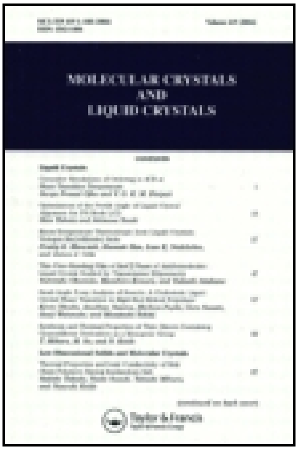

Molecular Crystals and Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/gmcl16

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M. I. Barnik [a] , V. A. Baikaiov [a] , V. G. Chigrinov [a] & E. P. Pozhidaev [a]
[a] Organic Intermediates and Dyes Institute, Moscow, 103787, USSR
Version of record first published: 28 Mar 2007.

To cite this article: M. I. Barnik , V. A. Baikaiov , V. G. Chigrinov & E. P. Pozhidaev (1987): Electrooptics of a Thin Ferroeiectric Smectic C* Liquid Crystal Layer, Molecular Crystals and Liquid Crystals, 143:1, 101-112

To link to this article: http://dx.doi.org/10.1080/15421408708084615

Mol. Cryst. Liq. Cryst., 1987, Vol. 143, pp. 101-112
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Printed in the United States of America

ELECTROOPTICS OF A THIN FERROELECTRIC SMECTIC C* LIQUID CRYSTAL LAYER

M.I.BARNIK, V.A.BAIKALOV, V.G.CHIGRINOV, E.P.POZHIDAEV
Organic Intermediates & Dyes Institute, Moscow, 103787, USSR

Abstract The form of ferroelectric smectic C* electrooptical response vs the layer thickness and the angle β between the polarizer and analyser is investigated. The criterion of the smectic C* switching rate is propozed and the method for the rotational viscosity measurements is developed.

INTRODUCTION

The great interest is concentrating in studyng the electrooptic effect in thin homogeneously oriented smectic C^* layers, having small thicknesses $L \sim 1 - 5\mu$ [1 - 9]. In this case the smectic C^* helix pitch $P_0 > L$ and is unwound due to influence of boundary conditions. This smectic C^* director alignment, defined in[10] as Surfase Stabilized Ferroelectric Liquid Crystal Structure (SSFLCS), is characterized by several thermodynamically stable and optically distinguished states with the electrical field switching between them[10 - 12].

Though the switching rate of ferroelectric liquid crystal (LC) (the speed of electrooptical response) has been investigated in experimental[3-5,8] and theoretical[9, 12] works, there still does not exist the detailed study of this response in dynamics vs smectic C* physical parameters and the layer thickness. Consequently, the accurate criteria for measuring the smectic C* electrooptical response speed are also absent. To fill this gap is the aim of our paper. We also propose the method for determination of the rotational viscosity γ_φ with respect to rotations φ around smectic C* layer normal.

THEORY

Consider a homogeneously oriented layer of a smectic C* liquid crystal in linear electrooptic effect (Fig. 1). When the electric field E changes its sign the polarisation P_s of smectic C* is also reversed and the director rotates around the layer normal (Z - axis) to its new state (Fig. 1). While in the initial state the smectic C* director coincides with the polariser (n(-E) // P), in the final state the director n(+E) forms the angle $2\theta_o$ with the plane of the polariser. The analyser A, placed at the angle β with the polariser, provides the variation of the output smectic C* electrooptic transmission response.

According to phenomenological theory of S.A. Pikin[13], the director rotation around the smectic C* layer normal Z (parallel to the substrates) (Fig.1) may be described as follows:

$$\tilde{K}\,\theta_o^2 \frac{\partial^2 \varphi}{\partial z^2} + P_s E \cdot \sin\varphi = \gamma_\varphi \frac{\partial \varphi}{\partial t} \qquad (1)$$

where φ is the rotation angle, Θ_o - smectic C* director tilt in the layer, $\tilde{K}$, γ_φ - elastic and viscosity constants with respect to azimuthal φ deformations, t - time.

