polarisation plane. A microscopic description of the dynamical behaviour of such an ensemble was provided previously in the framework of a diffusion model (9). In general, the anchoring strength of the surface depends on the

order parameter of this system and can be regulated via the exposure dose at UV illumination.

We will now consider in more detail the interactions between the systems mentioned above.

B–S interactions

The strong “in-plane” electric field produces a twist-like deformation acting on the absorbed molecules due to a surface layer. To some extent this interaction is similar to that imposed by light in LC samples doped by a dye (8). It has been shown that in the latter case the light-induced torque acting on the bulk director results in a new direction in the layer of absorbed molecules described in terms of the second easy axis with anchoring strength growing with time. The main difference between the latter situation and that in our experiments is due to different molecular mechanisms responsible for the phenomena.

In the case of doped LCs, light illumination produces a reorientation of azo-dye molecules in the near-surface layer of the LC, which is absorbed by the surface. The new surface direction of the absorbed dye molecules is defined by the electric field direction in a light wave. The probability of the absorption process showing the rate of a change in number of dye molecules of a given orientation depends on the initial concentration of molecules in near-surface layer, the light intensity, the overall concentration and the orientation of already absorbed dye molecules. The latter can be induced by preliminary irradiation of a sample by light of a different polarisation, which produces its own preferred surface direction. The overall surface direction of LC molecules (LC easy axis \mathbf{n}_e) is defined by an interaction with dye molecules belonging to different surface directions mentioned above. The anchoring energies corresponding to different preferred surface directions are proportional to the doses of preliminary and current irradiation.

In our experiment, the strong electric field varies the angular distribution of near-surface molecules of the LC. This results in an increasing of a number of LC molecules in the bulk with orientations different from the initial one defined by the initial surface direction (\mathbf{n}_0). The distribution of these molecules depends on the distance from the surface. In principle, such new bulk distribution can modify the surface distribution of the absorbed LC layer due to absorption–desorption processes (12). The new preferable orientation \mathbf{n}_2 (orthogonal to \mathbf{n}_0 for our case) is determined by the orientation of the electric field. Obviously, such a mechanism is possible only at relatively weak anchoring. In this case, a strong electric field induces some deviation, $\delta\mathbf{n}_s$, in a surface

director, \mathbf{n}_s , and so in the overall orientation of LC molecules migrating to the surface before absorption. The rate of changing of the surface distribution has to depend on the intensity of the electric field via the dependence $\delta\mathbf{n}_s(E)$. It is reasonable to put the anchoring strength $W_2^{(E)}$ connected with the new electrically induced surface direction \mathbf{n}_2 to be proportional to the number $N_2^{(E)}$ of absorbed molecules with essentially different orientation. To describe the dynamics of the latter process we will use the same exponential law as that proposed previously (8) for time-dependant concentration of dye molecules transformed by light:

$$N_2^E(t) = N_2^{(E)}(\infty) \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(E)}\right) \right], \quad (8)$$

where $N_2^{(E)}(\infty)$ depends on the electric field intensity. In the first approximation:

$$N_2^{(E)}(\infty) \sim E^2. \quad (9)$$

The relaxation time $\tau^{(E)}$ referred to saturation is considered to be independent of E .

So, the expression for the part of anchoring strength induced by a strong electric field can be written as:

$$W_2^{(E)} = A^{(E)} E^2 \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(E)}\right) \right]. \quad (10)$$

For relatively weak electric field and (or) short exposure time t_{exp} (which is valid for our case), Equation (10) results in a linear dependence between $W_2^{(E)}$ and t_{exp} :

$$W_2^{(E)} = A^{(E)} E^2 t_{\text{exp}} / \tau^{(E)} = \beta^{(E)} E^2 t_{\text{exp}}. \quad (11)$$

The expressions obtained can be used for an explanation of some peculiarities of electrically induced gliding phenomena reported previously (15).

S–D interactions

The influence of light illumination on an easy axis gliding can be easily explained in the framework of the proposed description. Indeed, a molecule of a dye illuminated by light transforms its orientation in accordance with a new direction of light polarisation. In our case it leads to an occurrence of the same new surface direction \mathbf{n}_2 as that induced by an electric field. So, both factors act in the same manner. We can connect the contribution of light, $W_2^{(L)}$, with the anchoring strength, W_2 , with the number of activated dye molecules, N_2^L . The expressions for these

parameters are analogous to Equations (8) and (10):

$$N_2^L(t) = N_2^{(L)}(\infty) \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(L)}\right) \right] \quad (12)$$

and

$$W_2^{(L)} = A^{(L)} I_2 \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(L)}\right) \right], \quad (13)$$

where the relaxation time is considered to be not dependent on light intensity. It is worth mentioning that this reflects the principal difference in molecular mechanisms for light-induced easy direction between the cases of a surface dye layer and of a doped LC. In the latter case, light illumination stimulates absorption-desorption processes, so the relaxation time depends on light intensity (8).

