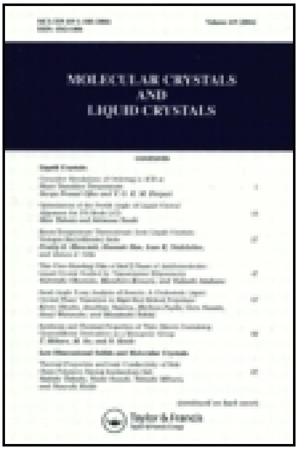

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Helix Dynamics and Electro-Optic Switching in Ferroelectric Smectic C Liquid Crystals

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Helix Dynamics and Electro-Optic Switching in Ferroelectric Smectic C Liquid Crystals

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The responses of symmetric square and triangular wave pulses have been investigated in planar cells of two ferroelectric liquid crystalline mixtures FLC-6430 and SCE-13 in the SmC* phase. The samples were sandwiched between two parallel polyimide coated substrates. The cells containing SCE-13 and FLC-6430 were considered in the surface stabilised state (p>d) and volume stabilised state (p<d) respectively, (p is the helix pitch and d is the sample thickness). Dynamic processes associated with the helix unwinding and winding by applying bias −10V – 0V - + 10V has been studied. The spontaneous polarisation (P_s), response time (τ_R) and torsional viscosity (η) have been evaluated in these materials. Materials in surface stabilised configuration show surface switching while in DHF configuration switching is due to bulk and surface effects.

Keywords: Surface stabilised; helix dynamics; short pitch; spontaneous polarisation; response time; torsional viscosity

I. INTRODUCTION

Ferroelectric liquid crystals (FLCs) are tilted chiral smectic phases having a spatially modulated layered structure. The molecular director precesses helicoidally while going from one layer to another successive layer maintaining a constant tilt angle [1–3]. An electric field applied perpendicular to the helix, unwinds it giving rise to linear electro-optic effects. The strong coupling between applied electric field **E** and the polarisation **P** of the molecules makes these materials interesting for use in fast sub-microsecond electro-optic switching devices [4–5].

Electro-optic properties of FLCs depend on film thickness and the surface properties of the substrates. In 1980 Clark et al. [5] proposed a novel surface stabilised technique of ferroelectric liquid crystal (SSFLC) device which showed

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fast electro-optic responses. In this device, the helix is suppressed by the forces arising from the surfaces of the bounding substrates when pitch is much larger than the cell thickness. They also showed that the director of the SSFLC unwound films rotate uniformly under applied fields so that the polarisation follows this field. Soon after the field reversal, the polarisation is anti-parallel to the field and leads to delay in responses. However, with the advancement in the analysis of switching mechanisms in SSFLC cells, it was found that the electro-optic performance was not as good as anticipated [6]. Cladis et al. [7] showed that for stable helical structure, the applied field only disturbs the helix by a mechanism called "switching by solitary waves". In this case the switching time is expected to be proportional to $1/E^{1/2}$ in contrast to 1/E dependence expected for unwound films. Infact, understanding the ferroelectric switching mechanisms in the surface stabilised (SS) and bulk configurations is being pursued by several research groups [8].

The responses of electric field to the FLC films also gives information about molecular reorientation dynamics and its material properties [9]. The application of symmetric triangular and square wave pulses was found convenient for the measurement of spontaneous polarisation (P_s), response time (τ_r), torsional viscosity (γ), twist elastic constant (K) and to understand the mechanisms of helix unwinding and winding. Bawa et al. [10] proposed this technique for understanding the molecular reorientation processes in bulk and surface domain layers by preparing the cells in

i) helicoidal configuration where one cannot obtain the two stable states of polarisation and

ii) surface stabilised state, which is attained by suppressing the helicoidal structure of the bounding surfaces [11–12].

A review of literature [10–18] showed that less effort has been made to study these effects in large P_s and short pitch materials to understand their molecular reorientation processes.

In this paper, we report on helix dynamics and measurements of electro-optic parameters in two FLC mixtures using symmetric triangular and square wave pulses technique. The material parameters have been evaluated using transient switching.

II. EXPERIMENTAL TECHNIQUE

Experiments for the understanding of helix dynamics and determination of electro-optic parameters were performed on two room temperature multi-component ferroelectric liquid crystal mixtures FLC-6430 (obtained from Hoffmann-La-Roche, Switzerland) and SCE-13 (obtained from BDH, UK). The phase sequence of these FLC mixtures is given by [19]:

FLC-6430

$$Crystal \xrightarrow{-11^{\circ}C} SmC^{*} \xrightarrow{57^{\circ}C} SmA \xrightarrow{65^{\circ}C} Isotropic$$

