Response characteristics and related material properties of modern LCDs for TV applications

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Abstract

Analytical solutions are obtained for the director reorientation dynamics of both VA- and IPS modes by considering a possible effect of the molecular flow, providing a theoretical basis of the relations between the response characteristics of the display and the physical properties of the liquid crystal material used. The relevant properties of practical liquid crystal mixtures are quantitatively reviewed and the features of superior substances, used in formulating those mixtures, are presented.

1. Introduction

Both VA (Vertically Aligned) and IPS (In-Plane-Switching) modes are the major electro-optic effects of liquid crystals (LCs) utilized especially in the present large-size LC display (LCD) panels for TV applications. One of the features common to the VA and IPS modes are the fast response characteristics to achieve a high image quality of moving pictures, to which the physical properties of the LC material used are strongly related. In this paper, a study will be made on the relations between the response characteristics of both the VA- and IPS- modes and the physical properties of LC materials by taking the “back-flow” effect into account. In the author’s previous paper[1], the equations of the director relaxation time were introduced on the analogy of the orientational fluctuations of the director causing a light scattering, for instance[2]. In this paper, it will be confirmed that the equations can be analytically obtained to strengthen the theoretical basis of the effect of the back-flow on the material constants dependence of the response times. The analytical calculations will be proceeded by following the approach by P. Pieranski, et al.[3]. Further considerations to simplify the contribution of the back-flow effect to the effective viscosity in the VA mode in connection with the rotational viscosity will be made based upon a molecular theory of the Leslie coefficients of viscosity by M.A. Osipov and E.M. Terentjev [4,5]. The analysis of the dependence of the response characteristics on the LC material constants will be followed by a review of those properties of practical LC materials.

2. Analysis of response characteristics for VA and IPS electro-optic modes

The principal is identical for both VA and IPS LCDs in the sense that the intensity of the transmitted light changes due to the change of the optical birefringence of the LC medium in the display panel, which is caused by the field-induced reorientation of the director in the medium. Nevertheless, the director reorientation time is different between VA and IPS LCDs due to the difference in the LC molecular dynamics of the both electro-optic modes. In this session, the correlations between the physical parameters affecting the director response characteristics and the relaxation times of the director reorientation are analyzed for the VA mode in the manner to compare with the IPS mode.

In the present analysis, some simplifications are made in the model of the director dynamics so far as the essential difference between the two modes is not lost. The director is considered to change its orientation uniformly in a plane. That is, by choosing Cartesian axes such that the z-axis is normal to the substrate surface, the director is uniformly oriented parallel either to the z-axis (VA mode) or to the x-axis (IPS mode) at the field-free state and is assumed to stay either in the z-x plane (VA mode) or in the x-y plane (IPS mode) under a uniform electric field parallel either to the z-axis (VA mode) or to the y-axis (IPS mode). The dielectric anisotropy $\Delta\varepsilon$ of the LC material used is assumed to be negative in case of VA LCD and positive in case of IPS LCD.

The interfaces between the LC layer and the substrate are regarded to exist infinitely in two dimensions at z=d/2 and there the strong anchoring condition is assumed.

2-1. VA mode

When the director is represented as

$$\boldsymbol{n} = (\sin\theta(z,t), 0, \cos\theta(z,t)),$$

the equation of torque balance, neglecting the inertial force, is given by

$$\gamma_1(\partial\theta/\partial t)= (K_{11}\sin^2\theta + K_{33}\cos^2\theta)(\partial^2\theta/\partial z^2)+ +[(K_{11}-K_{33})(\partial\theta/\partial z)^2-\varepsilon_0\Delta\varepsilon E^2]\sin\theta\cos\theta + +(1/2)(\gamma_1-\gamma_2\cos 2\theta)(\partial v_x/\partial z) \qquad (1)$$

and the equation of motion is by

$$(\partial/\partial z)\{[\alpha_1\sin^2\theta\cos^2\theta-(1/2)\gamma_2\cos 2\theta + +(1/2)(\alpha_3+\alpha_4+\alpha_5)](\partial v_x/\partial z)+ +(\gamma_2\cos^2\theta-\alpha_3)(\partial\theta/\partial t)\}= 0, \qquad (2)$$

where K_{ii} ($i = 1, 2, 3$) are the Frank elastic constants, α_i ($i = 1$-6) the Leslie viscosity coefficients, and $\gamma_1 = \alpha_3-\alpha_2$ and $\gamma_2 = \alpha_3+\alpha_2$. Here, only one gradient in the z-direction of the velocity component v_x remains.

