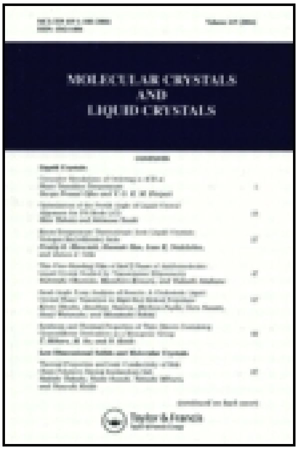

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C-V Hysteresis Observed in a Splay-Bend Transition: a Novel Method for the Evaluation of a Transition Speed

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The director distributions in thin nematic slabs with parallel structure have been calculated as a function of the applied electric field. They are different from the cells with the anti-parallel structure, in that three solutions exist in a specified voltage range which predict a transition of the director deformation from splay to bend configurations in the parallel structure. This splay-bend transition has been confirmed experimentally by a capacitance-voltage (C-V) hysteresis method. The C-V characteristics showed a hysteresis around the deformation transition and this magnitude corresponded to the facility of a splay-bend transition: a comparison of these hysteresis characteristics for different materials enables us to evaluate the splay-bend transition speed easily.

Keywords: liquid crystal; continuum theory; parallel structure; C-V hysteresis; bend transition

INTRODUCTION

There has been considerable interest in the director distribution of a nematic liquid crystal (LC) slab both in the bulk and at surfaces.

in both basic science and technology[1]. So far, the strong anchoring condition, in which the director near the surface adopts a fixed orientation, has been adopted to understand the director distribution in the bulk of a LC slab. But, recently, it has come to be recognized that the surface of practical liquid crystal devices (LCDs) show the weak anchoring condition where the surface forces are not strong enough to impose a well-defined director orientation at the surface[2].

In LCDs, especially in LCDs with phase compensators, the display performance is largely influenced by the control of LC director distributions. The investigation and clarification of the orientation mechanism at surfaces is practically meaningful.

Optically self-compensated birefringence (OCB) mode where a display is performed in a bend configuration has been drawing attention as a mode where wide viewing angle is compatible with quick response. The problems to be solved in this mode are divided into the development of retardation films and the initialization of the LC configuration.

Several routes are proposed for the splay-bend transition in which the transition rate is influenced by the LC configurations through which the transition passes[3]. Generally, it takes more than several ten seconds for the transition to be completed in whole the pixels following the application of 1V/μm electric field strength.

Hence, in order to initialize a LC configuration, it is necessarily to apply a voltage of about 4V/μm to the cell to cause the splay-bend transition forcibly. However, to do this, a new driving circuit is needed to replace the conventional LCD circuit. This needs improved LC materials which show quick splay-bend transition with the application of several voltages.

Conventionally, the time required for the transition from the splay configuration to the bend configuration in the entire electrode area is measured by visual observation. However. this method is not suited for an automatic measurement and its reproducibility is poor.

In this study. we calculate the change of the LC director distributions in a homogeneously aligned parallel cell with an applied electric field. We then confirm experimentally the predicted hysteresis of the C-V characteristics. We also investigate the relationship between the magnitude of this C-V hysteresis and the splay-bend transition speed.

CALCULATIONS

Total free energy F in a nematic LC slab that are put with two substrates is given as follows .

$$F = \int g_d dz + \int g_e dz + \int g_s^- ds^- + \int g_s^+ ds^+ . \quad (1)$$

where the integral is over the Z coordinate (corresponding to the direction normal to the glass plate). Here, terms of g_d, g_e and g_s are associated with elastic distortions, interaction with an electric field and surface anchoring, respectively. g_s^+ and g_s^- show the surface energy density on the surfaces of the upper substrate and the lower substrate, respectively.
The free energy due to the electric field is of the form

$$g_e = -\varepsilon_0 \Delta\tilde{\varepsilon}(\vec{E} \cdot \vec{n})^2/2 . \quad (2)$$

The application of a voltage across the LC slab results in an electric displacement $\vec{D}$,

$$D_\alpha = \varepsilon_0 \tilde{\varepsilon_\perp} E_\alpha + \varepsilon_0(\tilde{\varepsilon_\parallel} - \tilde{\varepsilon_\perp}) n_\alpha n_\beta E_\beta . \quad (3)$$

where ε_0 is the permittivity of free space and $\tilde{\varepsilon_\parallel}$ and $\tilde{\varepsilon_\perp}$ are the principal values of the bulk dielectric susceptibility tensor, parallel and normal to the director. Assuming that $\vec{D}$ and $\vec{E}$ vary only in the Z direction, and neglecting the effects of space charge, $\nabla \cdot \vec{D}=0$ implies that D_z is a constant across the bulk. D_z can be found from Eq.(3) as

$$D_z = [\varepsilon_0 \tilde{\varepsilon_\perp} + \varepsilon_0 \tilde{\varepsilon} \sin^2\theta(z)] E_z(z) . \quad (4)$$