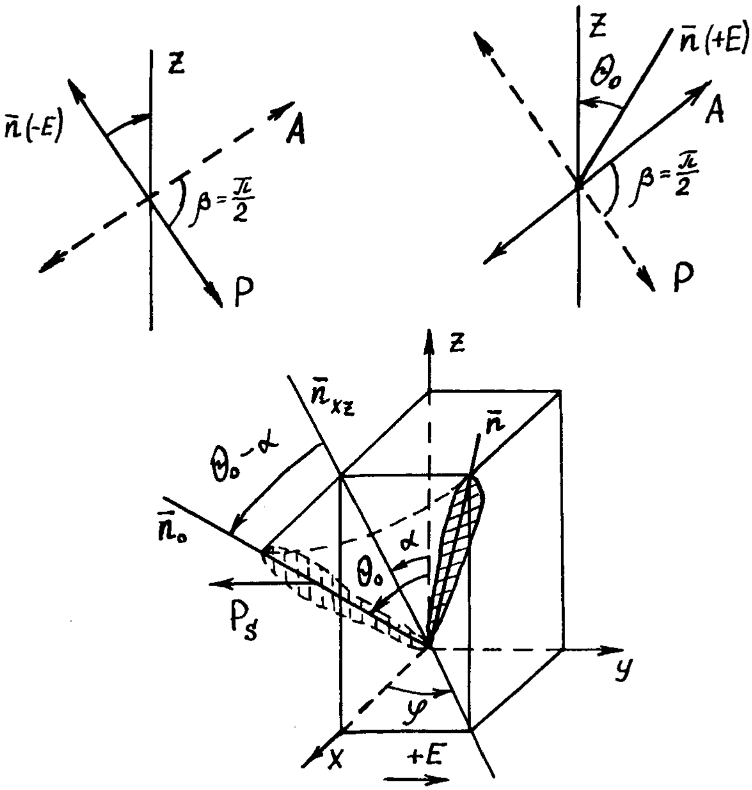

Fig.1. At the top: the location of the polarizer (P), analyser (A) and C* director angle in the initial n(-E) and final n(+E) states.

Bottom: The intermediate position of the director during its rotation around the smectic C* layer normal.

The equation (1) ignores the variations of the smectic C* layer tilt angle under the influence of the electric field E, which is correct, if the working temperature is not too close to the smectic C* - smectic A transition point[13]. Our qualitative theoretical description also does not take into account the boundary conditions and the elastic term $\sim \tilde{K}\Theta_0^2 \frac{\partial^2\varphi}{\partial z^2}$ in equation (1). According to [9 - 12] this is reasonable in case of sufficiently large switching fields. Thus, neglecting the first term in (1) we have:

$$\varphi = \operatorname{arctg}\left(A\cdot\exp(t/\tau_c)\right), \quad A = \operatorname{tg}\varphi_0/2, \qquad (2)$$
$$\varphi_0 = \varphi(t=0), \quad \tau_c = \gamma_\varphi / P_s E$$

The value of τ_c in (2) may be taken as a criterion for the evaluation of smectic C* switching rate in linear electrooptical effect.

Since (2) is an approximate solution for the director angle and the constant A in (2) has no clear physical origin[12], its value may be chosen from the best matching of theoretical and experimental characteristics of smectic C* electrooptic response.

The variation of the optical contrast $\bar{I}/\bar{I}_0$ ($\bar{I}_0$ - is the initial intensity level, $\bar{I}$ - transmitted intensity) in linear electrooptic effect may be described as follows[14]:

$$\bar{I}/\bar{I}_0 = \sin^2\left(\frac{4\Theta_0 f^2}{1+f^2}\right)\cdot \sin^2\left(\frac{\Delta\Phi}{2} - \delta_0\cdot\frac{2f}{1+f^2}\right) \qquad (3)$$

where $f = A\cdot\exp(t/\tau_c)$, $\delta_0 = \frac{\pi L n_\parallel}{\lambda}\left(\frac{n_\parallel^2}{n_\perp^2} - 1\right)\Theta_0^2$,

$\Delta \Phi_0 = \frac{2\pi L}{\lambda} \cdot (n_{\parallel} - n_{\perp})$, λ - light wavelength, $n_{\parallel}$, $n_{\perp}$ - smectic C* refractive indices parallel and perpendicular to the director respectively, $\beta = \frac{\pi}{2}$ - the angle between the polariser and analyser.