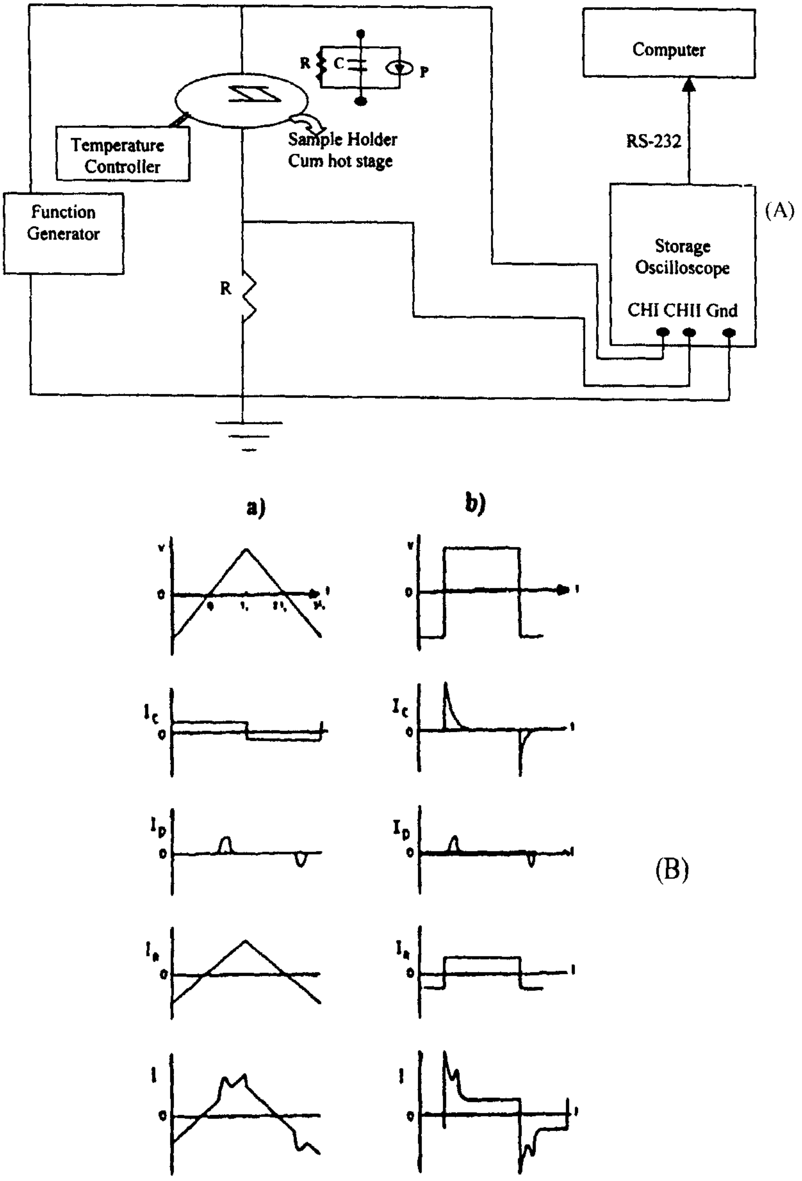
SCE-13

$$Crystal \xrightarrow{-20^{\circ}C} SmC^{*} \xrightarrow{61^{\circ}C} SmA \xrightarrow{91^{\circ}C} N^{*} \xrightarrow{115^{\circ}C} Isotropic$$

The transition temperatures and phase sequence was confirmed using thermal polarising microscopy. At 20°C, SCE-13 has long pitch (p = 10–15μm) and tilt angle $\theta = 20.5^{\circ}$ whereas Deformed Helix Ferroelectric (DHF) liquid crystal mixture FLC-6430 has short pitch (p ≈ 0.435μm) and $\theta = 27^{\circ}$ [19,20]. The electro-optical and transient switching responses using symmetric triangular and square wave pulses have been studied in 5μm cells. These cells (obtained from LUCID, UK) [21] consists of two indiun tin oxide (ITO) coated conducting glass substrates, pre-treated with polyimide (parallel rubbing direction). These cells were filled with FLC mixture by capillary action at their isotropic temperature and cooled to SmA and then to SmC* phase @ 0.1°C/min. in the presence of an electric field (2V/μm, 5Hz). This was done to ensure the planar alignment. The thermal polarising microscopy of the samples was studied using LINKAM hot stage THS600 mounted on the GETNER polarising microscope stage.

In order to study the molecular reorientation processes associated with the helix dynamics, the symmetric −10V- 0V- +10V square and triangular wave pulses were applied to the sample cells. The experimental set-up is shown in Fig.1(a). The triangular and square wave pulses were applied to the cells through Function Generator (PHILIPS model FG8002). The current and voltage pulses were detected on a Digitising Storage Oscilloscope (TEKTRONIX TDS210) across 100 kΩ standard resistor. The whole set up was interfaced with computer for data acquisition and analysis was done using wavestar software.

As can be seen from Fig.1(a), the sample cell acts as a parallel combination of a standard resistor (R), a capacitor (C) and a polarisation realignment device (P). The spontaneous polarisation using the field reversal current technique can be measured by separating the resistive and capacitive terms from the polarisation term by drawing a base line.