The surface anchoring energy, g_s, may be expressed as [1]

$$g_s = -(A/2)(\vec{n} \cdot \vec{e})^2 . \quad (5)$$

Here A is a surface anchoring strength and $\vec{e}$ and $\vec{n}$ are the easy direction and the orientation of the director at the nematic-wall interface.

We consider simply a nematic LC cell located between the two planes $z = 0$ and $z = \lambda$ with a symmetry with respect to the middle plane $z = \lambda/2$ as shown in Figure 1.

In Figure 1, the tilt angle between the LC director n in the bulk and the substrate is expressed by $\theta(z)$, while at the surface the value of the tilt angle of the director with respect to the substrate is θ° and the tilt angle of the easy axis e is θ_o. A^- and A^+ are the surface anchoring strength at $z = 0$ and $z = \lambda$, respectively. The suffixes $-$ and $+$ denote the plane $z = 0$ and the plane $z = \lambda$, respectively. The electric field E shall be applied in the direction of the Z axis.

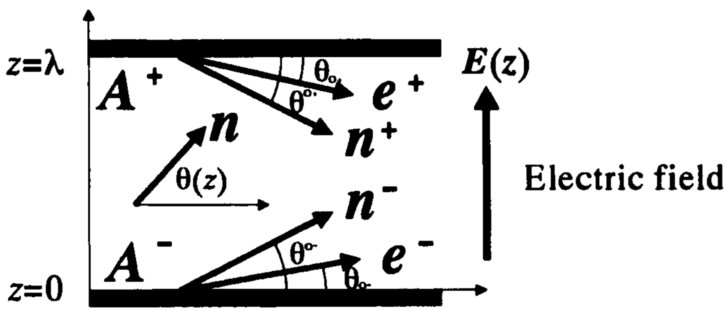

FIGURE 1 The geometry of the coodinate system of the homogeneous liquid crystal cell with a parallel structure

For simplicity, the one constant approximation ($k=k_{11}= k_{22}=k_{33}$, where k_{11}, k_{22} and k_{33} are the splay, twist, and bend elastic constants of the nematic LC, respectively) is used. As is shown in Figure 1, the director $\vec{n}$ and electric field $\vec{E}$ are written as

$$\vec{n} = (\cos\theta(z), 0, \sin(\theta(z))) . \tag{6}$$

$$\vec{E} = (0, 0, E(z)) . \tag{7}$$

The normal Euler-Lagrange approach to minimize the total free energy, including the unified surface anchoring energy, leads to the basic equations from which to calculate the director distribution $\theta(z)$ [see Eqs. (18), (19), (22), and (23) in Ref. 1].

In a homogeneous cell, the torque balance equations in the bulk and at the top and bottom substrates surface are expressed as

$$f(\theta)\frac{d^2\theta}{dz^2}+\frac{1}{2}\frac{df(\theta)}{d\theta}\left(\frac{d\theta}{dz}\right)^2+\frac{\varepsilon_0\Delta\varepsilon}{2}E^2(z)\sin 2\theta=0\,, \tag{8}$$

$$f(\theta)\frac{d\theta}{dz}\Big|_{z=0}=\frac{A^-}{2}\sin 2(\theta^{o-}-\theta_{o-})\,, \tag{9}$$

$$f(\theta)\frac{d\theta}{dz}\Big|_{z=\lambda}=-\frac{A^+}{2}\sin 2(\theta^{o+}-\theta_{o+})\,. \tag{10}$$

In our calculations, the perturbation of the electric field is given as follows,

$$\frac{d}{dz}\left[\varepsilon_0\varepsilon_\perp+\varepsilon_0\Delta\varepsilon\sin^2\theta(z)\right]E(z)=0\,,$$

$$V=\int_0^\lambda E(z)dz\,,$$

where ε_o, $\varepsilon_\perp$ and $\Delta\varepsilon$ are the dielectric constant in vacuum, the dielectric constant in the normal direction to the LC director and the dielectric anisotropy. We then calculate the changes of the LC director distribution with the applied electric field in the condition of $\theta(0)=\theta^\circ$, $\theta(\lambda)=-\theta^\circ$ and $\theta(0)=\theta^\circ$, $\theta(\lambda)=\theta^\circ$ for a parallel cell and an anti-parallel cell, respectively.

