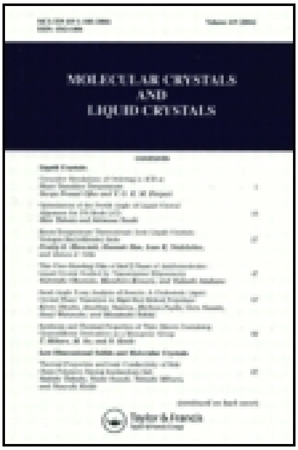

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Comparative Study of Director Responses in IPS and VA Modes Based Upon Physical Properties of Practical LC Materials

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Comparative Study of Director Responses in IPS and VA Modes Based Upon Physical Properties of Practical LC Materials

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The director response times of pure IPS and VA modes were compared by inserting respective material constant values of practical LC mixtures into the equations based upon the Leslie-Ericksen theory. The VA mode was confirmed to be superior to the IPS mode from this aspect due to the difference of the Frank elastic constants for bend and twist. Further superiority was shown quantitatively because of the contribution of the back-flow effect in the VA mode. These results were supported by referring to the molecular theory of the physical properties of LC substances.

Keywords: Frank elastic constants; nematic liquid crystal; response time; switching

INTRODUCTION

Both IPS (In-Plane-Switching) and VA (Vertically Aligned) modes are considered to be the most promising electro-optic effects of nematic liquid crystals (LCs) for uses in large LC-TV screens with features of high image quality of moving pictures. There still exists the request, however, to improve the image quality further and many efforts have been being made to actualize the quasi-impulse response in LC displays (LCDs), by introducing the over-driving method together with the blinking backlight technology, for example. In order to make this

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approach successful, faster electro-optic switching characteristics are essentially needed to LCs.

In this study, some physical properties of practical-use LC mixtures will be reviewed and will be used for the quantitative comparison of the director switching speed both in IPS and VA modes. Here, the switching times to be considered correspond to the relaxation of the director when an electric field is applied or removed. Moreover, when a fluid motion can be caused by the reorientation of the director, the relaxation of the vortices is also taken into account. This additional contribution is generally called as the back-flow effect. As the relaxation time depends on the field strength, the comparison will be made at a constant field normalized by the threshold of Freedericksz transition, in which IPS and VA modes differ.

From practical application point of view, the comparison is preferably to be made on optical switching and further more on gray-scale switching. As this makes the comparison extremely complicated, however, the present study will be limited to the motion of the director and consequently any optical property of LC materials will not be involved. The expansion of the present study to more practical arguments on optical switching will be left for further consideration in more sophisticated manner.

In the followings, a brief review will be made first on the theoretical investigations of the dynamics of nematic LCs in the basic IPS and VA display panel configurations within the framework of the Leslie-Ericksen theory. This will provide an idea that Frank elastic constants and Leslie viscous coefficients are the direct contributors among the physical properties of LC materials. This will be followed by a review of the measurements of those material constants of practical LC mixtures. In addition to the visco-elastic properties, the dielectric constants are also included in the argument related to the reduced electric-field. The arguments of these two sessions covering theories of director dynamics and experiments of material properties will provide some qualitative comparison of the switching characteristics of IPS and VA LCDs from a viewpoint of material property. Finally, some discussions will be made on a validity of the results based upon the molecular theories of those material properties.

DYNAMICS OF DIRECTOR REORIENTATION

The director is considered to be uniformly oriented within a nematic LC slab with the thickness d in the absence of an external electric field. The nematic slab is contacted with solid substrates at $z = -d/2$

and $z = d/2$ and is infinite in the directions perpendicular to the z axis, where a local right-handed system of Cartesian coordinates is adopted.

In the basic IPS-LCD panel configuration, the x axis is selected to coincide with the direction of the director. The internal electric field, which is assumed to be identical to the externally applied field, is uniform and in the direction at an angle of $\Phi = 45^\circ$ from the x axis in the x–y plane at the origin. The Frank–Oseen theory of curvature deformations of nematic LCs teaches us that the threshold field of the Freedericksz transition is given by

$$\mathrm{E}_{\mathrm{th,IPS}} = (\pi/d)\sqrt{}[K_{22}/(\varepsilon_0|\Delta\varepsilon|)], \tag{1}$$

assuming strong anchoring at both interfaces. Here K_{22} is the Frank elastic constant for twist and ε_0 is the permittivity in vacuum, leading to the dielectric constant $\varepsilon = \varepsilon_r\varepsilon_0$, where ε_r stands for the relative dielectric constant. The dielectric anisotropy is defined as $\Delta\varepsilon = \varepsilon_{\|} - \varepsilon_{\perp}$, by representing the relative dielectric constant ε_r in the direction parallel to the director by $\varepsilon_{\|}$ and that perpendicular to the director by $\varepsilon_{\perp}$.

When the LC slab is subject to an electric field E above the threshold, a twist deformation is created and the director $\boldsymbol{n}$ has azimuthal components

$$\boldsymbol{n} = (\cos\phi, \sin\phi, 0) \quad (0 \le \phi \le \pi/4). \tag{2}$$

The distribution of the azimuthal angle ϕ along the z axis can be analyzed by considering the balance between the elastic torque and the electric torque. This is due to so-called field effects.