Response of Ferroelectric Liquid Crystal to an Electric Field

FIGURE 1 (A) Experimental set up to study helix dynamics and transient electro-optic switching (B) Illustration of current induced by the application of a) triangular and b) square wave pulses observed on the oscilloscope i) Capacitive contribution I_C ii) Polarisation contribution I_P iii) Resistive term contribution iv) Overall current profile I

III. RESULTS AND DISCUSSION

Determination of Spontaneous polarisation

A symmetric triangular wave (-10V - 0V - +10V) applied to FLC mixtures reorients the dipoles between two stable polarisation states (i.e. UP and DOWN). As the field was switched on, the molecular realignments in the form of voltage drop were detected on the storage oscilloscope across R as shown in Fig. 1(a).

In the SmC* phase for a certain applied voltage **V**, the current response **I** consists of three components – the capacitive term I_C (a differentiating component which shows an abrupt jump when the slope of applied voltage changes abruptly) and the ionic conduction term I_R. The third term is the polarisation current I_P, due to the charge induced by the dipole realignment in the form of a polarisation hump.

A schematic representation of these responses for triangular wave pulses is shown in Fig.1(b). Thus the total current I(t) across the resistor R can be written as [17]:

$$I(t) = I_R + I_C + I_P = \frac{V(t)}{R} + C\frac{dV(t)}{dt} + a\frac{dP_S}{dt} \tag{1}$$

Where a is the area of the sample.

Fig.2 shows the voltage-time profiles of polarisation peaks of the two liquid crystal mixtures FLC-6430 and SCE-13 as recorded on the storage oscilloscope when an external voltage of $20V_{PP}$ and a frequency of 20Hz was applied to them. Below zero base line, the helix would be completely in the wound state. However, with the increase in the external applied voltage (above the zero base line), the helix first deforms and then starts unwinding at higher voltage. We noticed that at about $10V_{PP}$ ($2V_{PP}/\mu m$), the helix got completely unwound. At this stage the polarisation peak appeared in the form of a hump.

The area under the hump is a measure of spontaneous polarisation, which is given by:

$2aP_s$ = (Area under the curve) (Current × Time)

$$2aP_S = A(I \times t) \tag{2}$$

Thus

$$P_S = \frac{A(I \times t)}{2a} \tag{3}$$

The area under the curve [A(I × t)] was measured by integrating the polarisation hump in terms of current 'I' and time 't'.

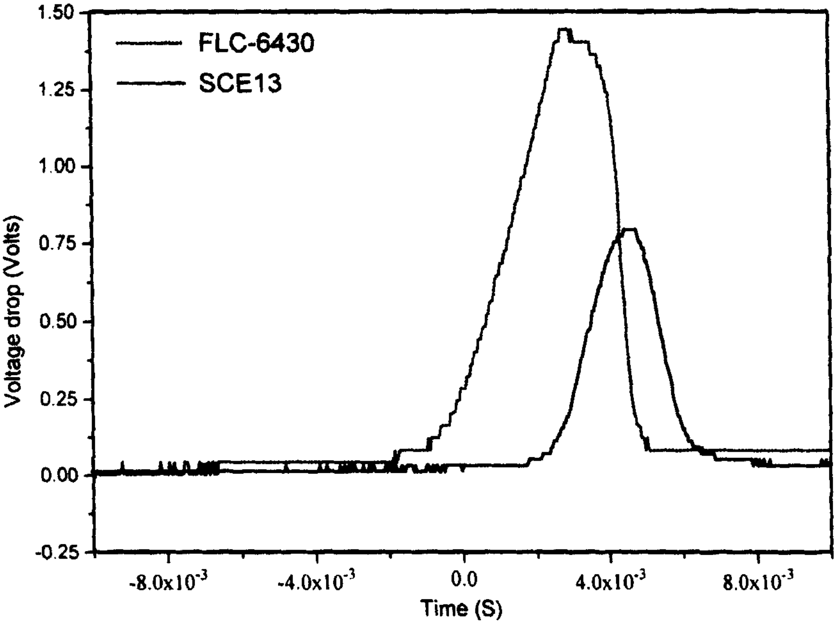


FIGURE 2 Polarisation current response to triangular wave for 5μm cells of FLC-6430 and SCE-13 at 32°C, 20V_{PP} and 20Hz

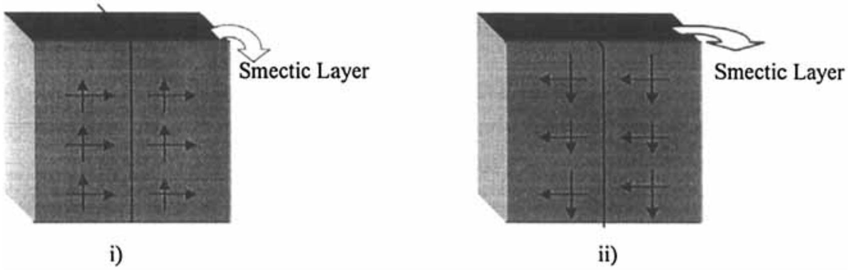


FIGURE 3 (a) Planar view of the molecular reorientation process in SSFLC configuration i) Uniform up UU and ii) Uniform down UD states