One has to take into account that increasing the number of activated dye molecules results also in a decrease of the initial number N_0 of molecules, corresponding to the first preferred direction \mathbf{n}_0 , described as:

$$N_0^L(t) = N_0 - N_2^{(L)}(\infty) \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(L)}\right) \right]. \quad (14)$$

So, the anchoring strength W_2 connected with the \mathbf{n}_0 direction will be decreased in accordance:

$$W_0^L(t) = W_0 - A^{(L)} I_2 \left[1 - \exp\left(-t_{\text{exp}}/\tau^{(L)}\right) \right], \quad (15)$$

where the initial strength W_0 defined by the preliminary UV radiation can be expressed as:

$$\begin{aligned} W_0 &= B^{(p)} I_p \left[1 - \exp\left(-t_p/\tau^{(p)}\right) \right] \\ &= \left[B^{(p)} D_p / \tau^{(p)} \right] \left[1 - \exp\left(-t_p/\tau^{(p)}\right) \right], \end{aligned} \quad (16)$$

where I_p , D_p and t_p are the intensity, the dose and the exposure time, respectively, of the preliminary UV irradiation and $\tau^{(p)}$ is the characteristic time for a saturation process. For relatively small illumination doses, as in our case, Equations (13) and (15) correspond to a linear increase (decrease) of anchoring strengths $W_2^{(L)}$ ($W_0^{(L)}$):

$$W_2^{(L)} = A^{(L)} I_2 t_{\text{exp}} / \tau^{(L)} = \beta I_2 t_{\text{exp}}, \quad (17)$$

$$W_0^L(t) = W_0 - A^{(L)} I_2 t_{\text{exp}} / \tau^{(L)} = W_0 - \beta I_2 t_{\text{exp}}. \quad (18)$$

At the same time, for preliminary UV irradiation the linear approximation holds only for low exposure

doses D_p (such as 0.25 J cm^{-2} in our case):

$$W_0 = B^{(p)} I_p t_p / \tau^{(p)} = \alpha D_p. \quad (19)$$

For higher doses (such as 5 J cm^{-2} in our case), the more general expression given by Equation (16) has to be used.

The modified phenomenological model has to take into account the main peculiarities of intermolecular interactions described above. This can be done by introducing into the previously proposed model for gliding (15) the new preferable surface direction \mathbf{n}_2 orthogonal to the first one \mathbf{n}_0 (Figure 6). This orientation reflects the mean direction of the new ensemble of LC absorbed molecules. According to the assumptions made above the anchoring strength (W_0 or W_2) may be connected with the control parameters of our experiments.

From the point of view of the above-mentioned model of gliding, the overall result of light action can be considered as the additional torque Γ_2 acting on the \mathbf{n}_e axis opposite to the torque Γ_0 connected with the first direction. The torques Γ_0 and Γ_2 can be expressed as:

$$\Gamma_0 = - \left(K_{22} / 2L_e^{(0)} \right) \sin 2\varphi_e, \quad (20)$$

$$\begin{aligned} \Gamma_2 &= \left(K_{22} / 2L_e^{(2)} \right) \sin 2(\pi/2 - \varphi_e) \\ &= \left(K_{22} / 2L_e^{(2)} \right) \sin 2\varphi_e, \end{aligned} \quad (21)$$

where the corresponding lengths $L_e^{(0)}$ and $L_e^{(2)}$ are defined as:

$$L_e^{(0)} = K_{22} / W_0^{(L)}, \quad L_e^{(2)} = K_{22} / W_2^{(E,L)}. \quad (22)$$

The anchoring strength $W_0^{(L)}$ is determined by Equations (15)–(19), whereas integral anchoring strength $W_2^{(E,L)}$ is defined as:

$$W_2^{(E,L)} = W_2^{(E)} + W_2^{(L)}, \quad (23)$$

with the contributions expressed by Equations (10) and (13).