Equations (1) and (2) can be simplified by applying the small angle approximation as

$$\zeta(\partial^2\theta/\partial z^2)-\theta = \lambda_1[(\partial\theta/\partial t)+\lambda_2(\partial v_x/\partial z)], \qquad (1')$$

where $\zeta = K_{33}/(\varepsilon_0\Delta\varepsilon E^2)$,

$\lambda_1 = \gamma_1/(\varepsilon_0\Delta\varepsilon E^2)$,

$\lambda_2 = \alpha_2/\gamma_1$,

and

$$(\partial/\partial z)[\eta_1(\partial v_x/\partial z)+\alpha_2(\partial\theta/\partial t)]= 0, \qquad (2')$$

where $\eta_1=(1/2)(-\alpha_2+\alpha_4+\alpha_5)$.

The form of the general solution of Eqs. (1') and (2') in a dynamic behavior can be [3]

$$\theta(z,t)= \theta_0[\cos(qz)-\cos(qd/2)]\exp(st) \qquad (3)$$

$$v_x(z,t) = v_0[\sin(qz)-(2z/d)\sin(qd/2)]\exp(st), \qquad (4)$$

satisfying the initial condition,

$$\theta(\pm d/2, 0) = 0, \quad v_x(\pm d/2, 0) = 0$$

$$\theta(0, 0) = \theta_0[1-\cos(qd/2)], \quad v_x(0, 0) = 0,$$

and also the boundary condition,

$$\theta(\pm d/2, t) = 0, \quad v_x(\pm d/2, t) = 0.$$

Here, q represents the wave vector of the distortion and s the reciprocal of the time constant τ.

The on-time τ_{ON} corresponding to the time needed for the distortion of the director field to become e-times larger than its initial state after an application of the electric field is obtained as

$$\tau_{ON} = (\gamma_1-\alpha_2^2/\eta_1)/(-q^2K_{33}-\varepsilon_0\Delta\varepsilon E^2) \qquad (\Delta\varepsilon<0). \qquad (5)$$

The off-time τ_{OFF} corresponding to the time needed for the distortion of the director field to become 1/e of its initial state after an removal of the electric field is obtained by inserting E=0 to Eq.(1) and attending to $s < 0$ as,

$$\tau_{OFF} = (\gamma_1 - \alpha_2^2/\eta_1)/(q^2K_{33})\ . \qquad (6)$$

In the case if the velocity gradient $\partial v_x / \partial z$ is omitted in Eq.(1), the numerator of both Eq.(5) and Eq.(6) becomes γ_1 and these formulas for the mode $q = \pi / d$ are identical to those familiar for the optical response of VA-LCD neglecting the back-flow effect[6].

2-2. IPS mode

In case of the IPS mode, the director is represented as

$$\boldsymbol{n} = (\cos\phi(z,t),\ \sin\phi(z,t),\ 0)$$

and, neglecting the inertial force, the equation of torque balance yields

$$\gamma_1(\partial\phi/\partial t) = K_{22}(\partial^2\phi/\partial z^2) + \varepsilon_0\Delta\varepsilon E^2 \sin\phi\cos\phi \quad (7)$$

and $\partial v_x/\partial z = \partial v_y/\partial z = 0$. The same argument as for the VA mode provides both the on-time and the off-time as

$$\tau_{ON} = \gamma_1 / (-q^2K_{22} + \varepsilon_0\Delta\varepsilon E^2) \quad (\Delta\varepsilon > 0)\ (8)$$

$$\tau_{OFF} = \gamma_1 / (q^2K_{22})\ , \qquad (9)$$

which are also familiar for the optical response of IPS-LCD ($q = \pi / d$).

