Switching responses of ferroelectric liquid crystals

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The switching time of the FLC material has been calculated by using dielectric and electro-optic techniques. The electro-optic measurements have been carried out by direct pulse technique using different resistances and capacitors. The results obtained from these methods are compared. It is observed that measurement of response time using capacitor gives more reliable results as compared to those given by resistor method in the direct pulse technique.

Keywords: Liquid crystal, Ferroelectric liquid crystal, Switching

1 Introduction

Ferroelectric liquid crystals (FLC), especially chiral smectic C (smC*) gained considerable interest soon after their discovery by Meyer et al.1, in 1974. They represent a spatially modulated structure characterized by the tilt of the long molecular axis that precesses helicoidally from one smectic layer to another. This helicoidal arrangement is very sensitive to external forces like, electric field (resulting in a response time of the order of micro or sub-micro seconds), temperature, pressure, etc. The electro-optical effects of FLCs have attracted substantial interest for their use in the fast switching devices. These materials can be successfully used in image converters, alphanumeric data displays and flat television screens, etc. The use of these materials in various displays depends on their physical parameters like response time (τ), spontaneous polarization (P_s), tilt angle (θ) and rotational viscosity (γφ) etc.

Different methods have been reported for the measurement of these parameters. These methods involve pyroelectric technique, Sawyer-Tower method2, field reversal method and dielectric method. Out of these, field reversal method, using square waves, is most widely used for the measurement of response time3-6. The dynamics of helix winding and unwinding have been successfully studied by using this technique. The response time is found to be inversely proportional to field showing the validity of domain theorem7-8. Dielectric relaxation method can also be used to measure the response time9-10.

In this paper, a precise method is reported, for the measurement of response time of a FLC mixture. The results have been compared with other techniques and theories.

2 Experimental Details

The material used in the present investigation was FLC-6304 (obtained from Hoffman La Roche). At 20 °C, it has large spontaneous polarization (110 nC/cm²) and tilt angle (27 deg). Its phase sequence and transition temperatures are11

\[ \begin{align*}
-20^\circ C & \rightarrow \text{SmC}^* & 59^\circ C & \rightarrow \text{SmA} & 64^\circ C & \rightarrow I \\
\end{align*} \]

The cells of thickness 7.5 μm and 25 μm were used in the investigation. These were prepared using m-cresol on indium tin oxide (ITO) coated glass substrates rubbed unidirectionally to obtain planar alignment. The material was then filled in these cells by capillary action at or above the isotropic temperature. A well-aligned texture was obtained by cooling down the sample to room temperature @ 0.1 °C/min, using Linkam programmable temperature controller cum hot stage (Model TP94 & THMS600). The micro-textures of the samples were visualized through the Olympus polarizing microscope (Model BX51P) interfaced with computer. Fig. 1 shows the

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A square wave voltage – 10 V – 0 V - + 10 V was applied to the FLC cell through Scientech function generator (Model ST4060). The current flowing through the cell was integrated by the capacitor/resistor connected in series with the sample cell. The output voltage was obtained on a Tektronix digitizing storage oscilloscope (Model TDS210) interfaced with computer for further data acquisition. Standard resistors in the range from 2kΩ to 1MΩ, and standard capacitors in the range from 10 nF to 100 nF, were used for the measurements. Dielectric measurements were performed in the frequency range from 100 Hz to 1 MHz using Fluke multi-frequency RCL meter (Model PM306).

A schematic diagram used for measuring the physical parameters of the liquid crystals with the field reversal technique is shown in Fig. 2. The field reversal technique is further classified on the basis of the shape of the waveform. While the triangular wave method is widespread due to its simplicity, the square wave method provides more rigorous measurements.

It can also be divided depending on whether the voltage is taken across a capacitor or resistor. Since the triangular wave method gives only the measurement of polarization, the square wave method has been used in the present investigation for the measurement of response time.

3 Theoretical Considerations

3.1 Dielectric measurement of \( \tau \)

The relationship between response time (\( \tau \)) and dielectric parameters of the ferroelectric liquid crystals (FLC) is obtained. In FLC, the goldstone mode (GM) obeys the molecular dynamics of helix winding and unwinding. The equation of motion of smC* helix in an ac field is given by

\[
\gamma_e \frac{d\phi}{dt} = K \frac{\partial^2 \theta}{\partial x^2} - P_s E(t) \sin(\phi) \quad \ldots \quad (1)
\]

where \( \phi \) is the azimuthal angle and \( \gamma \) is the rotational viscosity with respect to the rotations about smectic layer normal, which defines z-direction. \( K \) is the mean elastic constant, \( P_s \) the magnitude of spontaneous polarization of smC* phase and \( E \) the amplitude of applied electric field.