The dynamic of the Freedericksz transition is governed by the interaction between the dielectric torque and the mechanical torques. By using a kinematic viscosity η, the switching times between the uniform state with $\phi(z) = 0$ $(-\,d/2 \le z \le d/2)$ and the twist deformation can be obtained as follows:

$$\tau_{\mathrm{on,IPS}} = \eta/[\varepsilon_0|\Delta\varepsilon|\mathrm{E}^2 - (\pi^2\mathrm{K}_{22}/d^2)] \tag{3}$$

$$\tau_{\mathrm{off,IPS}} = \eta\, d^2/(\pi^2\mathrm{K}_{22}). \tag{4}$$

The switching time τ_{on} corresponds to the Freedericksz transition due to the field application ($\mathrm{E} > \mathrm{E}_{\mathrm{th,IPS}}$) and the switching time τ_{off} to the relaxation to the field-free state. By referring to Eq. (1), the switching-on time can be rewritten as

$$\tau_{\mathrm{on,IPS}} = \eta/[\varepsilon_0|\Delta\varepsilon|(\mathrm{E}^2 - \mathrm{E}^2{}_{\mathrm{th,IPS}})]. \tag{5}$$

By defining the total switching time τ as

$$\tau = \tau_{\mathrm{on}} + \tau_{\mathrm{off}} \tag{6}$$

the following is obtained for the IPS-mode:

$$\tau_{\mathrm{IPS}} = (d/\pi)^2(\eta/\mathrm{K}_{22})(\mathrm{E}/\mathrm{E}_{\mathrm{th,IPS}})^2/[(\mathrm{E}/\mathrm{E}_{\mathrm{th,IPS}})^2 - 1)]. \tag{7}$$

In the VA-LCD panel configuration, the director aligns uniformly in parallel to the z axis in a field-free state. When the electric field is applied parallel to the z axis, a bend deformation of the director field is created providing that the dielectric anisotropy of the LC material is negative in sign. Assuming that the deformation occurs in one plane, the director $\boldsymbol{n}$ has polar components, for instance,

$$\boldsymbol{n} = (\sin\theta, 0, \cos\theta) \quad (0 \leq \theta \leq \pi/2). \tag{8}$$

Similar arguments as the IPS-mode yield the following equations:

$$\tau_{\mathrm{on,VA}} = \eta/[\varepsilon_0|\Delta\varepsilon|(\mathrm{E}^2 - \mathrm{E}^2{}_{\mathrm{th,VA}})] \tag{9}$$

$$\tau_{\mathrm{off,VA}} = \eta\, d^2/(\pi^2\mathrm{K}_{33}). \tag{10}$$

Here K_{33} is the Frank elastic constant for bend and the threshold field of the Freedericksz transition in the bend deformation is given by

$$\mathrm{E}_{\mathrm{th,VA}} = (\pi/d)\surd[\mathrm{K}_{33}/(\varepsilon_0|\Delta\varepsilon|)], \tag{11}$$

under the strong anchoring boundary-condition. Thus, the total switching time of the VA-mode is yielded as

$$\tau_{\mathrm{VA}} = (d/\pi)^2(\eta/\mathrm{K}_{33})(\mathrm{E}/\mathrm{E}_{\mathrm{th,VA}})^2/[(\mathrm{E}/\mathrm{E}_{\mathrm{th,VA}})^2 - 1)]. \tag{12}$$

When neglecting the gravity center movement, the coefficient η characterizes the energy dissipation produced by the rotation of director [1], but it is pointed out that the gradient of the angular velocity of the director produces a back-flow motion of the fluid [2].

The hydrodynamic theory, known as Leslie-Ericksen theory, provides an insight in the dynamic properties of incompressible nematic LCs by considering an additional torque due to frictional forces to the dielectric and elastic torques. The viscous torque can be described by introducing two frictional coefficients γ_1 and γ_2, which are related to the viscosity coefficients α_{i} (i = 1–6) introduced by Leslie as follows

$$\begin{aligned} \gamma_1 &= \alpha_3 - \alpha_2 \\ \gamma_2 &= \alpha_6 - \alpha_5 \\ &= \alpha_3 + \alpha_2 \end{aligned} \tag{13}$$

For the IPS-mode, as far as it is assumed that the deformation is the pure twist mode and the angle is small enough, the torque balance leads to [1]

$$K_{22}(\partial^2\phi/\partial z^2) = \gamma_1(\partial\phi/\partial t), \tag{14}$$

yielding

$$\begin{aligned} \phi(\mathrm{z,t}) &= \phi(\mathrm{z},0)\exp(-\mathrm{t}/\tau_{\mathrm{off}}) \\ \tau_{\mathrm{off}} &= (d^2/\pi^2)(\gamma_1/K_{22}). \end{aligned} \tag{15}$$

That is, the kinematic viscosity η in Eq. (4) corresponding to the director rotation in the IPS-mode is understood as the rotational viscosity γ_1.