3. LC material properties related to the response characteristics

As shown in the analytical session 2, both the elastic property and the viscous property of the LC material used dominantly affect the response characteristics of LCDs. Regarding the elastic property, the effective material constant for the VA mode is K_{33} for the bend deformation and that for the IPS mode is K_{22} for the twist deformation.

As is often argued theoretically, both the constants, K_{22} and K_{33}, of a LC material are mutually correlated and typically K_{33} is measured to be two to three times larger than K_{22} as is shown in Fig.1 for many kinds of LC mixtures.

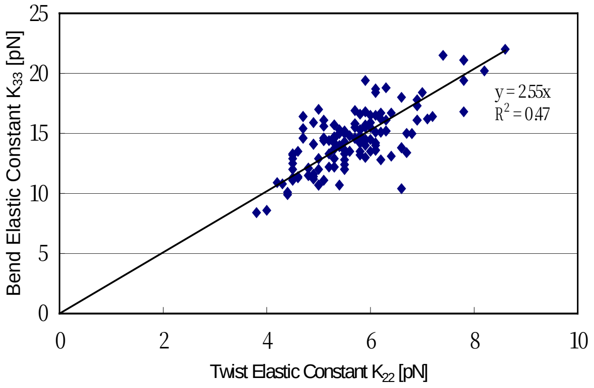

Fig.1 Frank elastic constants K_{22} and K_{33} of LC mixtures measured at 20℃ [1]

The viscous property of LC materials is a bit more complicated with regard to its contribution to the response characteristics of LCDs. According to the previous analysis, the effective viscous coefficient is the rotational viscosity γ_1 for both VA and IPS modes and another factor of α_2^2/η_1 can exhibit further contribution to reduce the response times of VA LCDs related to the back-flow effect.

If a molecular theory of the Leslie coefficients [4,5] is referred, α_2 and α_3 are related respectively to the rotational viscosity as

$$\alpha_2 = -(\rho\lambda/2)\langle P_2\rangle - (1/2)\gamma_1 \qquad (10)$$

$$\alpha_3 = -(\rho\lambda/2)\langle P_2\rangle + (1/2)\gamma_1\ , \qquad (11)$$

where ρ is the number density, λ is the microscopic friction constant and P_2 is the second Legendre polynomial, whose ensemble average $\langle P_2\rangle$ corresponds to the orientational order of LC molecules.

By taking it into account that α_3 is typically one to two orders of magnitude smaller than α_2 [7,8], an assumption of α_3 0 provides a primitive formula for the rotational viscosity,

$$\gamma_1 = \rho\lambda\langle P_2\rangle , \qquad (12)$$

and then,

$$\alpha_2 = -\rho\lambda\langle P_2\rangle = -\gamma_1 . \qquad (13)$$

The assumption of α_3 0 corresponds to γ_2/γ_1 -1 and is also experimentally proven [7,9,10]. A recent study on a transient current in the VA cell also provides a good agreement between measurement and numerical simulation by taking the back-flow effect into account under the assumption of α_3 0 [11].

Other two Leslie coefficients, α_4 and α_5, are given by

$$\alpha_4 = (\rho\lambda/35)\langle P_2\rangle \times$$
$$[7/\langle P_2\rangle - 5 - 2\langle P_4\rangle / \langle P_2\rangle] \qquad (14)$$
$$\alpha_5 = (\rho\lambda/2)\langle P_2\rangle \{(1/7)[(p^2-1)/(p^2+1)] \times$$
$$(3+4\langle P_4\rangle / \langle P_2\rangle)+1\} , \qquad (15)$$

where p is the molecular length-to-width ratio and P_4 is the 4th Legendre polynomial, which is also related to the orientational order. By utilizing Eq.(13), the viscous coefficient effective on the on- and off-times of the VA mode is deduced from Eqs. (14) and (15) as

$$\gamma_1 - \alpha_2^2/\eta_1 = \gamma_1 - 2\alpha_2^2/(\alpha_4 + \alpha_5 - \alpha_2)$$
$$= A(R, S)\gamma_1 \quad . \qquad (14)$$

Here, a coefficient A is a function of S, which is a measure of the orientational order consisting of $\langle P_2\rangle$ and $\langle P_4\rangle$, and R $(\equiv(p^2-1)/(p^2+1))$, which is a parameter related to the molecular aspect ratio.