Figure 2 and Figure 3 show the calculated results using the following values for the LC materials; k_{11}=6.605pN, k_{33}=7.813pN, $\varepsilon_\perp=7.08$, $\Delta\varepsilon$=10.63, where $\theta_o=6^\circ$, $\lambda=6.0\mu$m, and $A^-=A^+=5\times10^{-4}$J/m^2.

In the case of an anti-parallel cell (Figure 2), the LC director distribution changes continuously with the external applied voltage as is well known and no deformation transition has been observed. The director distribution is symmetrical with respect to the center plane $z=\lambda/2$.

On the other hand, in the case of a parallel cell, three director distributions are obtained in a specific applied voltage range. That is, a transition from splay to bend deformation appears as the applied voltage is increased. Four line types in Figure 3 show different director deformations for various applied voltages.

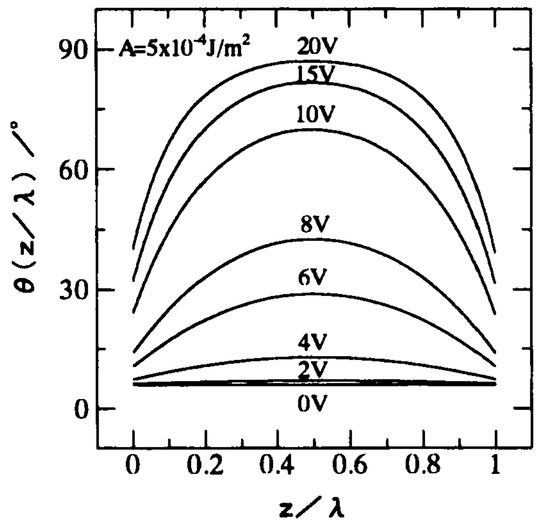

FIGURE 2 The changes of the LC director distributions in the anti-parallel cell with the external applied voltage

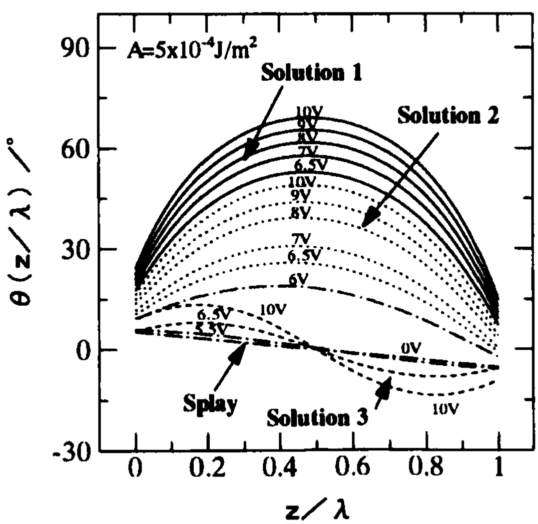

FIGURE 3 The changes of the LC director distributions in the parallel cell with the external applied voltage

Director distributions in solution 1 and solution 2 show bend configurations and those in solution 3 show deformed splay configurations. This means that a parallel cell has a possibility to have two bend configurations with the same applied voltage. Here, the director distribution is not symmetrical with respect to the center plane $z = \lambda/2$.

Figure 4 shows the calculated voltage dependence of the tilt angle of the LC director on the bottom substrate surface $\theta^{\circ-}$. This figure would suggest that in the OCB cells with the parallel structure, a splay-bend transition will take place and the hysteresis characteristics of C-V curve will appear on increasing the voltage.

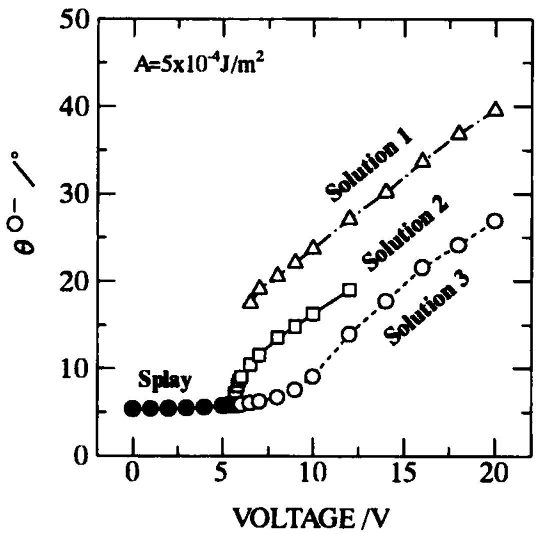

FIGURE 4 Voltage dependence of the tilt angle of the LC director on the bottom substrate surface $\theta^{\circ-}$

EXPERIMENTAL

Materials

Table 1 shows the physical properties of LC materials used in this experiment. SE-7992 and SE-7492 supplied by Nissan Chemical Industries, Ltd. were used as a polyimide (PI) alignment layer.