In the bend mode, LC molecules undergo a translatory movement and, in addition to the torque balance, the equation of motion has to be taken into account. The contribution of this kind of fluid motion to the reorientation of the director, which was named later as a back-flow effect, was first reported as transient effects in the light transmission of a twisted nematic (TN) LCD [3] and was analyzed by neglecting the inertia term in the Leslie-Ericksen equations [4,5].

Regarding the back-flow effect in the pure VA-mode in one dimension, only one velocity component v_x has to be considered. In this case, the shear torque is to be added to the equation of the torque balance, resulting in the equation under the small angle assumption and the strong anchoring condition:

$$K_{33}(\partial^2\theta/\partial \mathrm{z}^2) = \gamma_1(\partial\theta/\partial \mathrm{t}) + \alpha_2(\partial_{v_x}/\partial_z). \tag{16}$$

The equation of motion is given by

$$\rho(\partial_{v_x}/\partial_t) = (\partial/\partial_z)[\eta_1(\partial_{v_x}/\partial_z) + \alpha_2(\partial\theta/\partial \mathrm{t})], \tag{17}$$

by assuming the non-slip condition at the interface and neglecting the pressure variation, characteristic time of which is considered to be much longer than the orientation relaxation time. Here ρ is the density and η_1 is the Miesowicz viscosity corresponding to (1/2) $(\alpha_4 + \alpha_5 - \alpha_2)$.

The solutions of the system of two linear differential equations (16) and (17) are obtained [6] following the procedure developed by P. G. de Gennes [7] and the Orsay Liquid Crystal Group [8] under the condition, v_x (z, 0) = 0, yielding the relaxation time of the similar form as Eq. (15)

$$\tau_{\mathrm{off}} = (d^2/\pi^2)(1/K_{33})(\gamma_1 - \alpha_2^2/\eta_1), \tag{18}$$

by assuming $K_{33}/\gamma_1 \leq \eta_1/\rho$. Thus, the viscosity coefficient η in Eq. (10) of the VA-mode is approximately given by the rotational viscosity γ_1 corresponding to the uncoupled bend mode and the coupling coefficient (α_2^2/η_1) corresponding to the bend mode coupled to the shear wave by neglecting the uncoupled shear mode [9].

To sum up the above arguments, the total switching time of both the IPS and VA modes is given by

$$\tau_{\text{total}} = (d/\pi)^2(\eta/\mathrm{K_{ii}})[\mathrm{A}^2/(\mathrm{A}^2 - 1)], \tag{19}$$

where

$$\mathrm{A} = \mathrm{E}/\mathrm{E_{th}},$$
$$\mathrm{E_{th}} = (\pi/d)\sqrt{[\mathrm{K_{ii}}/(\varepsilon_0|\Delta\varepsilon|)]}.$$

The differences between the IPS and the VA modes are as follows:

for IPS-mode; $\mathrm{i} = 2$ $(\mathrm{K_{ii}} = \mathrm{K_{22}})$ and $\eta = \gamma_1$,
for VA-mode; $\mathrm{i} = 3$ $(\mathrm{K_{ii}} = \mathrm{K_{33}})$ and $\eta = \gamma_1 - 2\alpha_2^2/(\alpha_4 + \alpha_5 - \alpha_2)$.

That is,

$$\tau_{\text{total}}^{\text{VA}}/\tau_{\text{total}}^{\text{IPS}} = \eta^{\text{VA/IPS}}(\mathrm{K_{22}}/\mathrm{K_{33}}), \tag{20}$$

where

$$\begin{aligned}\eta^{\text{VA/IPS}} &= [\gamma_1 - 2\alpha_2^2/(\alpha_4 + \alpha_5 - \alpha_2)]/\gamma_1 \\ &= 1 - 2\alpha_2^2/(\alpha_4 + \alpha_5 - \alpha_2)(\alpha_3 - \alpha_2)\end{aligned}$$

Furthermore, $\Delta\varepsilon > 0$ for IPS-mode and $\Delta\varepsilon < 0$ for VA-mode.

MATERIAL CONSTANT VALUES OF LC MIXTURES

Physical properties of more than 300 LC mixtures were summarized and analyzed from various aspects as shown in the following figures. The material constants of main interest in this study are, as shown in Eqs. (19) and (20), Frank elastic constants K_{22} and K_{33}, the rotational viscosity γ_1, and the dielectric constants $\varepsilon_{\|}$ and $\varepsilon_{\perp}$. All the values used in the following arguments are those measured at 20°C.

Figure 1 shows the correlation between K_{22} and K_{33} values. The twist elastic constant K_{22} is related to the switching characteristics of the IPS-mode and the bend elastic constant K_{33} is to that of the VA-mode. As is shown in Figure 1, the K_{22} values are distributed within a window of 4∼9 pN and the K_{33} values 10∼26 pN. There clearly exists an inequality $K_{33} > K_{22}$ and the ratio K_{33}/K_{22} is

