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Akihiko Sugimura[a]; Ou-Yang Zhong-can[b]
[a] Department of Information Systems Engineering, Faculty of Engineering, Osaka Sangyo University, Osaka, Japan [b] Institute of Theoretical Physics, Academia Sinica, Beijing, China

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Dynamic behaviour of electric properties in a liquid crystal cell with polyimide boundaries

by AKIHIKO SUGIMURA* and OU-YANG ZHONG-CAN†

Department of Information Systems Engineering, Faculty of Engineering
Osaka Sangyo University, Nakagaito, Daito, Osaka 574, Japan

†Institute of Theoretical Physics, Academia Sinica, P.O. Box 2735,
Beijing 100080, China

Dynamic behaviour of electrical properties accompanying an application of a DC step voltage to a liquid crystal cell, including polymer thin films, has been studied theoretically and experimentally. A 4 component equilibrium circuit of a liquid crystal cell is introduced to elucidate the electrical properties. In this circuit the electric response of a polymer film is represented by a series circuit of resistance R_1 and a capacitance C_1, considering dielectric loss of the layer. An effective voltage applied to a liquid crystal bulk (which is usually mistaken for an external applied voltage U_0 in liquid crystal displays) is found to be apparently different from U_0.

1. Introduction

Liquid crystal displays (LCD) including polymer thin films are widely utilized as a man–machine interface. In these devices polymer layers play important roles as the treatment layers for the molecular alignment and the blocking layers for charge injection from the electrodes. In addition, it has been reported [1] that this layer has an important meaning for an opto-electrical effect. However the influence of the polymer layer on the switching behaviour of an LCD is not fully understood at the present time. The dielectric property of the polymer film may play a more important role. In addition to the effects of carrier transport [2–4], electric double layer [5–7], and two kinds of charge [8], it is valuable to investigate the electric behaviour in the LCD by combining liquid crystal (LC) bulk and insulating polymer films as a unified system under DC or AC excitation.

In this paper detailed theory and experimental results on the dynamic behaviour of the electric properties in an LCD are presented. A 4 parameter circuit is proposed to describe the electric response of the system. Two parameters C_1 and R_1 connected in series represent the capacitance and dielectric relaxation in a polymer layer, respectively, and another two parameters connected in parallel, resistance R_0 and capacitance C_0, are introduced to take into account the bulk effect of the LC. R_0 is also related to the charge carrier density and its mobility. Based on this model the transient current induced by an applied voltage is calculated and these results are verified by the experiments. The theoretical results are excellent in agreement with the experimental data. These derivations provide the measurement methods to obtain all four parameters independently. An effective voltage applied to the LC bulk (which is usually mistaken for an external applied voltage U_0 in liquid crystal displays) is also calculated and is found to be apparently different from U_0.

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*Author for correspondence.

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2. 4 component circuit [9]

Considering one kind of sign of the charge and neglecting diffusion, the electric field $E(x, t)$ related to charge carrier density $\rho^{\pm}$ in the LC bulk is given by Poisson's equation,

$$\frac{\partial E(x,t)}{\partial x}=\pm(4\pi/\varepsilon)\rho^{\pm}(x,t), \tag{1}$$

where x is the normal direction to the substrate surface. The current density is given by

$$i(t)=\frac{\varepsilon}{4\pi}\frac{\partial E(x,t)}{\partial t}+\mu^{\pm}\rho^{\pm}E(x,t), \tag{2}$$

where $\mu^{\pm}$ is the mobility. Substituting $\rho^{\pm}$ in equation (1) into equation (2), this expression can be integrated with respect to x, and is simplified by the continuing condition of $i(t)$ as

$$l\cdot i(t)=\frac{\varepsilon}{4\pi}\frac{dU_{\mathrm{eff}}(t)}{dt}\pm\mu^{\pm}\frac{\varepsilon}{8\pi}\{E(l,t)^2-E(0,t)^2\}, \tag{3}$$

where $E(l, t)$ and $E(0, t)$ are the boundary values at each interface between the polymer and the LC layer, and l is the thickness of the LC bulk. The effective voltage on the LC layer is defined by

$$U_{\mathrm{eff}}=\int_0^l E\,dx.$$

The values of $E(l, t)$ and $E(0, t)$ can be analytically obtained only for the assumption of a very simple charge distribution. Here we simplify $E(l, t)^2-E(0, t)^2$ by the following average consideration

$$\begin{aligned}E(l,t)^2-E(0,t)^2&=\{E(l,t)-E(0,t)\}\{E(l,t)+E(0,t)\}\\&\approx 2\{E(l,t)-E(0,t)\}U_{\mathrm{eff}}(t)/l.\end{aligned} \tag{4}$$