One can use the relation (3) for the approximation of experimental I/I_0 curve, obtained in electrical field switching process (Fig.2).

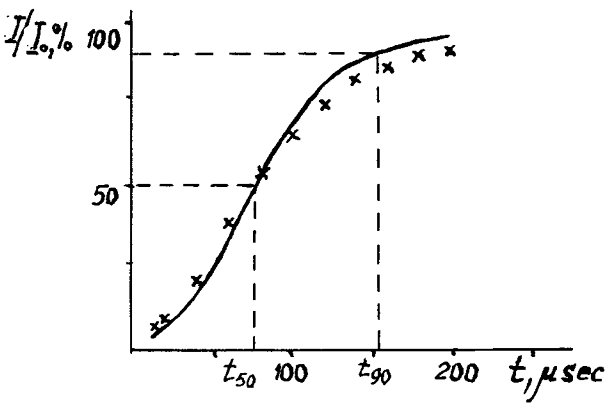

Fig.2. Electrooptical transmission response of DOBAMBC:(x)-experimental data (the external voltage U =4v), solid line - the result of computer fitting procedure by the least squares method with the help of the formula (3). The following parameters are used in calculations: L=5 μ , λ =0,63μ , $n_{\parallel}$=1,7, $n_{\perp}$=1,5, θ_0=0,44. The computer fitting gives A=2, τ_c=95 μsec, while according to the approximate formula (6) we have τ_c=90 μsec.

Let us note, that the optical contrast I/I_0 considerably depends on the smectic C* layer thickness (Fig.3). One can easily show, that for $L = K\lambda/(n_{\parallel} - n_{\perp})$ (K =0, 1, 2,...) the curve

I/I_0 (t) passes through the maximum, while for L= (K+1/2) $\lambda/(n_\parallel - n_\perp)$ (K=0,1,2,...) the optical contrast I/I_0 (t) always increases with rising the time t (Fig.3). Thus the layer thickness non-uniformity Δ L within the smectic C* electrooptic cell working area must satisfy the requirement[14]

$$\Delta L \lesssim \frac{\lambda}{8(n_\parallel - n_\perp)} \qquad (4)$$

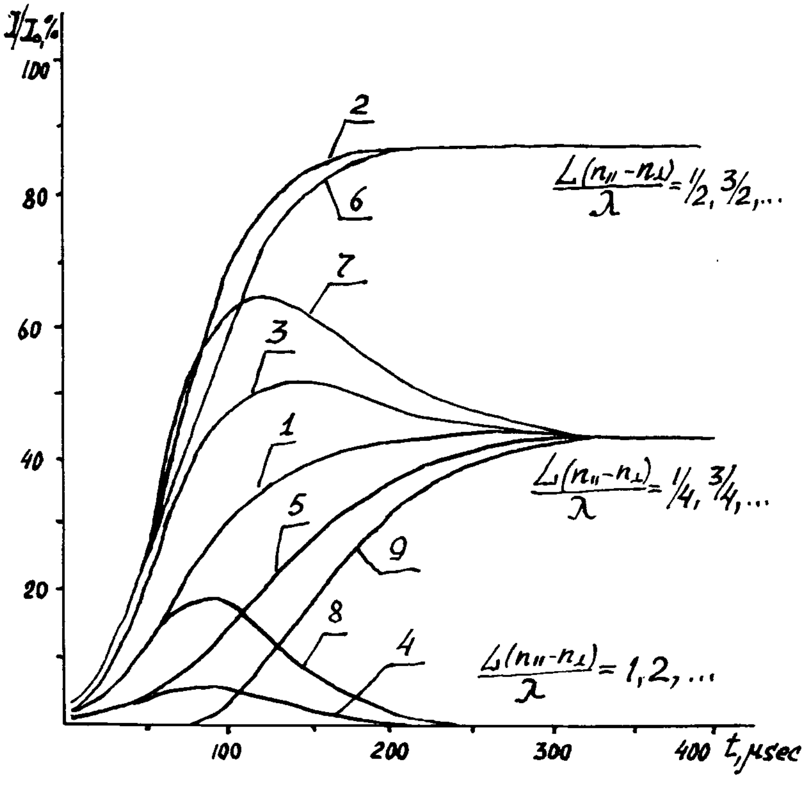

Fig.3. Electrooptical transmission response of ferroelectric smectic C* liquid crystal, calculated by means of (3), vs the layer thickness L. We use in the calculations: λ =0,63μ,