As the helix pitch of SCE-13 is more than the cell thickness (surface stabilised state) we expect that it would show surface switching (due to surface pinning effects) in the presence of an external electric field as is reflected in Fig.2. At this stage the molecules which were completely suppressed by the bounding plates may transform from the UU (uniform up) to the UD (uniform down) state with-

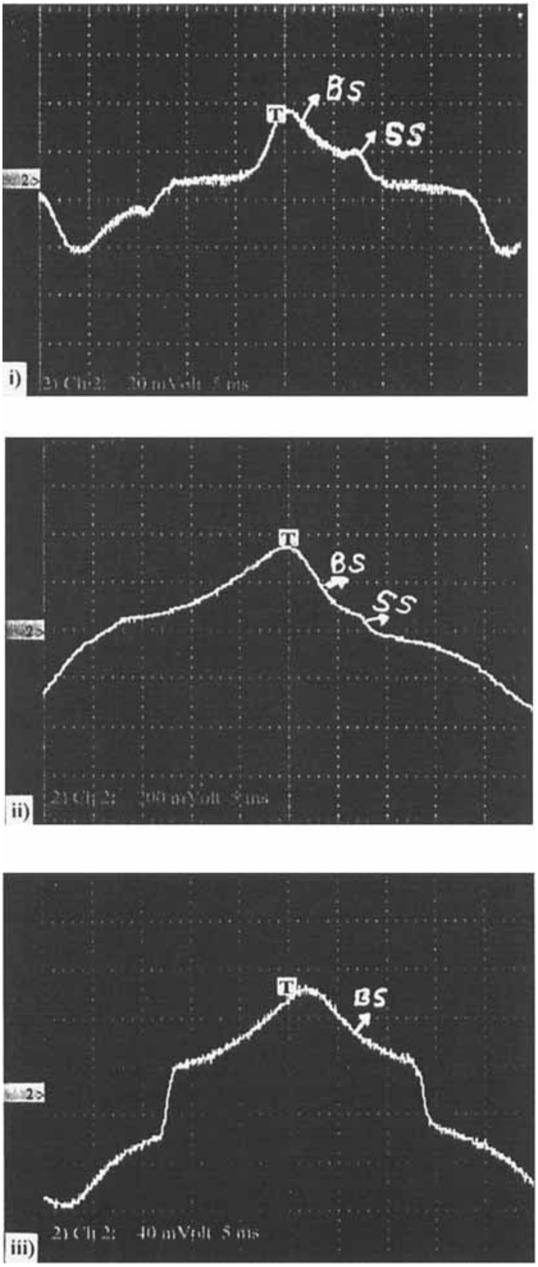


FIGURE 3 **(b)** Oscillograph trace of FLC-6430 sample at 1V/μm, 20Hz and at 32°C for **i)** 2.5μm **ii)** 5μm and **iii)** 7.5μm cells, reflecting Bulk switching (BS) and Surface switching (SS)

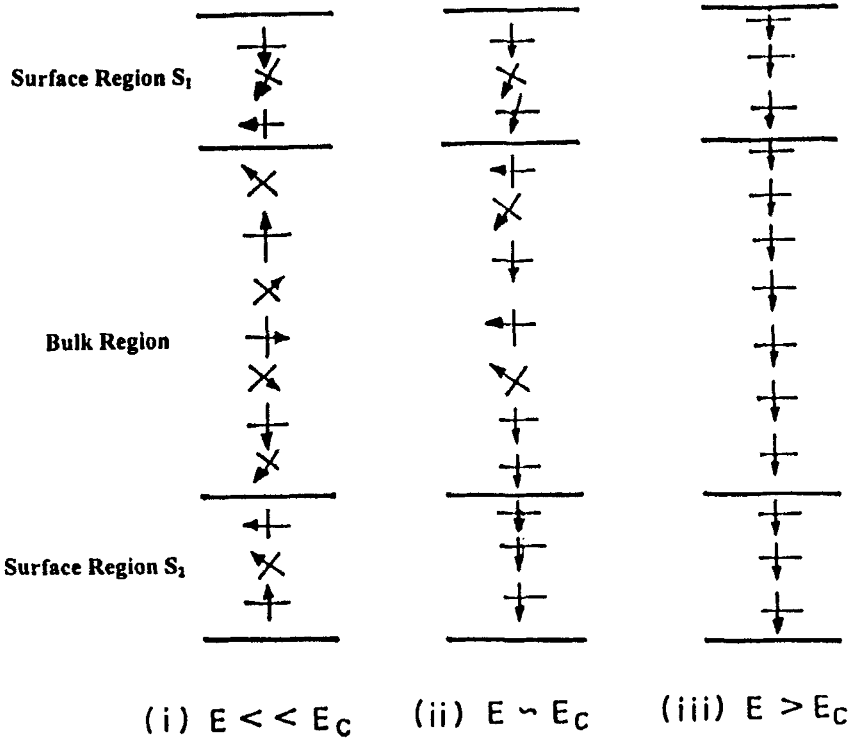


FIGURE 4 Molecular reorientation process in short pitch DHF-FLC cell at $E<E_C$, $E\sim E_C$, and at $E>E_C$