While the Gauss' theorem gives

$$E(l,t)-E(0,t)=\pm\frac{4\pi Q^{\pm}}{\varepsilon A}, \tag{5}$$

where $Q^{\pm}=\int\rho^{\pm}\,dv$ is the total charge in the LC bulk and A is the electrode area of the LCD. From equations (3–5), $i(t)$ is related to U_{eff} by the following equation:

$$I(t)=C_0\frac{dU_{\mathrm{eff}}(t)}{dt}+\frac{1}{R_0}U_{\mathrm{eff}}(t), \tag{6}$$

where $I=i\cdot A$ is a current across a LC sample and

$$C_0=\frac{\varepsilon A}{4\pi l}, \tag{7}$$

$$R_0=\frac{l^2}{\mu^{\pm}Q^{\pm}}=\frac{l}{\mu^{\pm}\rho^{\pm}A}, \tag{8}$$

are the capacitance and resistance of the LC layer, respectively. The electric response of a LC layer is described as a parallel circuit of C_0 and R_0 as shown in equation (6).

Concerning the polymer, the polymer boundary may be seen as the perfect insulating medium at room temperature. However, one should note that the dielectric parameter ε_1 of and organic medium is different from an inorganic one and may have an additional dispersion at low frequencies in a radio frequency region [10]. In this meaning, the dielectric constant for a polymer layer should be written in the complex function of the frequency ω by

$$\varepsilon_1(\omega)=\varepsilon'_1(\omega)-i\varepsilon''_1(\omega). \tag{9}$$

This is equivalent to the electric response of a polymer film being represented by a series circuit with a resistance R_1 and a capacitance C_1. A complex impedance for equation (9), i.e. $1/\bar{C}_1\omega$ written by

$$\frac{1}{(\varepsilon_1(\omega)A/4\pi l)i\omega}=\left(\frac{\varepsilon'_1(\omega)}{i\omega}+\frac{\varepsilon''_1(\omega)}{\omega}\right)\left(\frac{4\pi l}{A(\varepsilon'^2_1(\omega)+\varepsilon''^2_1(\omega))}\right)=\frac{1}{C_1\omega i}+R_1 \tag{10}$$

show the practical meaning of C_1 and R_1. The relaxation time $\tau_1=R_1C_1$ relates to the dipolar reorientation. The difference between dipole moments of polymers in a ground and excited state can be extremely large. So it is necessary to consider the contribution of τ_1, i.e. R_1, to the electric behaviour of LCDP.

In the following study the DC switching behaviour of LCDP is discussed based on a 4 component linear circuit as shown in figure 1.

3. Electrical response for a DC step voltage application

Where the LCD is driven by a step DC voltage as shown in figure 2 the image function of transient current $\hat{I}(p)$ is written using the Laplace transform $\hat{I}(p)=\hat{U}_0(p)/\hat{R}(p)$, where $\hat{R}(p)=2(R_1+1/C_1p)+R_0/(1+R_0C_0p)$ is the image resistance of the 4 component circuit. From the form of

$$\hat{I}(p)=[U_0C_1/2(\tau_a-\tau_b)][(\tau_a-\tau_0)/(1+\tau_0p)+(\tau_0-\tau_b)(1+\tau_pp)]$$