So, the sum of the two above-mentioned torques can be expressed as:

$$\begin{aligned} \Gamma_0 + \Gamma_2 &= - \left[\left(K_{22} / 2L_e^{(0)} \right) - \left(K_{22} / 2L_e^{(2)} \right) \right] \sin 2\varphi_e \\ &= - \left(K_{22} / 2L_e^{\text{eff}} \right) \sin 2\varphi_e, \end{aligned} \quad (24)$$

where the effective length L_e^{eff} is defined as:

$$L_e^{\text{eff}} = \left(L_e^{(2)} L_e^{(0)} \right) / \left(L_e^{(2)} - L_e^{(0)} \right). \quad (25)$$

Substitution allows the Equation for torques acting on the easy axis to be expressed in exactly the same form, Equation (2), as in original model:

$$K_{22}[(\pi/2) - \varphi_s]/(\xi - h) - (K_{22}/2L_e^{\text{eff}}) \sin 2\varphi_e - \gamma_e(\partial\varphi_e/\partial t) = 0. \quad (26)$$

Thus, all previously obtained results can be used with the only modification:

$$L_e \rightarrow L_e^{\text{eff}}. \quad (27)$$

In the general case, the effective length L_e^{eff} depends both on the parameters (intensity and exposure time) of applied electric field and on two sets of parameters (the light intensity and the exposure time) referred to the preliminary UV treatment and to illumination of light during voltage application. The static and dynamic behaviour of the system is totally defined by these parameters.

In particular, accordingly to Equation (25) the characteristic time of an easy axis gliding can be expressed as:

$$\tau_e^0 = (\gamma_e L_e^{\text{eff}}) / K_{22} = \gamma_e / \left(W_0 - W_2^{(E)} - 2W_2^{(L)} \right). \quad (28)$$

This can be simplified by using the linearised expressions given by Equations (11), (17) and (18):

$$\tau_e^0 = \gamma_e / \left(W_0 - \beta^{(E)} E^2 t_{\text{exp}} - 2\beta^{(L)} I_2 t_{\text{exp}} \right). \quad (29)$$

Equation (29) can be applied for a description of experiment results on slow dynamics of LC after turning off electric field and light. In particular, it predicts the essential increase of the relaxation time for increasing intensity and exposure time of both electric field and optical field for the combined action of these factors. At the same time, the increase of anchoring strength W_0 produced by preliminary UV irradiation has to decrease the relaxation time. All these predictions are in a qualitative agreement with the experimental results presented above.

One can try to extract information about phenomenological parameters entering into the proposed model by comparison of the theoretical expression given by Equation (29) for the relaxation time of an easy axis and the experimental data, presented in Table 1. In particular, the second relaxation time τ_2 presented in Table 1 can be connected with the time τ_e^0 defined by Equation (29) and describing the last

stage the easy axis relaxation as [15]:

$$\tau_e^0 = 2\tau_2. \quad (30)$$

Taking into account this connection, we fitted of the data from the Table 1 by Equation (29) and obtained the following values for the phenomenological parameters in the proposed model:

$$\beta^{(E)} / W_0 = 7.57 \times 10^{-17} \text{ V}^{-2} \text{ m}^{-2} \text{ s}^{-1} \text{ at } d = 50 \mu\text{m};$$

$$\beta^{(L)} / W_0 = 8.21 \times 10^{-4} \text{ m}^2 \text{ s}^{-1} \text{ W}^{-1} \text{ at } I_2 = 74 \text{ mW m}^{-2};$$

$$\gamma_e / W_0 = 880 \text{ s}.$$

The initial anchoring strength W_0 for an easy axis provided by preliminary UV treatment can differ from the anchoring strength W_s usually used at description of surface director motion and can be determined by nonlinear analysis of the initial stationary state of the LC layer (15), which is beyond the scope of this paper. According to our previous data, obtained in the absence of additional light illumination, the values of W_0 and W_s are of the same order of magnitude (10^{-4} – 10^{-3} J m^{-2}). This means that the reciprocal length $L_e^{(0)}$ is of order 10^{-8} – 10^{-7} m , which seems to be reasonable. The value of the gliding viscosity, γ_e , for $W_0 = 10^{-7} \text{ J m}^{-2}$ is about 1 Pa m s .

The surface plotted in Figure 7 using the parameters of the approximation presented above demonstrates the character of dependence of a characteristic time of gliding, τ_e^0 , on the electric field strength and the exposure time. The numerical values of τ_e^0 presented in Table 1 show good agreement with the experimental ones (τ_2) at least at relatively moderate values of applied voltage when the linear approximation used in deriving Equation (29) is obviously valid. Such an approximation has to break down in the vicinity of critical increasing relaxation times. Nevertheless, we can estimate the critical exposure time, t_{exp}^c , corresponding to the critical slowing down of the easy axis relaxation from the linearised Equation (29):

$$t_{\text{exp}}^c = W_0 / \left[\beta^{(E)} U^2 + \beta^{(L)} I_2 \right]. \quad (31)$$