$n_{\parallel}=1{,}7$, $n_{\perp}=1{,}5$, $\theta_0=0{,}3$, $A=0{,}43$, $\tau_c=66\,\mu sec$, $L_o=\lambda/(n_{\parallel}-n_{\perp})=3{,}15\,\mu$. The layer thickness $L^o=KL_o/4$ ($\Delta\Phi_o=\pi K/2$), where K=1,2, ...9 - the number of the corresponding curve.

The form of smectic C* electrooptic response I/I_o (t) can be affected by varying the angle β between the polariser and analyser (Fig.1). Using the well known formula[15] we have:

$$\left(I/I_o\right)_{\beta}=\cos^2\beta-\sin\left(4\theta_o\frac{f^2}{1+f^2}\right)\cdot \sin\left(4\theta_o\frac{f^2}{1+f^2}-2\beta\right)\cdot\sin^2\left(\frac{\Delta\Phi_o}{2}-\delta_o\cdot\frac{2f}{1+f^2}\right) \tag{5}$$

Fig.4 shows, how altering the angle β , one obtains the monotonous rise of the optical contrast for the sufficiently high values of time t.

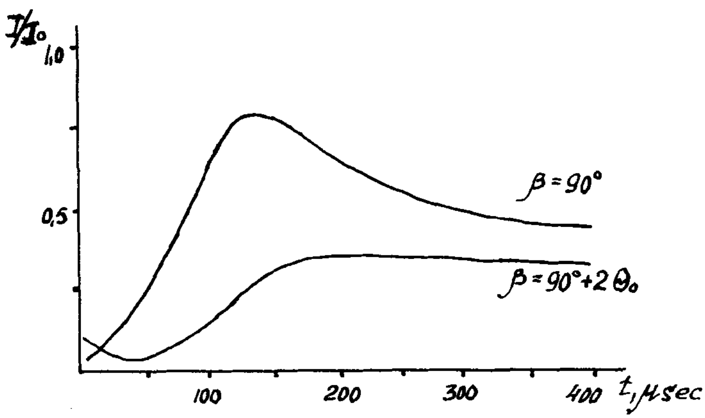

Fig.4. The electrooptical response of ferroelectric smectic C* liquid crystal vs the angle β between the polariser and analyser for the curve №7 ($L=7L_o/4$) of Fig.3.

EXPERIMENTAL AND DISCUSSION

We investigated in experiment the electrooptical transmission response of homogeneously oriented ferroelectric smectic C^* liquid crystal (DOBAMBC), placed between the polarizer and analyser (Fig.1). He-Ne laser with $\lambda = 0,63\mu$ was used as a light source. The external voltage, applied to the cell, was taken in the form of bipolar pulses, which makes it possible to study the dynamics of smectic C^* transmission after the abrupt change of the voltage sign. The layer thickness $L \sim 5 - 8\mu$.

Fig.2 shows the experimental dynamical transmission curve of DOBAMBC in case, when the phase retardation $\Delta\Phi_0 = \frac{2\pi L(n_\parallel - n_\perp)}{\lambda} \sim 3\pi$. The computer fitting of the I/I_0 (t) electrooptic response with the help of the formula (3) is seen to provide a good agreement with the experimental data. The time constant, obtained by the least squares technique was $\tau_c = 95\mu$sec.

Using the equation (3) we derive a simple formula for τ_c, which makes possible the direct evaluation of τ_c without the procedure of computer fitting the experimental I/I_0 (t) data:[14]

$$\tau_c = \frac{t_{90} - t_{50}}{\ln\sqrt{5}} \sim \frac{t_{90} - t_{50}}{0.8} \qquad (6)$$

The approximate value of $\tau_c = 90\mu$sec received by means of (6), matches the value of τ_c, taken from the procedure of the computer fitting with the accuracy of 6%.