TABLE 1 Physical properties LC materials used

LC materials	thickness λ [μm]	T_C [°C]	$\varepsilon_{\parallel}$ [-]	$\Delta\varepsilon$ [-]	Δn [-]	k_{11} [pN]	k_{22} [pN]	k_{33} [pN]
LC-1	5.2	81.0	14.0	9.8	0.160	12.4	5.90	15.5
LC-2	5.4	77.8	13.0	9.1	0.130	6.60	5.30	12.5
LC-3	5.7	80.9	16.5	12.4	0.130	6.35	5.70	14.1
LC-4	5.3	97.0	13.0	9.2	0.129	12.0	6.85	13.6
LC-5	5.3	80.0	12.7	8.3	0.160	10.2	5.00	12.0
LC-6	5.7	81.0	14.1	9.7	0.158	13.3	7.62	14.7

Cell Preparation

Cells were prepared by assembling pairs of substrates with parallel rubbing direction (as in Figure 1). The PI film was deposited on the substrate from a dilute polymer solution by the spinning method and was then baked at 180°C for an hour. The thickness of PI film was measured by the alphastep^R(TENCOR INSTRUMENT) and found to be about 80nm. The area of the electrode was 2cm^2 and the LC layer thickness λ was set in the range of 5.2 to 5.7μm by using plastic beads. The thickness was measured by using the LCD thickness meter TM-230N(Canon Sales Co., Inc.).

Measurement of Cell Capacitance

The capacitance measurement was carried out with HP-4284A Precision LCR meter. Timing chart of the applied voltage is shown in Figure 5 where the applied voltage is raised step by step in a cell in which the LC configuration is initially splayed. The frequency of the signal is 1kHz.

The applied voltage was raised step by step at the rate of 0.1V/10 minutes in a region where the LC director distribution changes largely from the splay configuration to the bend configuration. Typical change of the capacitance of the cell is also plotted in Figure 5 as an example.

After achieving the bend configuration, the voltage is lowered at the same rate as in Figure 5. However, prior to lowering the voltage, it is maintained for several minutes at 20V to cause the splay-bend transition forcibly.

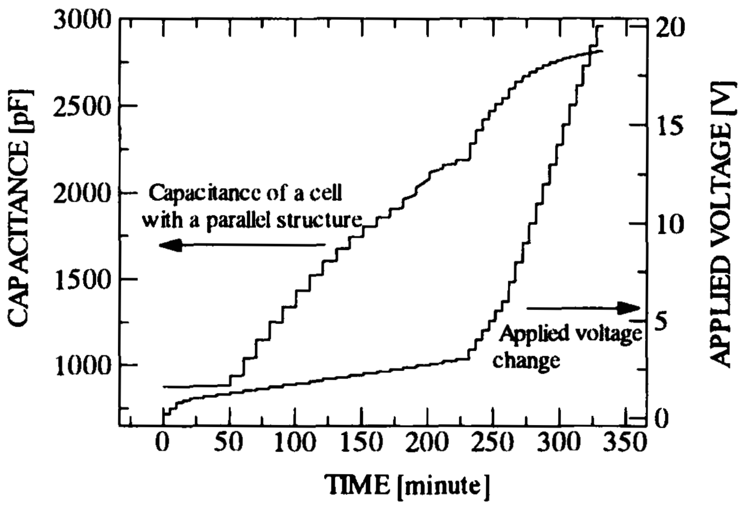

FIGURE 5 Timing chart of an applied voltage and the cell capacitance change with time in a capacitance-voltage measurement

Evaluation of the Splay-Bend Transition Speed

When we evaluate a splay-bend transition speed by visual observation, we define a ratio, r, of the bend-transferred area to the entire electrode area after the application of 10V to a LC cell for 10 seconds as the index of the bend transition speed.