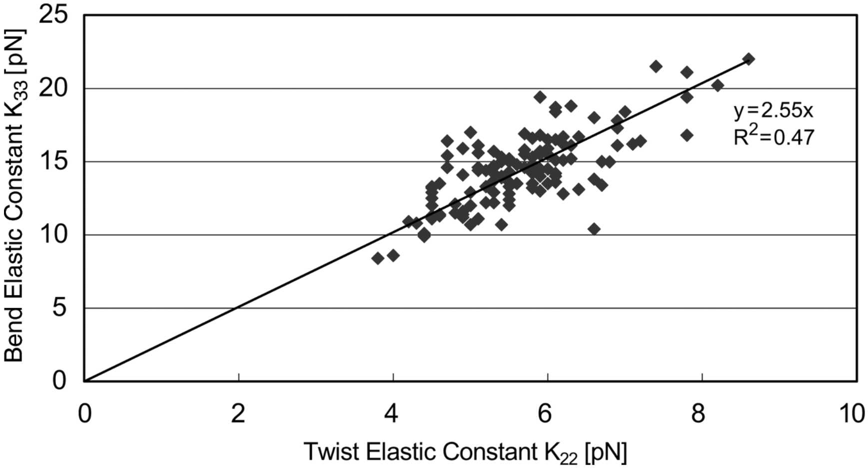

FIGURE 1 Correlation between Frank elastic constants of LC mixtures K_{22} for twist and K_{33} for bend.

2.55 ± 0.47. This can provide an idea that the VA-mode is superior to the IPS-mode in terms of the contribution of the elastic property of LC materials. This is for the total response time as the sum of the switching-on time and the switching-off time under the condition that the applied field is same for both modes with regard to its reduced value normalized by the threshold field. As a larger elastic constant induces a higher threshold, the absolute value of the applied field, assumed in the present comparison, is higher for the VA-mode.

The threshold field also depends on the absolute value of the dielectric anisotropy $|\Delta\varepsilon|$ and the sign must be negative for VA-mode use LC mixtures and positive for mixtures for uses in practical IPS-LCDs. Figure 2 shows both the relative dielectric constant $\varepsilon_{||}$ parallel to the director and $\varepsilon_{\perp}$ perpendicular to the director. The solid line in Figure 2 corresponds to the LC mixtures satisfying $\varepsilon_{||} = \varepsilon_{\perp}$, that is $\Delta\varepsilon = 0$, and the normal distance from the line $\varepsilon_{||} = \varepsilon_{\perp}$ represents the $\Delta\varepsilon$ value. That is, the LC mixtures in the region above this line are those with positive $\Delta\varepsilon$ and mixtures below this line are those with negative $\Delta\varepsilon$. Figure 2 suggests that an increase of $|\Delta\varepsilon|$ value in a negative sign is not easy for LC mixtures compared to increasing a positive $\Delta\varepsilon$ value. This also means that the threshold field of VA-mode is higher than IPS-mode from a viewpoint of the dielectric anisotropy of practical LC mixtures.

The LC mixtures, whose K_{22} and K_{33} are plotted in Figure 1, contain those with positive-$\Delta\varepsilon$ and negative-$\Delta\varepsilon$. Therefore, for more precise arguments, it is desirable to compare the K_{22} value of

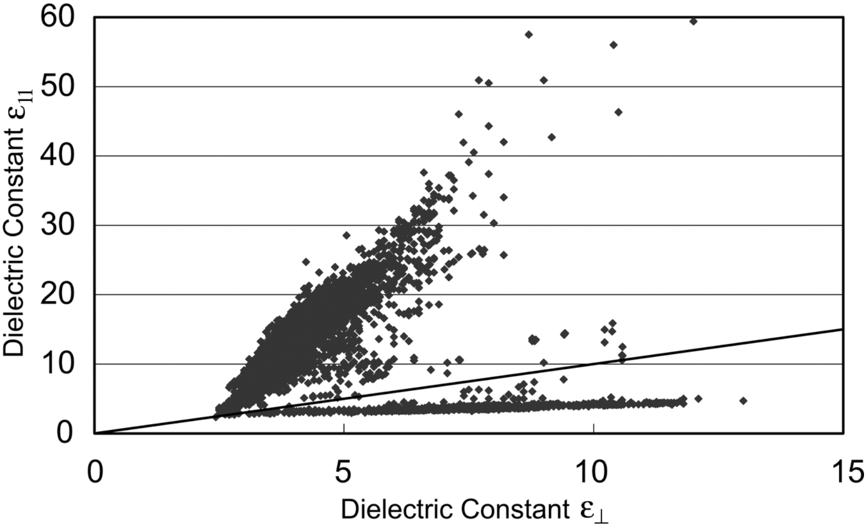

FIGURE 2 Correlation between the relative dielectric constant $\varepsilon_{\|}$ of LC mixtures parallel to the director and $\varepsilon_{\perp}$ perpendicular to the director. (The solid line corresponds to $\varepsilon_{\|} = \varepsilon_{\perp}$, that is $\Delta\varepsilon = 0$.)

positive-$\Delta\varepsilon$ mixtures for uses in IPS LCDs and the K_{33} value of negative-$\Delta\varepsilon$ VA use mixtures. Figure 3 shows K_{22} and K_{33} of positive-$\Delta\varepsilon$ mixtures together with their $\Delta\varepsilon$ values. No significant differences can be seen in the corresponding figure for negative-$\Delta\varepsilon$ mixtures. That is, the inequality $K_{33} > K_{22}$ is valid independent from the sign of $\Delta\varepsilon$ and the elastic constant values of $K_{22} = 4 \sim 9\,\text{pN}$ and $K_{33} = 10 \sim 26\,\text{pN}$ can be obtained independent from its absolute value $|\Delta\varepsilon|$.