out attaining the 0V relaxed state as shown in Fig.3(a). In the case of FLC-6430 (DHFLC), volume stabilised configuration both bulk and surface switching takes place, which is reflected in the form of two polarisation peaks at a bias voltage less than the threshold voltage as shown in Fig.3b(ii). The first peak is due to the bulk switching and other peak of smaller magnitude is due to the surface switching. Here initially the bulk reorientation and then the surface switching would have taken place due to the elastic couplings, indicating faster switching due to the bulk property as compared to that of the surface effects. The cell thickness dependence of this mechanism is shown in Fig.3b(i,ii,iii), which shows the oscillograph profiles of FLC-6430 mixture confined in 2.5μm, 5μm and 7.5μm cells respectively at 20Hz and 1V/μm. It is seen from the oscillograph profiles that the surface switching in the 2.5μm cell is more dominant due to the strong surface pinning effects whereas 7.5μm cell shows only the bulk switching. The expected switching mechanisms for volume stabilised state is shown schematically in

Fig.4. Here we consider that at low fields ($E<E_C$), the switching appeared due to the helix deformation and at intermediate fields ($E \sim E_C$), the switching was due to the domains of both unwound and the wound states (surface-bulk-surface reorientation). At $E>E_C$, helix unwinds completely and the polarisation peak was mainly due to the bulk reorientation of the molecules. The optical textures at these voltages are shown in Plates 1,2,3 respectively.

The voltage-time oscillograph profile of two FLC-mixtures reveals that the area under the polarisation peak in the SmC* phase decreases with increasing temperature and the amplitude of the polarisation peak decreases sharply near $T_C{}^*{}_A$(inset Fig.5). The calculated values of P_S of the two mixtures as a function of temperature are shown in Fig.5. The spontaneous polarisation P_S obeys the law $P_S= P_o\ (T_C{}^*\text{-}T)^\beta$, Where $\beta = 0.5$ from the mean field model. Near $T_C{}^*{}_A$, higher values of P_S in SCE-13 mixture (SSFLC cell) is due to the combined effects of electro-clinic and induced polarisation. Here the applied voltage is more than the helix-unwinding field.

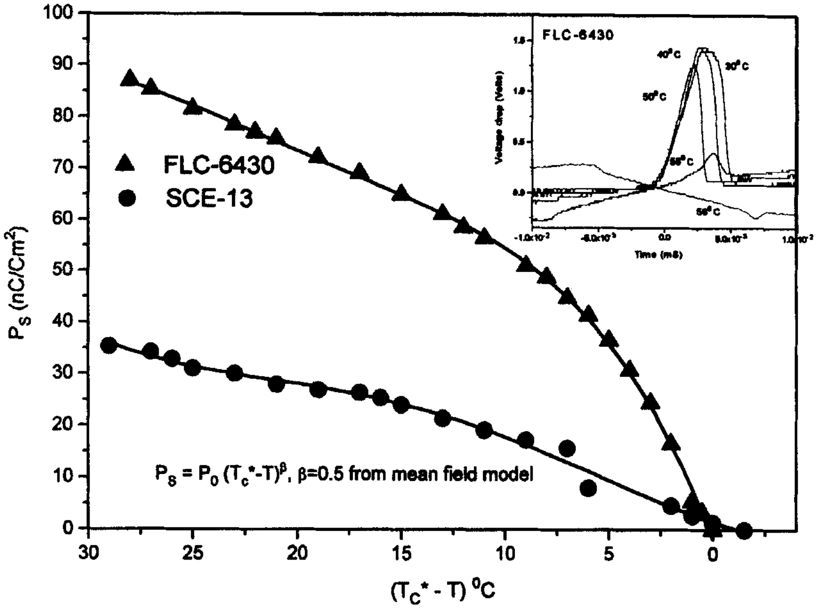


FIGURE 5 Spontaneous polarisation as a function of reduced temperature measured by reversal current technique, Solid line represents the least square polynomial fit

The variation of spontaneous polarisation (calculated by using Eq.3) as a function of applied voltage for both the mixtures is shown in Fig.6. It is interesting to