RESULTS AND DISCUSSION

Figure 6a and Figure 6b show capacitance changes with time of a parallel cell filled with LC-6 after the application of specified voltages. Figure 7a shows a C-V hysteresis characteristics of the parallel cell capacitance (average capacitance during a period of 595-600 seconds after the voltage application) with applied voltage when it is raised (closed circle) and lowerd (open circle). On the other hand, an anti-parallel cell shows no C-V hysteresis characteristics as seen in Figure 7b.

These measured C-V characteristics shows good agreement with the calculated result. The capacitance change corresponds to a change of the LC director distribution and the deformation transition in a cell with a parallel structure predicted from the calculation has been confirmed experimentally.

Comparing C-V characteristics in Figure 7a with that in Figure 7b, it is pointed out clearly that hysteresis exists between two bend configurations in a parallel cell corresponding to solution 1 and solution 2. Also in a lower voltage region, although the capacitance of the antiparallel cell increases gradually, that of the parallel cell does not change very much. This phenomena agrees with the computer simulation result that, in a lower voltage region, the director distribution in a parallel cell does not change very much compared with an anti-parallel cell.

Although capacitance usually reaches a constant value within a few seconds after the voltage application, as is seen in Figure 6a or in Figure 6b, it takes more than several minutes or more when particular voltages are applied. Approximately, these voltages correspond to the upper limit voltage and the lower limit voltage in the hysteresis area of Figure 7a and it is considered that a relaxation of the LC configuration from one bend state to the other bend state whose configurations are shown in Figure 3 as solution 1 or solution 2 is taking place.

Here, an area S that hysteresis curve depicts in Figure 7a is considered to correspond to an energy difference between two bend configurations. If this could be applied to the relation between S and the energy difference between a splay configuration and a bend configuration, we can evaluate splay-bend transition speed easily by measuring S. That is, the smaller the hysteresis area, the faster the splay-bend transition.

Although this area is determined by elastic constants and pretilt angle of LC materials and anchoring energy on a surface of an alignment layer, it may be considered that this area reflects the LC characteristics, as the used PI alignment layer is the same and shows strong anchoring energy. The measured pretilt angles $\theta°$ have been found to be $1.8° - 2.0°$ for cells with SE-7992 as an alignment layer.

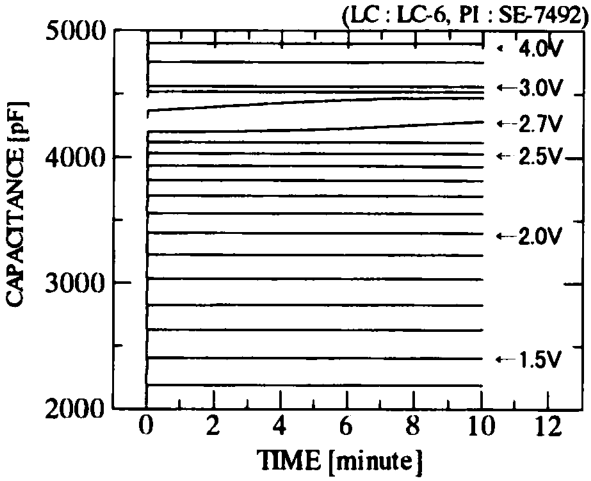

FIGURE 6a Capacitance change of a cell with time (with increasing voltage)

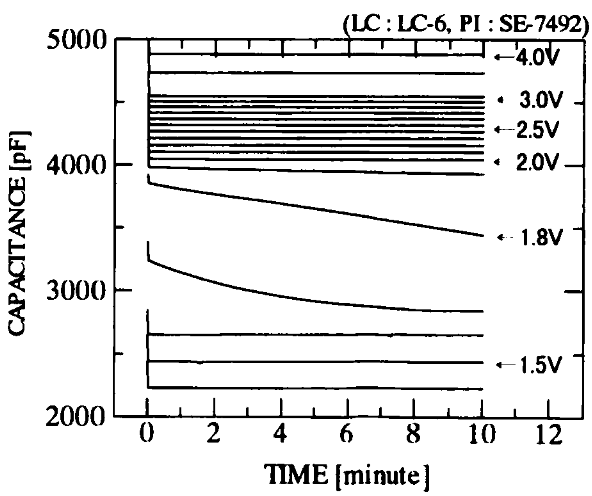

FIGURE 6b Capacitance change of a cell with time (with decreasing voltage)