The total switching time also depends on the viscous coefficient η, which corresponds to the rotational viscosity γ_1 for the IPS-mode and to the combination of γ_1 and a coupling coefficient representing the contribution of the back-flow effect in the case of the VA-mode. First, the pure rotational viscosity term is discussed. The question is whether it is possible to design the rotational viscosity of LC mixtures independent from their elastic constants. In Figure 4, plots are made for the γ_1 values of LC mixtures against its elastic constants K_{22} (symbols■) and K_{33} (symbols■). The rotational viscosity shows no correlation with either of the twist or the bend elastic constant. Moreover, Figure 5 shows that there is no clear correlation between the γ_1 value and the absolute value of the dielectric anisotropy for both positive-$\Delta\varepsilon$ and negative-$\Delta\varepsilon$ LC mixtures. In Figure 5, symbols ■ are for the positive-$\Delta\varepsilon$ materials and symbols■ for the negative-$\Delta\varepsilon$ ones.

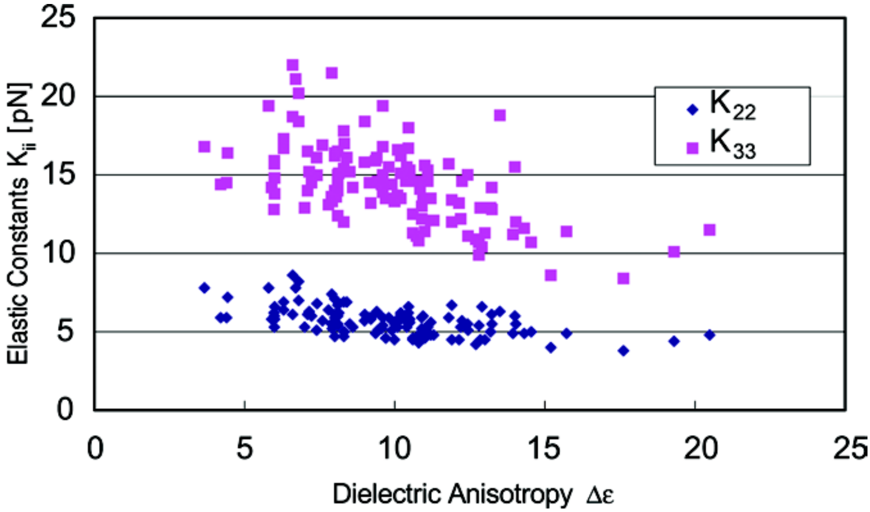

FIGURE 3 Frank elastic constants K_{22} (symbols ◆) and K_{33} (symbols ■) of LC mixtures with positive-Δε, plotted against their Δε value.

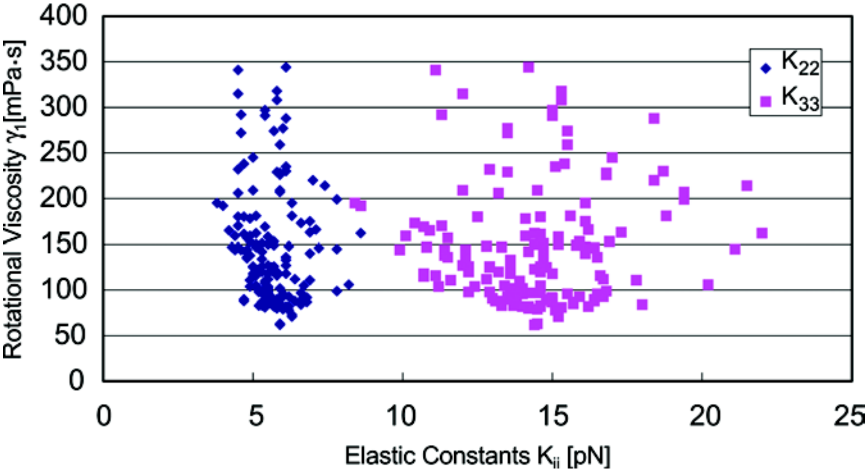

FIGURE 4 Rotational viscosity γ_1 of LC mixtures, plotted against their Frank elastic constants K_{22} (symbols ◆) and K_{33} (symbols ■).