It is known that the collective molecular motion in smC* phase with constant tilt angle gives rise to goldstone mode (GM). The relation between the dielectric parameters of GM and response time is given by\(^9-10\):

\[
\tau = \frac{\tau_G P_s}{2\varepsilon_0 \Delta\varepsilon_G E} \quad \ldots \quad (2)
\]
where $\Delta \varepsilon_G$ and $\tau_G$ are dielectric strength and relaxation time of GM, respectively. The main feature of this equation is that $\tau$ depends only on dielectric parameters and can be measured by dielectric technique. The dielectric strength and relaxation frequency of the liquid crystal is obtained by using Cole-Cole plots between real and imaginary part of permittivity.$^{12-13}$

3.2 Electro-optic method

(a) Using Capacitor: For planar geometry, the equation for director motion is given by Eq. (1). Panarin et al. and V Panov et al.$^{14-15}$ have shown that by neglecting the contribution from the moment of inertia and surface interactions and assuming simultaneous conical rotation of molecules in smectic layers with cone apex $2\theta$, the solution to the above equation can be obtained. It follows that the polarization part of the voltage ($V_p$) across the capacitor is a function of $\phi(t)$. For $\alpha = 0$ (where $\alpha = \varepsilon_o \Delta \varepsilon E \sin^2 \theta / P_S$) and small $\phi_0$ [$\phi(t = 0)$], a simple expression for $V_p$ is given by

$$V_p(t) = \frac{AP_S}{C} \left[ \frac{2 \exp \left( \frac{t - t_0}{\tau} \right)}{\exp 2 \left( \frac{t - t_0}{\tau} \right) + 1} \right] \quad \ldots (3)$$

$$t_0 = \tau \left[ \frac{1}{\tan \phi_0} \right] \quad \ldots (4)$$

where $t_0$ is the switching delay $t_{0-50\%}$ in the present experiment. Using Eqs (3) and (4) one can calculate the value of $P_S$ and $\phi_0$. The response time $\tau$ is unambiguously connected with the rise time $t_{0.1-0.9}$, where $0.1$ and $0.9$ are the lower and upper threshold [Fig. 3(a)] used for the rise time measurement, respectively.

$$t_{0.1-0.9} = \tau \left[ \frac{1 - \delta}{\delta} \right] \quad \ldots (5)$$

These equations are valid$^{15}$ for $\alpha$ varying from 0 to +0.9.

The polarization part of the voltage ($V_p$) can be measured from the output waveform obtained after integration of the input signal with the capacitor. The shape of the waveform thus obtained and the
oscilloscope trace of the sample is shown in Figs 3(a, b), respectively. The instantaneous value of the output voltage \( V_0 \) over external capacitor \( C \) after integration can be written as\(^{14-15} \)

\[
V_0 = \frac{1}{C} \int_0^t dt = \frac{V_{IN}}{RC} t + \frac{2V_{IN}C^*}{C} + \frac{PSA}{C} \cos(\phi(t)) \bigg|_0^t = V_R + V_C + V_P
\]

where \( t = 0 \) represents the instant of reversing the sign of voltage. \( R \) is the resistance of the cell, \( C^* = (\varepsilon_0 \varepsilon_r A)/d \) the capacitance of the cell, \( V_{IN} \) the input voltage, \( \varepsilon_0 \) permittivity of air and \( \varepsilon_r \) permittivity of LC cell. \( A \) and \( d \) are the area and thickness of the cell, respectively. The output voltage is a sum of three components contributing to resistive part \( (V_R) \), recharging of cell capacitance \( (V_C) \) and voltage across \( C \) due to depolarization current in the cell \( (V_P) \). The response time of the material can be measured by neglecting the contribution from the resistive and capacitive part.

(b) Using Resistance: This method has been widely used for the measurement of response time in ferroelectric liquid crystals and it is assumed that the resulting waveform constitute of resistance, capacitance and the polarization part. The instantaneous value of the current over resistor can be presented as a sum of three contributions\(^{4-5} \)

\[
I = I_I + I_C + I_P = \frac{V}{R} + C^* \frac{dV}{dt} + \frac{dP}{dt} \quad \ldots \quad (7)
\]

The current induced in this case due to applied voltage is due to (i) ionic contribution, (ii) charge accumulation on the capacitor and (iii) polarization realignment represents the charge induced by the polarization reversal in the bulk and at the surface on application of electric field.

The polarization peak appears far away on the time scale from the square pulse edge of the applied phase as shown in Fig. 4. The delay in time corresponds to the response time of switching. Incidentally this representation of response time coincides with the electro-optical switching\(^{4-7} \). However, contribution from the resistive part cannot be removed, but it is assumed that the contribution of this part is negligible. The shape of the waveform and the oscilloscope trace are shown in Fig 4(a, b), respectively. The measure of response time is also represented in this figure [Fig. 4(a)]. The oscilloscope trace for FLC-6304 is given in Fig. 4(b).