As the coefficient A(R ,S), as well as γ_1, varies with the chemical structure of a molecule, the LC material can be optimized for use in VA or IPS LCD separately in terms of its viscous property. Nevertheless, in general for both VA- and IPS-LCD uses, the rotational viscosity γ_1 of LC material is preferred to be as small as possible. As shown in Fig.2, LC mixtures can be formulated to similarly exhibit a low rotational viscosity independent from the sign of their dielectric anisotropy $\Delta\varepsilon$.

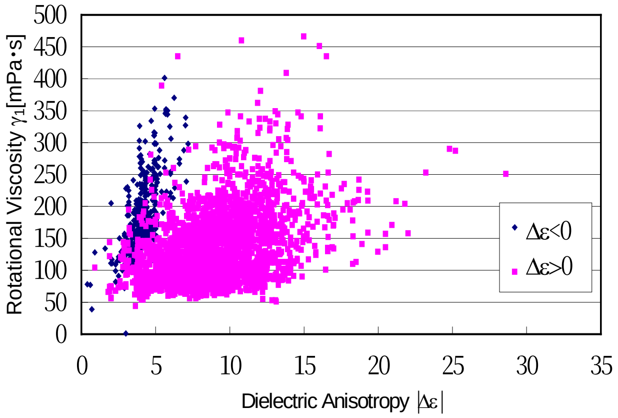

Fig.2 Rotational viscosity γ_1 and dielectric anisotropy $\Delta\varepsilon$ of LC mixtures measured at 20℃ [1]

4. Superior LC compounds featuring low γ_1

As is well known, a LC mixture is typically composed of more than ten compounds to fulfill the physical properties related to display performances. In this sense, in addition to a low viscosity for fast response, a large dielectric anisotropy enabling to reduce the operation voltage is also required for LC compounds to work effectively as the components of a mixture. The sign of the dielectric anisotropy is required to be either positive for an IPS-LCD use or negative for a VA-LCD use. Moreover, the optical birefringence of a LC mixture is required to be optimum from a viewpoint of the optical retardation of the LC medium in the LCD panel. Therefore, it is desired to have a variety of LC compounds with regard to their birefringence Δn.

The following Figs.3 - 6 show typical examples of superior LC compounds with different features and their physical properties.

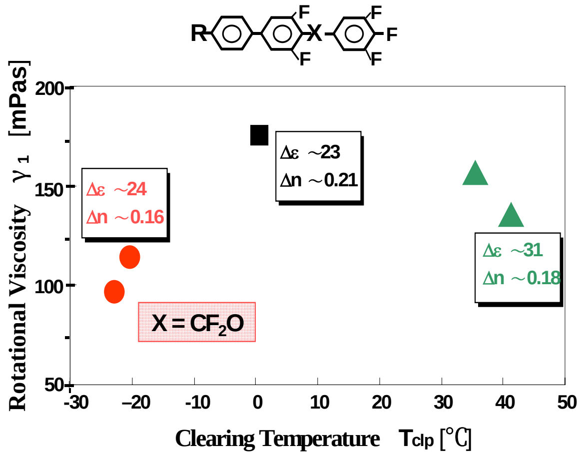

Fig.3 High- Δ n and positive- Δ ε LC substances featuring low γ 1 [12]