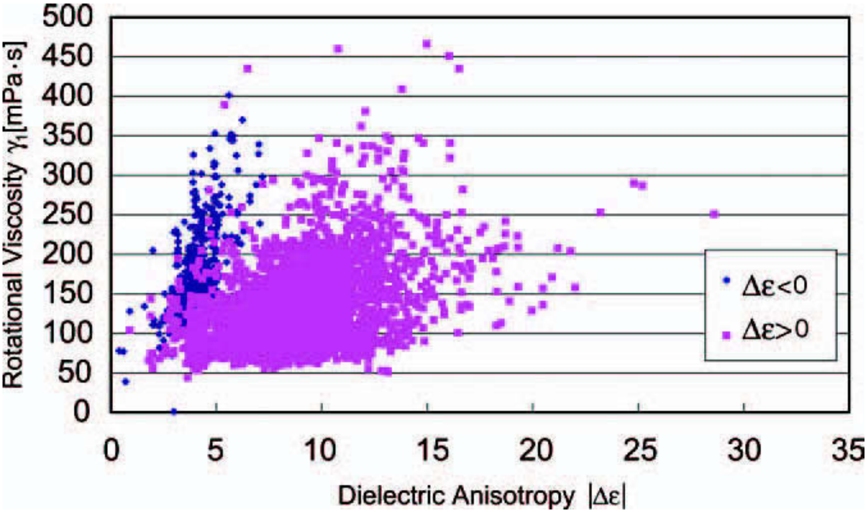

FIGURE 5 Rotational viscosity γ_1 of LC mixtures plotted against their absolute value of the dielectric anisotropy $|\Delta\varepsilon|$ (symbols ■; positive-$\Delta\varepsilon$ LC mixtures, symbols ◆; negative-$\Delta\varepsilon$ LC mixtures).

Figures 4 and 5 teach us that the viscous property, as far as the rotational viscosity is concerned, can be designed for LC mixtures with $\Delta\varepsilon$ in both signs independent from their absolute value as well as their elastic constant value. Actual γ_1 values of the practical use LC mixtures are down to around $60\,\mathrm{mPa\cdot s}$.

The data are summarized in Figure 6 in such a manner to compare the visco-elastic property (γ_1/K_{ii}) of the positive-$\Delta\varepsilon$ materials ($i = 2$) and the negative-$\Delta\varepsilon$ materials ($i = 3$) against the absolute value of their dielectric anisotropy $|\Delta\varepsilon|$. The low end of the visco-elastic property is around 6×10^9 Pa·s/N for γ_1/K_{33} of negative-$\Delta\varepsilon$ materials (symbols ■; VA-mode) and around 12×10^9 Pa·s/N for γ_1/K_{22} of positive-$\Delta\varepsilon$ materials (symbols ■; IPS-mode). As can be seen in Eq. (19), this visco-elastic property is the direct measure of the switching property of LC mixtures for uses in IPS and VA modes as the first approximation by neglecting the back-flow effect. The main difference of the (γ_1/K_{ii}) values comes from the difference of the elastic constant, that is K_{22} for IPS-mode LC mixtures and K_{33} for VA-mode.

Finally, the contribution of the back-flow effect is considered. The number of measured values is quite limited with regard to a set of the Leslie viscous coefficient of LC mixtures. Nevertheless, if the reported values for a typical LC mixture ZLI-2293 from Merck

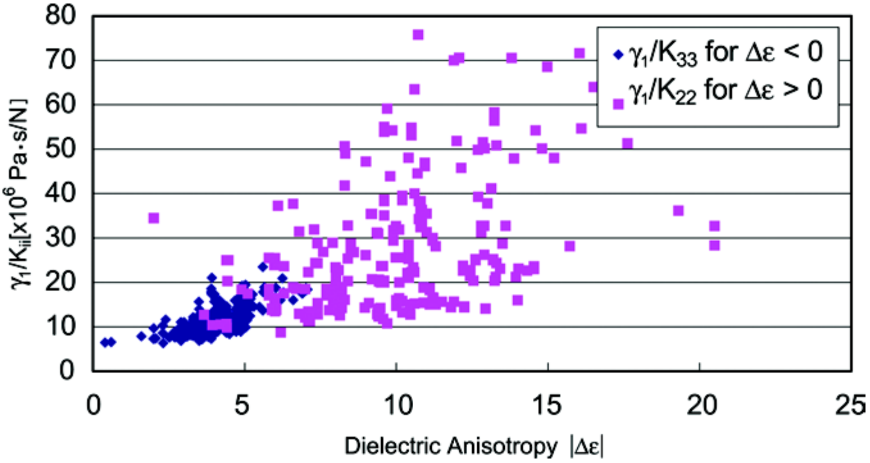

FIGURE 6 Comparison of the visco-elastic property (γ_1/K_{ii}) of positive-Δε LC mixtures (i = 2, symbols ■) and negative-Δε LC mixtures (i = 3, symbols ◆) against their absolute value of the dielectric anisotropy |Δε|.

KGaA [10],

$$\begin{aligned}\alpha_2 &= -0.151\,(\mathrm{Pa\cdot s})\\ \alpha_3 &= -0.0015\,(\mathrm{Pa\cdot s})\\ \alpha_4 &= 0.0809\,(\mathrm{Pa\cdot s})\\ \alpha_5 &= 0.1084\,(\mathrm{Pa\cdot s})\end{aligned}$$

are referred, the contribution of the back-flow effect can be estimated as

$$\begin{aligned}\eta^{\mathrm{VA/IPS}} &= 1 - 2\alpha_2^2/(\alpha_4+\alpha_5-\alpha_2)(\alpha_3-\alpha_2)\\ &= 0.104.\end{aligned}$$

This ratio together with the average (K_{22}/K_{33}) value of 1/2.55 yields the value ($\tau_{\mathrm{total}}^{\mathrm{VA}}/\tau_{\mathrm{total}}^{\mathrm{IPS}}$) as low as 0.04.