4 Results and Discussion

The response time measurements have been carried out using standard resistors and capacitors in the current reversal technique. The impedance of these electrical elements was smaller than that of the liquid crystals cell. The variation of response time \( (\tau) \) as a function of resistance and capacitance for 7.5 \( \mu \)m and 25 \( \mu \)m thick samples is shown in Fig 5(a, b), respectively. It is interesting to note that the change in capacitance [Fig. 5(b)] has negligible effect on response time, whereas it increases with increase in resistance [Fig 5(a)]. The response time also depends

![Fig. 4](image_url) — (a) Shape (b) oscilloscope trace of the output waveform by the resistor method
on sample thickness. This change is steep in 25 \( \mu \text{m} \) cell in comparison to the 7.5 \( \mu \text{m} \) cell beyond 20 k\( \Omega \). The response time is found to be almost constant at lower resistances (< 20-2 k\( \Omega \)), in both cases. Although more precise measurements can be made at even lower resistances, it was difficult to obtain output waveform below 2 k\( \Omega \). Response time was determined precisely by extrapolating the curve obtained in Fig. 5(a). The value thus obtained was approximately the same as in the case of dielectric and capacitor methods (~200 \( \mu \text{s} \), at room temperature).

A typical plot of frequency dependence of the response time at different resistances is shown in Fig. 6. It is observed that increase in frequency has almost negligible effect on \( \tau \) until the time period of applied square pulse is greater than the response time of the ferroelectric liquid crystal. So, for resistances of say 1 M\( \Omega \), one can use higher working frequency (i.e. > 20 Hz, used generally), depending upon the response time of the liquid crystal material. It is expected that the range could be still widened at the lower resistances. This is because \( \tau \) is directly proportional to the external resistance used and thus decreases with resistance.

It is also observed that while using the capacitor in the circuit, one can use higher frequency as compared to resistance method. It can be explained with the help of relation between time constant of the circuit \( R_C C \) and time period of the input signal \( T \).

For resistance method (RM), we get desired shape of the output waveform, when

\[
R_C C_C << T \quad \text{... (8)}
\]

whereas, for capacitor method (CM), one can get output signal, when

\[
R_C C_C >> T \quad \text{... (9)}
\]
These relations suggest that for CM, the peak will be observed at higher frequencies and the maximum frequency that can be used for the measurement is relatively low in case of RM.

The temperature dependence of the response time $\tau$ for FLC-6304 in 7.5 $\mu$m sample using dielectric and electro-optic methods is shown in Fig. 7. It shows an Arrhenius behaviour of the response time dependence on temperature, near the SmC* to SmA transition, for a FLC material. The minimum value of $\tau$ (182 $\mu$s, at room temperature) is obtained by using dielectric method (DM). It may be due to the minimum losses in case of this method, as $\tau$ is measured from the dielectric strength and relaxation frequency of the materials. The authors did not consider the effect of stray capacitance. However the losses are maximum in case of resistance and increases with increase in resistances, resulting in a larger response time. Nearly the same value of $\tau$ is obtained, as given by LC material using dielectric method, if output is taken across a capacitor. This may be because of the fact that in the capacitor the losses are negligible as compared to resistance. So, $\tau$ obtained by using capacitor in the circuit is more close to that obtained by dielectric method.

The reason for the changing value of response time may also be explained with the help of following relations. The output voltage across the resistor is given by

$$V_O = \frac{1}{C} \int_0^t \frac{V_i}{R_C} dt$$

$$V_O = \frac{1}{C} \int_0^t i_C dt$$

The above equation signifies that if $R_C$ is large, current $i$ in the circuit become small, so the charging of the capacitor to a required voltage takes longer time. It may also be explained on the basis of the relation

$$Q = C_V \left( V_O - e^{-\frac{t}{R_CC_V}} \right)$$

where $Q$ is the charge induced in the circuit on application of field. This equation represents that for large resistance the time constant increases and hence the charging of the capacitor will be delayed resulting in the increase of $\tau$. This may be the reason for the changing value of response time using resistance.

In case the response time is measured using the external capacitor, the input current is same for both the capacitors and it is decided by the resultant capacitance of the circuit. As the capacitors are connected in series the resultant capacitance will always be close to the smaller one, the LC cell. It is also confirmed by the experimental results, which show that the results of dielectric and capacitor method are more comparable as compared to the resistance method.

So one can say that in case of electro-optic methods the switching time measurements using capacitor gives more reliable and accurate determination of response time.

5 Conclusions

Response time measurements had been performed using three different methods, viz. dielectric, capacitor and resistor. In dielectric measurement, $\tau$ was taken directly from the internal parameters of the cell, whereas in electro-optic method the output was taken across the capacitor or resistor. It is observed that the value obtained by capacitor method is more close to the one obtained from dielectric method.

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References
10 Hsiue Ging Ho, Lee Rong Ho and Jeng Ru Jong, Polymer, 38 (1997) 887-895.
11 Data Sheet from Hoffman La Roche, Switzerland.