In experiment we appraised the DOBAMBC director free relaxation time $\tau_{rel} \sim 30 - 60$ msec, which is much longer than the characteristic director response time τ_c (Fig.2). We also chose the layer thickness L for which the apparent dynamical threshold was less than 0,5v, while the working voltage was 4v. Then our experimental data may be described within the framework of the qualitative theory. According to that, the electrooptical switching rate of smectic C^* τ_c was measured by the following procedure. First of all, the appropriate angle β between the polariser and analyser was chosen, to provide a monotonous rise of electrooptic response. Then the characteristic times t_{90} and t_{50} were defined, and the value of τ_c (6) was calculated.

We also measured the temperature dependence of the smectic C^* DOBAMBC switching rate vs temperature. Taken into account the well-known temperature dependence of the polarisation of DOBAMBC $P_s(T)$, we obtained by means of (2) the corresponding temperature characteristic for the rotational viscosity γ_φ (Fig.5).

The rotational viscosity γ_φ , measured in our experiment, acts a role of a kinetic coefficient, describing the dynamics of the azimuthal smectic C^* director angle φ for the fixed polar angle θ_0. The paper[16] give the temperature dependence of the another smectic C^* rotational viscosity γ_{θ_0} , related to the dynamical relaxation processes of the polar (tilt) angle θ_0 at a constant value of φ (Fig.6). The comparison of the γ_φ and γ_{θ_0} leads to the conclusion, that, in general, one deals with the tensor of smectic C* viscosity, γ_φ and γ_{θ_0} being its principal components.

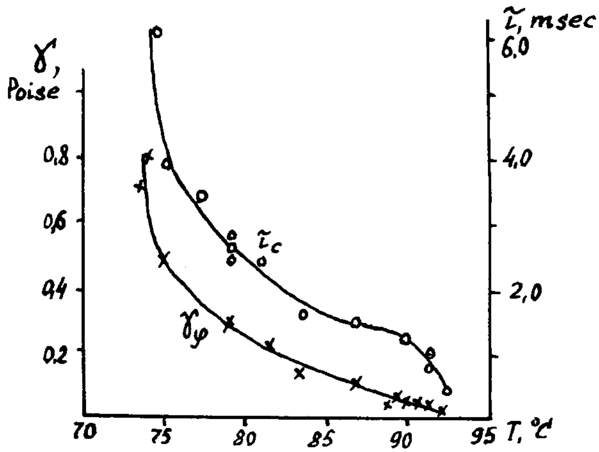

Fig.5. The switching rate τ_c and the rotational viscosity of DOBAMBC vs temperature. The layer thickness L = 7,3 μ . The bipolar rectangular voltage pulses with the amplitude U = 2v and frequency f = 50 Hz are used in experiment.

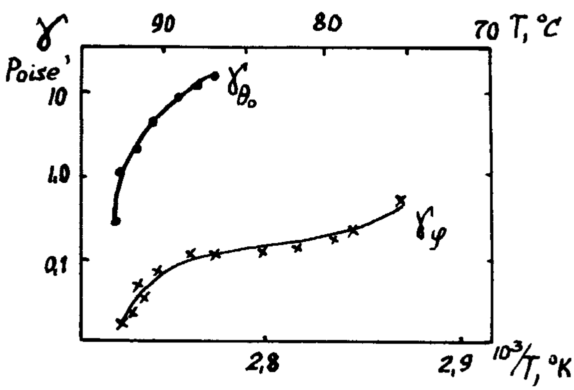

Fig.6. The DOBAMBC rotational viscosities with respect to azimuthal director variations

φ - γ_φ and tilt angle Θ_0 ones - γ_{Θ_0}.

However, if the Θ_0 variations are small, the electrooptuc response dynamics may be described only with the help of γ_φ rotational viscosity. Fig.5 and Fig.6 demonstrate, that the γ_φ compares in value with the typical rotational viscosity of nematic LCs at room temperatures (or even less), while γ_{Θ_0} remains by one or two orders of magnitude greater. The small values of chiral smectic C* liquid crystal viscosity γ_φ may be explained by the symmetric peculiarities of smectic C*: the dissipation of C* free energy process of the director rotation around the layer normal remains reasonably low.

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