It is reported that the reduction of the viscosity in an infinite medium due to the back-flow is, for instance, around 0.75 in the case of a typical LC substance MBBA [11], providing an expectation of the value $\eta^{\mathrm{VA/IPS}}$ around 0.25. The above ratio $\eta^{\mathrm{VA}}/\eta^{\mathrm{IPS}}$ of 0.104 can be a bit overestimated, but the general understanding of the superiority of the VA-mode to the IPS-mode in terms of the display response time is quantitatively supported from the viewpoint of the physical properties of practical use LC mixtures. As a conclusion, the contribution of the back-flow effect can be essential as is also emphasized in a recent publication [12]. Further quantitative investigation is under way in the responsible properties of LC materials. Furthermore, precise numerical simulation of the back-flow effect in VA-LCD is to be reported [13] and a theoretical study will be published separately.

DISCUSSIONS

As far as the director switching under a normalized field application is concerned, the VA-mode was shown to be superior to the IPS-mode with regard to the contributions of LC material properties. In this section, discussions are made on the responsible properties of LC mixtures by referring to the molecular theories of nematic LC substances.

First, the relation $K_{33}/K_{22} = 2.55$ observed in average between the Frank elastic constants K_{22} for twist and K_{33} for bend is reviewed. According to R.G. Priest [14], the following equations hold for Frank elastic constants including K_{11} for spray.

$$\begin{aligned} K_{22}/K^* &= 1 - 2\Delta - \Delta'\langle P_4\rangle/\langle P_2\rangle + \cdots \\ K_{33}/K^* &= 1 + \Delta + 4\Delta'\langle P_4\rangle/\langle P_2\rangle + \cdots, \end{aligned} \tag{21}$$

where $K^* = (K_{11} + K_{22} + K_{33})/3$, $\langle P_4\rangle = (35 < \cos^4\beta > -30 < \cos^2\beta > + 3)/8$, and $\langle P_2\rangle = (3 \; < \cos^2\beta > - 1)/2$, as β the angle between the molecular long axis and the director. The coefficients Δ and Δ' are the constants depending on the molecular interaction potential. By taking the three terms in the right-side of Eq. (21) into account, the following relation is obtained:

$$K_{33}/K_{22} = [(1+\Delta)\langle P_2\rangle + 4\Delta'\langle P_4\rangle]/[(1-2\Delta)\langle P_2\rangle - \Delta'\langle P_4\rangle]. \tag{22}$$

By introducing a parameter $R = L/D$, which represents a LC molecular structure using the sphero-cylinder model with the width D and the length $L+D$, Eq. (21) can be rewritten as

$$\begin{aligned} K_{22}/K^* &= [3R^2 + 24 + 27(\langle P_4\rangle/\langle P_2\rangle)(-R^2/16 + 1/6)]/(7R^2 + 20) \\ K_{33}/K^* &= [9R^2 + 18 + 27(\langle P_4\rangle/\langle P_2\rangle)(R^2/4 - 2/3)]/(7R^2 + 20). \end{aligned} \tag{23}$$

Thus, Δ and Δ' can be explicitly evaluated as

$$\begin{aligned} \Delta &= 2(R^2 - 1)/(7R^2 + 20) \\ \Delta' &= 27(R^2/16 - 1/6)/(7R^2 + 20). \end{aligned} \tag{24}$$

When $R = L/\mathrm{D}$ is large enough, Eqs. (22) and (24) yield

$$K_{33}/K_{22} = 4[12 + 9(\langle P_4\rangle/\langle P_2\rangle)]/[16 - 9(\langle P_4\rangle/\langle P_2\rangle)]. \tag{25}$$

It can be deduced that, in the ultimate case of $\langle P_4 \rangle \ll \langle P_2 \rangle$, that is, in the case when $\langle P_2 \rangle$ is infinitely small, K_{33} is equal to $3K_{22}$. This will allow us to conclude that the average value K_{33}/K_{22} of 2.6 obtained for practical LC mixtures can be reasonably used in a general comparison of the switching time of IPS and VA modes in a more or less quantitative manner.

Further considerations can be made on the estimation of practical values of the relative order $\langle P_4 \rangle / \langle P_2 \rangle$ and the molecular aspect ratio R governing the elastic constant as indicated in Eq. (23). Equation (23) together with the set of measured elastic constant values (K_{11}, K_{22}, K_{33}) provides both values of $\langle P_4 \rangle / \langle P_2 \rangle$ and R for each LC mixture. The average values are calculated as $\langle P_4 \rangle / \langle P_2 \rangle = 0.577 \pm 0.363$. Assuming roughly that the equation $\langle P_2 \rangle = (1 - T/T_{NI})^{0.220}$ [15] holds for all LC mixtures in the present study, the value $\langle P_2 \rangle$ can be calculated by using measured T_{NI} and $T = 293\,K$. The average value of $\langle P_2 \rangle$ is 0.676 ± 0.020 providing the average value of $\langle P_4 \rangle$ as 0.386 ± 0.236. All these values seem to be within an acceptable range as for the present rough estimation.