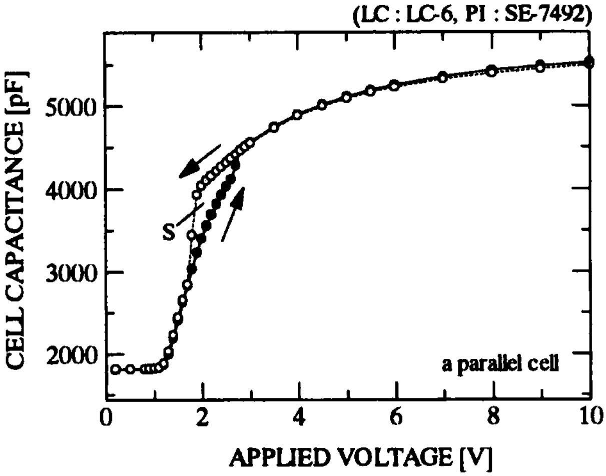

FIGURE 7a C-V hysteresis characteristics of the cell with parallel structure

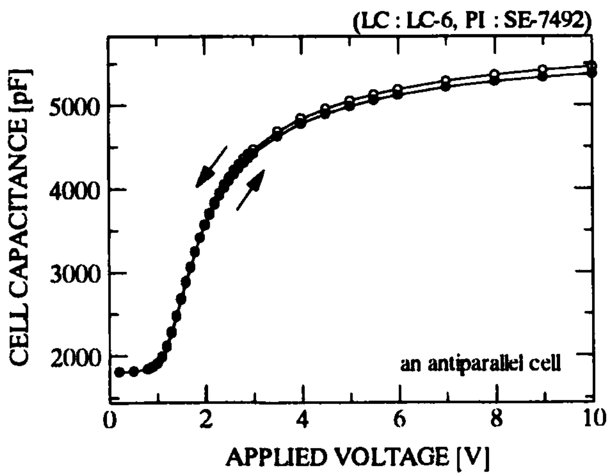

FIGURE 7b C-V hysteresis characteristics of the cell with anti-parallel structure

Figure 8 shows the relationship between the index which is given by dividing S with LC layer thickness λ and the splay-bend transition ratio, r, observed with eyes. Here, we defined S as the sum of the value $\Delta C/(C_1 - C_2)$ in the hysteresis area, where ΔC was the capacitance difference between two configurations in a cell with the same applied voltage. C_1 and C_2 are the capacitance of the cell with the applied voltage of 0.2V and 20V, respectively.

Apparently from Figure 8, this magnitude of the C-V hysteresis has a good correlation with the bend transition ratio, r, observed with eyes well and this evaluation method showed its effectiveness.

In this study, an alignment film which induces a comparatively low pretilt angle was used. A splay-bend transition speed is largely influenced not only by LC materials used but also by the pretilt angle. Evaluations of C-V hysteresis of the cells with alignment layers which show a high pretilt angle are things to do in the future.

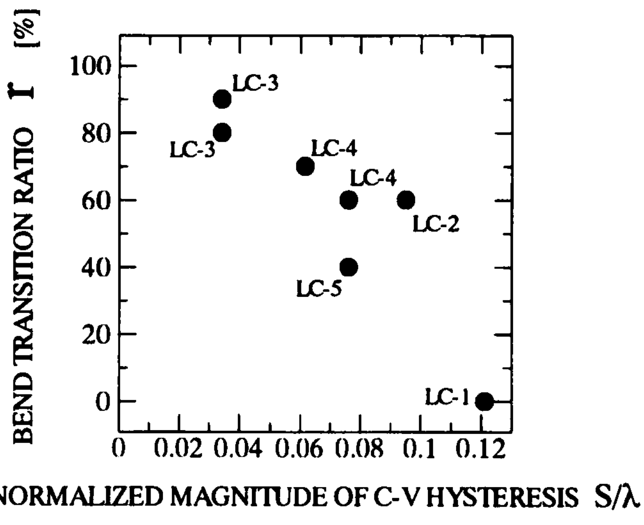

FIGURE 8 Relationship between the magnitude of the C-V hysteresis and the splay-bend transition speed in a parallel cell

CONCLUSION

LC director distribution change in a parallel cell with an applied voltage has been calculated. Three distributions were determined in the paticular voltage range and it was suggested that the C-V hysteresis would be appeared around the deformation transition.

We studied C-V hysteresis characteristics of the parallel cells and confirmed the abovementioned hysteresis characteristics experimentally. The magnitude of the area surrounded by the C-V hysteresis curve corresponds to the facility of the splay-bend transition and it was found that this C-V hysteresis method for the evaluation of the splay-bend transition speed was effective.

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