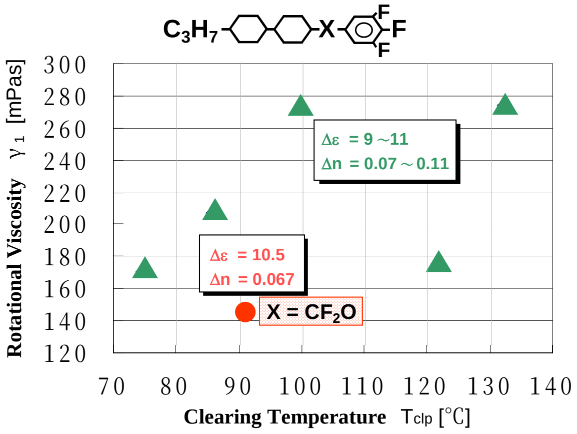

Fig.4 Low- Δ n and positive- Δ ε LC substances featuring low γ 1 [12]

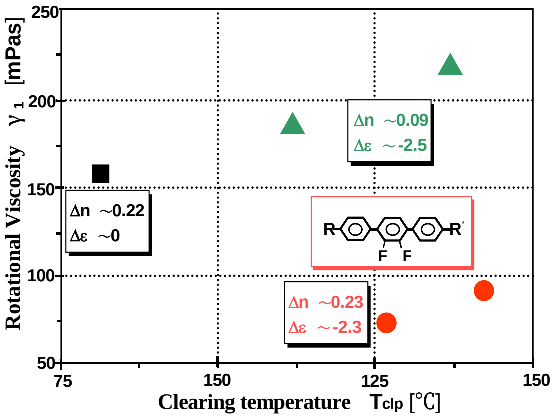

Fig.5 High- Δ n and negative- Δ ε LC substances featuring low γ 1 [12]

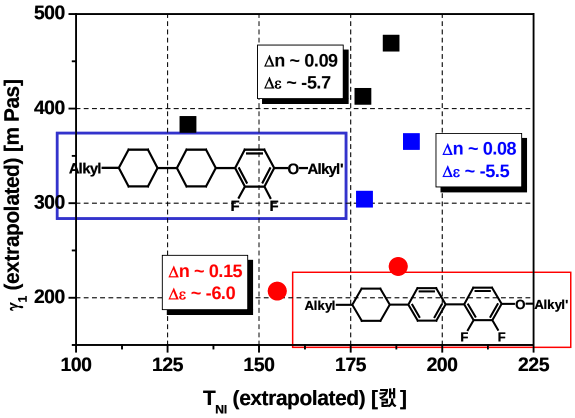

Fig.6 Low- Δ n and negative- Δ ε LC substances featuring low γ 1 [13]

5 Summary

The director response characteristics, corresponding to the optical response times of VA- and IPS-LCDs, were analyzed upon a basis of the Leslie-Ericksen theory, providing formulas of the response times as a function of the LC material constants. Furthermore, a molecular theory of the Leslie coefficient of viscosity was applied to prove that the response times of both VA- and IPS-LCDs are lineally proportional to the rotational viscosity under a practical assumption. It was also presented that, in case of VA-LCD, another coefficient acts to further reduce the effective viscosity and consequently the response times due to the contributions of the flow of LC molecules. From the viewpoint of the related material properties, LC mixtures and superior LC substances in formulating the mixtures were reviewed.

In addition to the VA-LCD and IPS-LCD, the OCB(Optically Compensated Bend)-LCD was recently commercialized, exhibiting the feature of fast response. It is also reported [14] that the flow of LC molecules contributes to the director response in the OCB-LCD, too. The so-called back-flow effect is now recognized to be playing an important role in the LCDs especially for TV applications, and efforts are also being made to develop novel methods to measure the related viscous property of LC materials [11,15]. These intensive studies will be of a great help for the development of further advanced LC materials actualizing LC-TV screens of an excellent picture quality.

Acknowledgements

The experimental results reviewed in this article were obtained by colleagues from Merck Ltd. at Atsugi in Japan and Merck KGaA at Darmstadt in Germany. The author would like to present his sincere thanks for their contributions to the development of LC materials and the characterization.

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