(where $\tau_0=R_0C_0\tau_2=C_1R_0/2$, $\tau_a\tau_b=\tau_0\tau_1$, and $\tau_a+\tau_b=\tau_0+\tau_1+\tau_2$), the time dependence of a transient current is obtained as a monotonically decreasing function,

$$I(t)=\frac{U_0C_1}{2(\tau_a-\tau_b)}\left[\left(1-\frac{\tau_0}{\tau_a}\right)\exp(-t/\tau_a)+\left(\frac{\tau_0}{\tau_b}-1\right)\exp(-t/\tau_b)\right]. \tag{11}$$

An effective voltage U_{eff} is obtained as

$$U_{\text{eff}}(t)=\frac{U_0C_1R_0}{2(\tau_a-\tau_b)}[\exp(-t/\tau_a)-\exp(-t/\tau_b]. \tag{12}$$

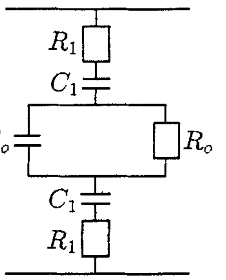

Figure 1. The 4 component circuit.

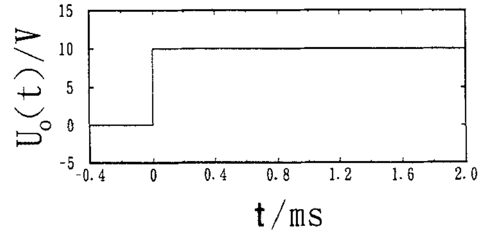

Figure 2. Schematic waveforms of an external applied step voltage $U_0(t)$.

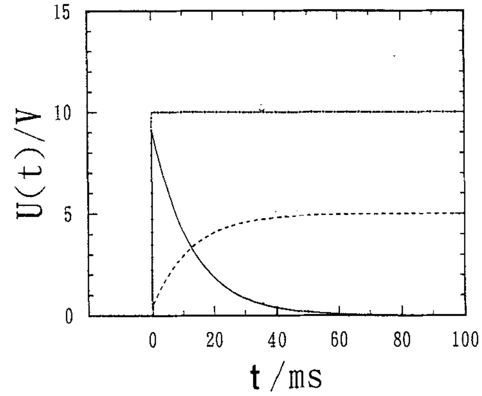

Figure 3. Calculated effective voltage shape of $U_{eff}(t)$ (——————) using equation (12) in response to a step voltage application, $U_0(t)=10$ V (—·—·), in which the dashed line shows the effective applied voltage, U_p, to the polyimide layer.

The formula for a step DC switching indicates that the effective voltage is always decreasing to zero because of the blocking effect of the polymers films. Figure 3 shows the calculated effective voltage which is never measured directly. In figure 3 the dashed line shows the effective voltage $U_p(t)$ applied to the polyimide layer which is obtained by the relation $U_p(t)=R_iI(t)+(1/C_1)\int_0^t I(t)\,dt+\alpha$ and is given,

$$U_p(t)=\frac{U_0C_1R_1}{2(\tau_a-\tau_b)}\left[\left(1-\frac{\tau_0}{\tau_a}\right)\exp(-t/\tau_a)+\left(\frac{\tau_0}{\tau_b}-1\right)\exp(-t/\tau_b)\right]$$

$$+\frac{U_0}{2}+\frac{U_0}{2(\tau_a-\tau_b)}[(\tau_0-\tau_a)\exp(-t/\tau_a)+(\tau_b-\tau_0)\exp(-t/\tau_b)] \qquad (13)$$

Since an effective voltage U_{eff} cannot be measured directly, the measurement of an optical response ia a useful method to observe the director rotation which reflects the time dependence of U_{eff}. Figure 4 shows the time dependence of the optical response after the application of a DC step voltage. The NLC cell with homogeneous alignment was set between crossed polarizers with the **n** director at a 45° angle to the incident linearly polarized light direction. The He–Ne laser light (wavelength 633 nm) beam was incident normal to the NLC cell. In this experiment the transmitted intensity of light increases and reaches the 'light on' state within several hundred milliseconds. These experimental results can be easily understood from the time dependence of U_{eff} applied to the LC layer as shown in figure 3. Hence the theoretical result of equation (12) is confirmed by this simple experimental result.