The average of calculated R values is also derived as 3.00 ± 0.62. The aspect ratio of the spheroid equivalent to a molecular volume can also be calculated by a MO method and, for instance, is found to be 3.63 for a typical two ring structure and 4.40 for a three ring structure. The obtained R value of around 3.00 in average also seems to be reasonable and the relatively small value for mixtures can be due to the dimer formation of polar molecules. That is, the elastic property of LC mixtures, especially those with a large positive-$\Delta\varepsilon$, is considered not to be additive. By inserting the R value into Eq. (24), the values of Δ and Δ' are also calculated for each LC mixture and derived as $\Delta = 0.187 \pm 0.027$ and $\Delta' = 0.122 \pm 0.033$ in average.

Next, the viscous properties are taken up for discussions. According to M.A. Osipov and E.M. Terentjev [16,17], the Leslie coefficients can be expressed in terms of molecular parameters as follows

$$\begin{aligned}
\alpha_1 &= -\rho\lambda[(p^2 - 1)/(p^2 + 1)]\langle P_4 \rangle \\
\alpha_2 &= -(\rho\lambda/2)\langle P_2 \rangle - (1/2)\gamma_1 \\
\alpha_3 &= -(\rho\lambda/2)\langle P_2 \rangle - (1/2)\gamma_1 \\
\alpha_4 &= (\rho\lambda/35)[7 - 5\langle P_2 \rangle - 2\langle P_4 \rangle] \\
\alpha_5 &= (\rho\lambda/2)\{(1/7)[(p^2 - 1)/(p^2 + 1)](3\langle P_2 \rangle + 4\langle P_4 \rangle) + \langle P_2 \rangle\} \\
\alpha_6 &= (\rho\lambda/2)\{(1/7)[(p^2 - 1)/(p^2 + 1)](3\langle P_2 \rangle + 4\langle P_4 \rangle) - \langle P_2 \rangle\}. \qquad (26)
\end{aligned}$$

Here, ρ is the number density, p is the molecular length-to-width ratio, and λ is the microscopic friction constant.

The inequality $|\alpha_3| \ll |\alpha_2|$, which can also be seen in the above values for ZLI-2293, yields $(\rho\lambda) \approx \gamma_1/\langle P_2\rangle$ providing the followings:

$$\begin{aligned}
&\alpha_2 \approx \gamma_1\\
&\alpha_4 \approx (1/35)[7/\langle P_2\rangle - 5 - 2\langle P_4\rangle/\langle P_2\rangle]\gamma_1 \qquad (27)\\
&\alpha_5 \approx (1/2)\{(1/7)[(p^2-1)/(p^2+1)](3 + 4\langle P_4\rangle/\langle P_2\rangle) + 1\}\gamma_1.
\end{aligned}$$

Equation (27) under the assumption $p = R$ together with the estimated average values of $R = 3.00$, $\langle P_2\rangle = 0.676$, and $\langle P_4\rangle = 0.386$ allows a rough estimation of the coupling coefficient (α_2^2/η_1) for the VA mode as

$$\begin{aligned}
\alpha_2^2/\eta_1 &= 2\alpha_2^2/(\alpha_4 + \alpha_5 - \alpha_2)\\
&\approx 0.8\gamma_1,
\end{aligned}$$

and the coefficient

$$\begin{aligned}
\eta^{\mathrm{VA/IPS}} &= (\gamma_1 - \alpha_2^2/\eta_1)/\gamma_1\\
&\approx 0.2.
\end{aligned}$$

This can be said to agree rather well to the above estimation of $\eta^{\mathrm{VA/IPS}} = 0.10 \sim 0.25$ using the measured Leslie coefficients.

Finally, the dielectric property is touched briefly. The well-known expression of the dielectric anisotropy given by W. Maier and G. Meier is the following:

$$\Delta\varepsilon = (NhF/\varepsilon_0)\ [(\alpha_\parallel - \alpha_\perp) + F(\mu^2/2k_B\mathrm{T})(3\cos^2\phi - 1)]\ \langle P_2\rangle. \qquad (28)$$

Here, N is the number density of LC molecules, h and F are the cavity field factors, $\alpha_\parallel$ and $\alpha_\perp$ are the electronic polarizability parallel and perpendicular to the director, and k_B is the Boltzmann constant. It is also well known that the absolute value $|\Delta\varepsilon|$ is mainly subject to the molecular dipole moment μ. Practical LC molecules are designed to have a large dipole μ parallel $(\phi = 0)$ to the molecular axis to obtain a large $\Delta\varepsilon$ value in a positive sign, and perpendicular $(\phi = \pi/2)$ to the molecular axis in a negative sign. Assuming the dipole μ is same in its value, however, the term $(3\cos^2\phi - 1)$ is equal to 2 in the case $\phi = 0$ and -1 in the case $\phi = \pi/2$. This means that the contribution of the molecular dipole to the $\Delta\varepsilon$ is two times larger when it is put in parallel to the molecular axis $(\phi = 0$ and $\Delta\varepsilon > 0)$ than the case when put in perpendicular to the molecular axis $(\phi = \pi/2$ and $\Delta\varepsilon < 0)$. This can also be reflected on the $\Delta\varepsilon$ value of LC mixtures and is clearly shown in Figure 2.

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