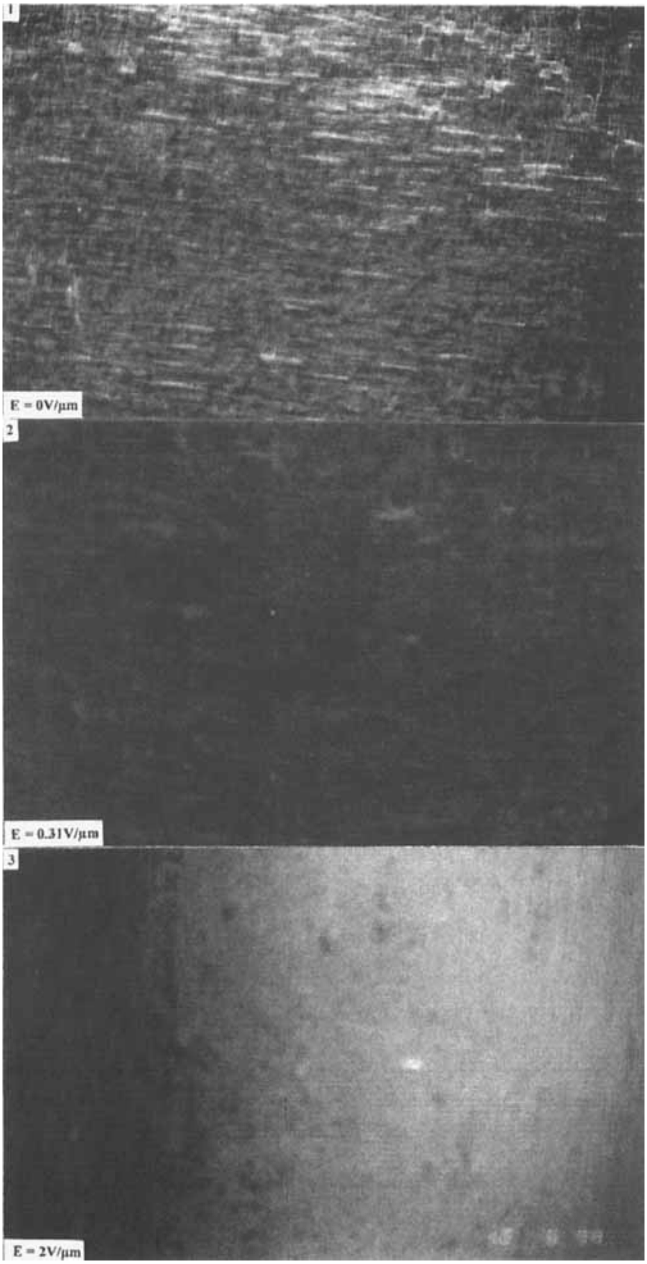


PLATE Microphotographs of FLC-6430 mixture at 31°C in 4μm cell under crossed polarisers at **1)** E=0 **2)** $E \cong E_C$ and **3)** $E>E_C$ at a frequency of 50Hz (See Color Plate XV at the back of this issue) note that in FLC-6430, P_S shows a linear behaviour at low voltage i.e. in the partially deformed helix region. At E~E_C, P_S is maximum and then attains a plateau. A comparison between P_S values of two mixtures reveals that in surface stabilised states E_C is lower than volume stabilised states. It may be due to the strong surface anchoring effects in SCE-13 (SSFLC) whereas in the case of FLC-6430 (DHFLC), the higher values are expected due to both surface and bulk sample cell properties.

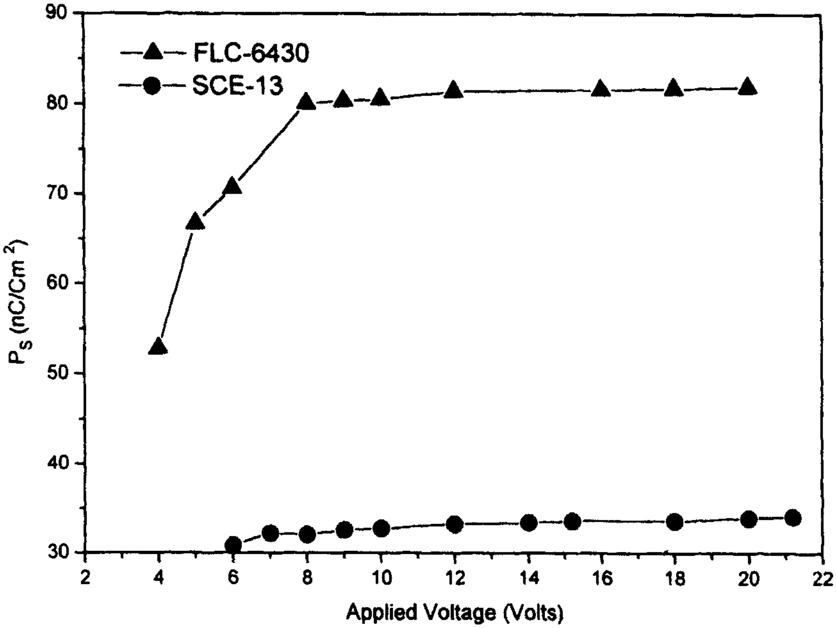


FIGURE 6 Spontaneous polarisation as a function of bias voltage at 30°C, 20Hz

Determination of Response Time and Torsional Viscosity

The response of FLC mixtures to the symmetric square wave also consists of three components I_R, I_C, I_P similar to triangular wave as is shown in Fig.1(b). The method for calculating the P_S is similar to the triangular wave method as discussed in section 3.1. However this technique can also be used to simultaneously measure the response times (τ_R) and the effective torsional viscosity (η) of the ferroelectric liquid crystals. An oscillograph trace of the polarisation peaks, which appears delayed from the time scale under the influence of a symmetric square wave, is shown in Fig.7.