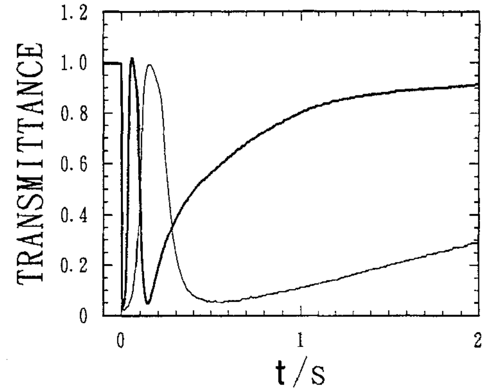

Figure 4. Time dependencies of transmitted intensity of light after the step voltage application of $U_0=10\,\text{V}$ (boldline) and 15 V (thin line) at 30°C.

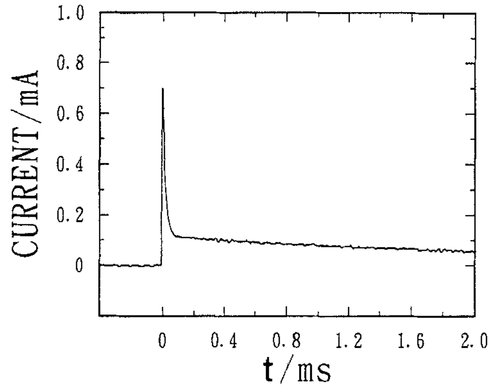

Figure 5. Measured current shape of $I(t)$ in response to the step voltage application of $U_0=10\,\text{V}$ at 30°C.

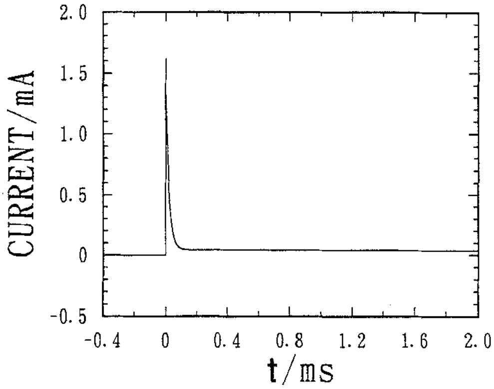

Figure 6. Calculated current shape of $I(t)$ using equation (17) in response to a step voltage application of $U_0=10\,\text{V}$.

4. Discussion

It has been shown that both the transient current and the effective voltage can well account for the LCDP device. Theoretical results were experimentally confirmed for a homogeneously oriented nematic LC sample with polymer boundaries. Here we only show the case of an application of a DC step voltage. However the same treatment gave good results for the effective voltages of a variety of applied voltage waveforms [9].

The evaluation of 4 components, R_1, C_0, R_1, and C_1, is now an easy matter by measuring the transient currents accompanying the application of appropriate exciting waveforms. From a plot of $\log(I(t))$ against time, using the first decay line of the experimental data as shown in figure 5, the fast response time constant τ_b for the sample used is obtained. Although there is no detailed description in this paper, other parameters and components can be estimated by the measurements of transient currents for the applications of rectangular, pulse rectangular, and triangular waveforms [9]. Using the parameters obtained for the LC sample used, the transient current is calculated for the case of the application of a DC voltage $U_0 = 10$ V. Figure 6 shows the calculated result and is in agreement with the experimental result as shown in figure 5. This agreement also shows that a 4 component circuit is useful for the analysis of the dynamic behaviour of the electrical properties in an LC cell with polyimide boundaries.

5. Conclusion

It has been shown that the 4 component circuit can faithfully describe the electric response to DC switching. The theory of the present 4 component circuit model does not yield information about the LC director dynamics. However, it does give the relative dependence of the electric transient of LCDP on various important material parameters and can be used for the purpose of designing an optimum device. This theory gives a simple method only using the measurements of the transient current to determine the material parameters for both the polyimide and the LC.

We have presented and experimentally verified a theoretical model which quantitatively accounts for the transient current and the effective voltage of an LCDP. This model is a useful tool which should enhance the development of the LCDPs performance. Moreover, we have shown that the dielectric property of the polyimide layers should be considered in addition to that of the LC layer.

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