For values of the parameters mentioned above, we estimated t_{exp}^c as 85 min and 40 min, respectively, for voltages $U = 50 \text{ V}$ and 100 V . Experimentally, for $U = 100 \text{ V}$ we observed an essential increase of relaxation times in the range 20–80 min (see Tables 1 and 2) which does not contradict the estimates mentioned above. It is also obvious that

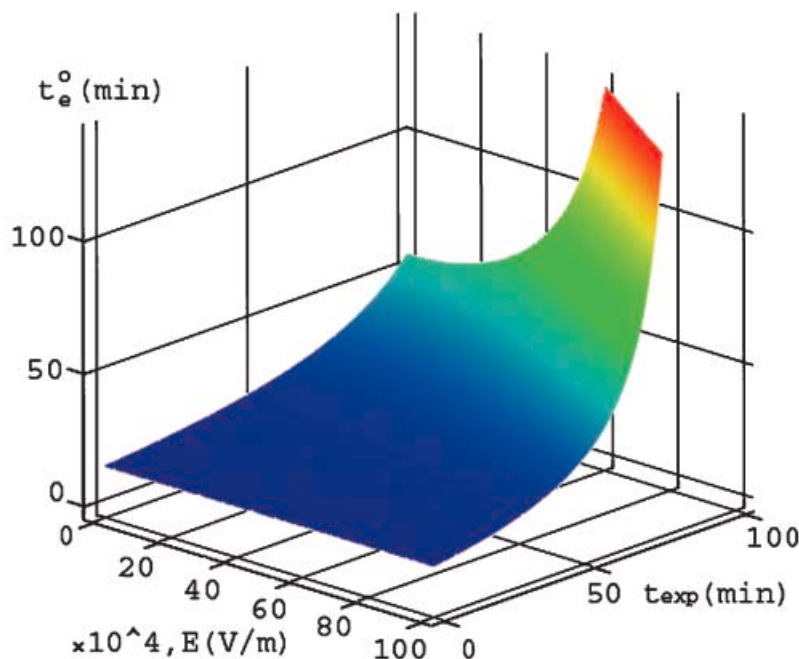


Figure 7. Characteristic time of gliding, τ_e^0 , as a function electric field strength, E , and exposure time, t_{exp} .

the decrease of extremely slow relaxation times presented in Table 2 with increase of the exposure dose D_p of preliminary UV irradiation can be partly referred to the increasing of the anchoring strength W_0 , in accordance with the nonlinear expression, Equation (28). At the same time it is difficult to exclude *a priori* the possible influence of preliminary UV irradiation not only on elastic (W_0) characteristics, responsible for a gliding process, but on viscous ones (γ_e) too due to changing of potential barriers of molecular motions. Such influence is also possible regarding to the light illumination in combination with electric field used in our experiments. Indeed, the fitting of our previous results on electrically induced gliding (15) by Equation (28) gives the value $\beta^{(E)}/W_0 = 7.2 \times 10^{-17} \text{ V}^{-2} \text{ m}^{-2} \text{ s}^{-1}$, which is close to that presented above. At the same time, the obtained value of γ_e/W_0 ($3.74 \times 10^3 \text{ s}$) for electrically induced gliding is essentially higher than that for the experiments with combined action of electric field and light described above. So, one can propose that additional illumination increases the rate of exchange between the absorbed surface layer of LC molecules and the bulk one. In this case, additional light illumination results in decreasing of the gliding viscosity γ_e describing absorption-desorption processes.

Further experiments are needed to clarify some essential questions arising due to description provided above. Firstly, the modified model predicts that the second preferred surface direction exists after

turning off electric field and light. In this case the anchoring strength connected with the initial surface direction has to decrease via application of field and light. Our preliminary experiments confirm such a conclusion. The more deep insight can be also obtained by application of microscopic approach like a diffusion model (9). This could provide the connection between the phenomenological parameters entering into the model and the molecular properties of the systems.

5. Conclusion

We have demonstrated for the first time that the combined action of a relatively weak electric field and polarised light on the LC cell preliminary treated by UV irradiation can induce an extremely slow process of relaxation after turning off both the field and light. The characteristic times of these processes are determined by a number of controlled parameters (exposure dose of preliminary UV irradiation, light intensity, applied voltage U , exposure time t_{exp}). A proper choice of control parameters provides the effective regulation of the time, corresponding to the changed optical state. So, devices for an operative memory of a controlled duration can be proposed on the basis of this effect. The results obtained have been explained in the framework of a modified phenomenological model taking into account the complicated mechanisms responsible for combined action of

electric field and light on ordered and interacting ensembles of molecules of LC and of a dye.

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