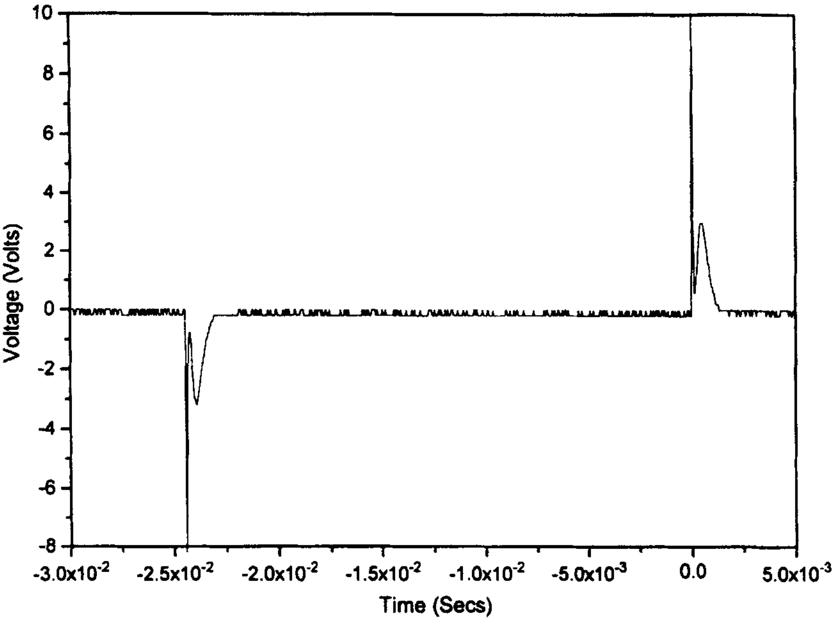


FIGURE 7 Current profile of square wave pulse applied to SCE13 ferroelectric LC mixture at 32°C, $20V_{PP}$, 20Hz

The delayed switching between the two stable states is a measure of the response time written in the form [22]:

$$\tau_R = \frac{\eta}{\mathrm{P.E}} \tag{4}$$

where η is the torsional viscosity of the material which arises from friction due to the rotation of director around the layer normal.

Using this method, the response time of two FLC mixtures has been calculated and plotted as a function of temperature shown in Fig.8(a). The response time in both the mixtures varies linearly but a marked divergence is noticed in FLC-6430 above $\Delta T \approx 17°C$. It is seen that SCE-13 shows slower responses than FLC-6430 although the former is surface stabilised. FLC-6430 has a short pitch and shows faster switching in the volume stabilised state. It is perhaps an indication of the dominance of polarisation due to bulk switching over the surface switching.

Fig.8(b) shows typical response time characteristics of both the mixtures as a function of applied voltage. The torsional viscosity of the mixtures as a function of temperature and bias voltage has been evaluated and is shown in Fig.9(a,b). It

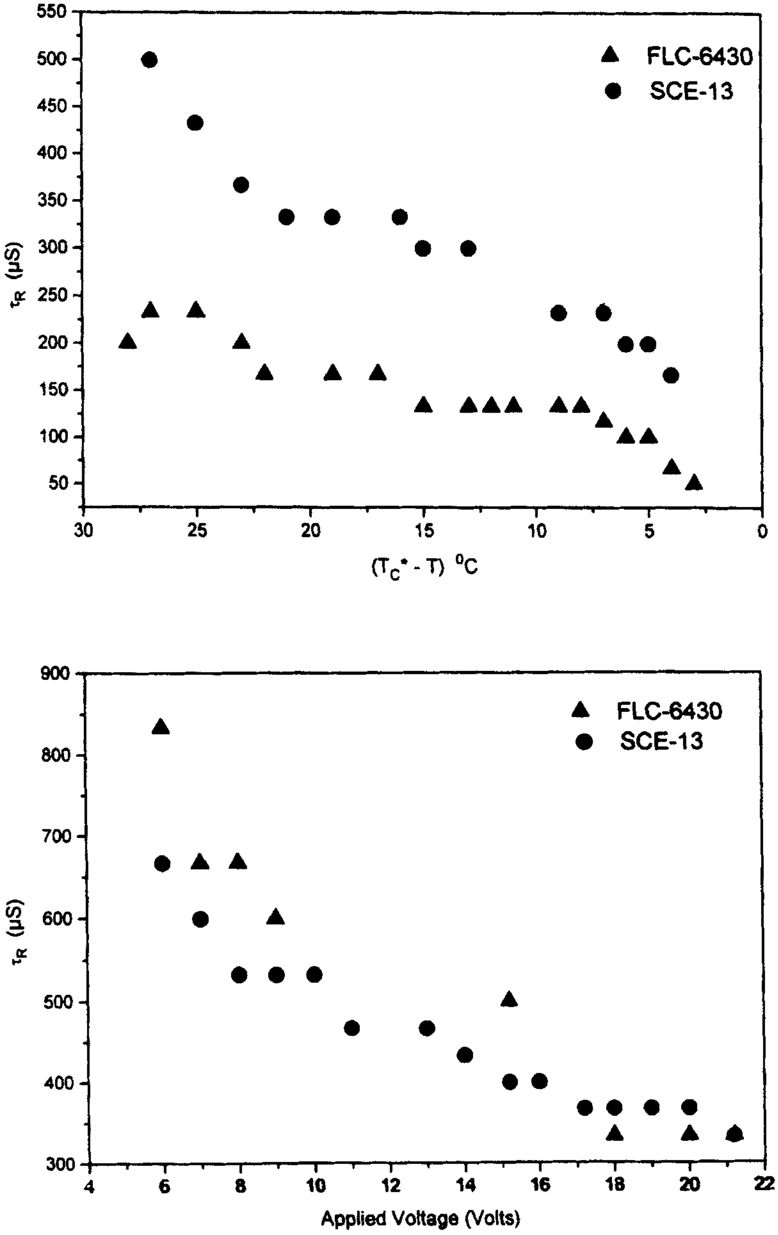


FIGURE 8 Response time (τ_r) of two FLC mixtures at 32°C, $20V_{PP}$ and 20Hz as a function of **a)** reduced temperature **b)** applied voltage

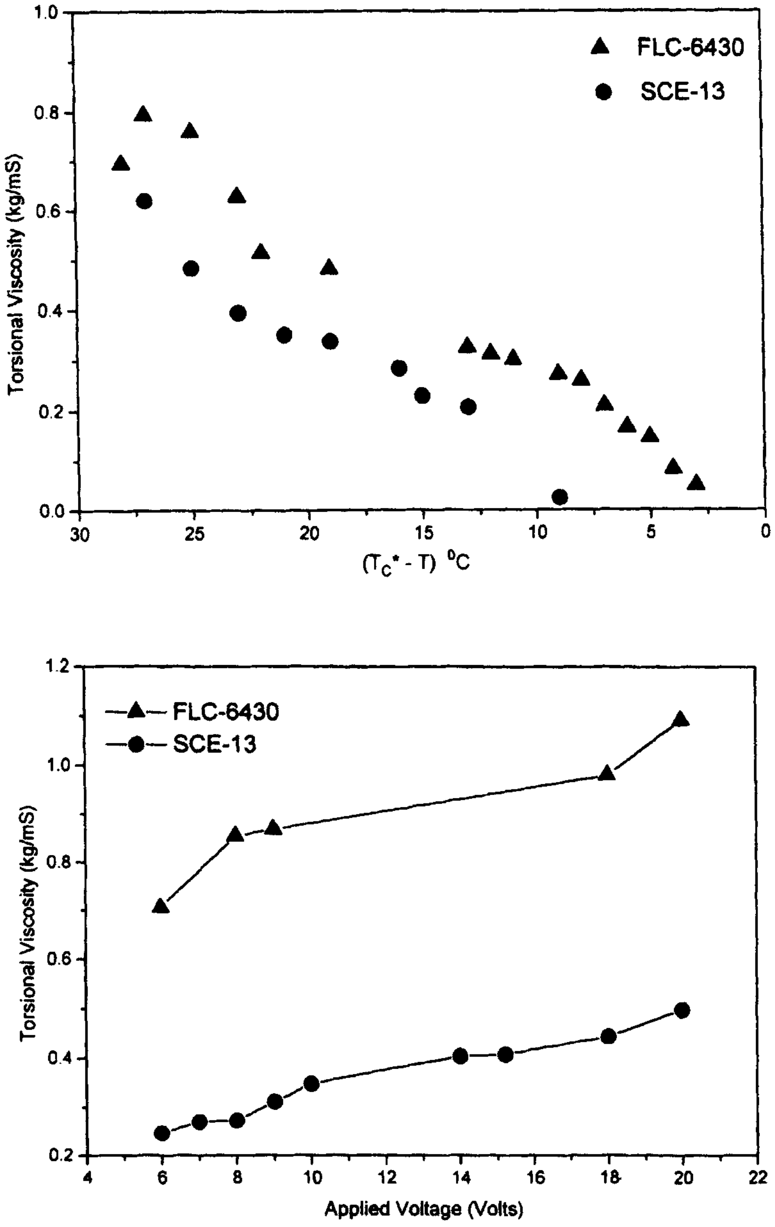


FIGURE 9 Torsional viscosity of two FLC mixtures as a function of **a)** reduced temperature **b)** applied voltage

is seen that the torsional viscosity strongly depends upon both the temperature and the applied voltage.

IV. CONCLUSIONS

- Helix dynamics and electro-optic switching has been studied in two FLC mixtures in different stable configurations (Surface stabilised and volume stabilised) using current reversal technique.
- Cells in SSFLC state shows only surface switching while in DHFLC configuration both bulk and surface switching has been observed. Here initially bulk switching and then the surface switching takes place due to the elastic couplings.
- The higher P_S values near $T_{C}{}^{*}{}_{A}$ in SSFLC cells is expected to be due to the combined contributions of electro-clinic effect and the induced polarisation.

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