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Yosuke Iwata [a], Hiroyoshi Naito [a b], Hideo Ichinose [c], Melanie Klasen-Memmer [d] & Kazuaki Tarumi [d]

[a] Department of Physics and Electronics, Osaka Prefecture University, Sakai, Japan

[b] The Research Institute for Molecular Electronic Devices, Osaka Prefecture University, Sakai, Japan

[c] Liquid Crystals Division, Merck Ltd., Aikawa, Kanagawa, Japan

[d] Liquid Crystals Division, Merck KGaA, Frankfurter Strasse, Darmstadt, Germany

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Effective Rotational Viscosity of Vertical Alignment Nematic Liquid Crystal Cells

YOSUKE IWATA,[1] HIROYOSHI NAITO,[1,2] HIDEO ICHINOSE,[3] MELANIE KLASEN-MEMMER,[4] AND KAZUAKI TARUMI[4]

[1]Department of Physics and Electronics, Osaka Prefecture University, Sakai, Japan
[2]The Research Institute for Molecular Electronic Devices, Osaka Prefecture University, Sakai, Japan
[3]Liquid Crystals Division, Merck Ltd., Aikawa, Kanagawa, Japan
[4]Liquid Crystals Division, Merck KGaA, Frankfurter Strasse, Darmstadt, Germany

An effective rotational viscosity of vertical alignment (homeotropic) nematic liquid crystal (NLC) cells with negative dielectric anisotropy is derived from a theory of NLCs in which flow effects under the free-slip boundary condition are taken into account. The effective rotational viscosity is a function of the Leslie viscosity coefficients and is much smaller than the rotational viscosity at the initial stage of the director reorientation induced by external electric field to the NLC cells. This is the origin of fast response of vertical alignment of NLC cells.

Keywords Effective rotational viscosity; flow effects; negative dielectric anisotropy; nematic liquid crystal; vertical alignment

Introduction

Fast electrooptic response of vertical alignment nematic liquid crystal (VA-NLC) displays has recently attracted much industrial attention [1]. We have investigated flow effects on the electric-field-induced director reorientation in homeotropic NLC cells with negative dielectric anisotropy ($\Delta\varepsilon < 0$, where $\Delta\varepsilon = \varepsilon_{//} - \varepsilon_{\perp}$ is the dielectric anisotropy of NLCs, $\varepsilon_{//}$ and $\varepsilon_{\perp}$ being the dielectric constants parallel and normal to the director, respectively) from the analysis of the transient current due to the director rotation induced by step voltage excitation, and have found that the flow effects under the free-slip boundary condition for fluid flow much reduce the response time of VA-NLC displays [2,3].

There are five independent Leslie viscosity coefficients α_i ($i = 1, 2, \ldots, 5$) in NLCs [4–8]. Although the response time of NLC cells is governed only by the rotational

Address correspondence to Hiroyoshi Naito, Department of Physics and Electronics, Osaka Prefecture University, 1-1 Gakuen-cho, Sakai 599-8531, Japan. E-mail: naito@pe.osakafu-u.ac.jp

viscosity $\gamma_1 = \alpha_3 - \alpha_2$ in case where the flow effects on the director rotation are negligible [9–11], the flow effects significantly affect the director rotation in homeotropic NLC cells with $\Delta\varepsilon < 0$ [2,3]; the response time of homeotropic NLC cells is governed not only by γ_1 but also by the other Leslie viscosity coefficients of NLCs with $\Delta\varepsilon < 0$.

In this paper, we first derive a director dependent effective rotational viscosity of homeotropic NLC cells with $\Delta\varepsilon < 0$ using the Ericksen-Leslie theory for coupled reorientation and fluid flow of NLCs. We then numerically examine the value of the effective rotational viscosity of homeotropic NLCs with $\Delta\varepsilon < 0$ as a function of the tilt angle of the director and compare the value of the effective rotational viscosity with that of the rotational viscosity to show fast response in VA-NLC displays.

Theory

In general, The coupling between the orientation motion of the director and fluid flow is described using the continuity equation, the linear momentum equation, and the angular momentum equation (the Ericksen-Leslie equations), according to the continuum theory of Ericksen and Leslie [4–8]. We have applied these equations to the problem of one-dimensional distortion of the director in a homeotropic NLC cell along the z-axis, which is perpendicular to the electrode surfaces of the NLC cells and is in the direction of an applied electric field [2]. The NLC slab is confined between two parallel electrodes located at $z = 0$ and L. In this geometry, the director $\boldsymbol{n}$ in the homeotropic NLC cell is expressed as $(\sin\theta, 0, \cos\theta)$, where θ is the tilt angle between the director and the z-axis. The fluid velocity $\boldsymbol{v}$ at position z and time t has the x-component $v_x(z, t)$ only, because the z-component is zero owing to the continuity equation ($\operatorname{div} \boldsymbol{v} = 0$), and because the y-component vanishes owing to the symmetry of the distortion. The linear momentum equation and the angular momentum equation in the homeotropic NLC cell have thus been reduced to

$$a(\theta)\frac{\partial v_x(z,t)}{\partial z} + b(\theta)\frac{\partial \theta(z,t)}{\partial t} = \sigma(t), \tag{1}$$

$$\begin{aligned}\gamma_1\frac{\partial \theta(z,t)}{\partial t} = {} & -b(\theta)\frac{\partial v_x(z,t)}{\partial z} + g(\theta)\frac{\partial^2 \theta(z,t)}{\partial z^2} \\ & + \frac{1}{2}\frac{dg(\theta)}{d\theta}\left[\frac{\partial \theta(z,t)}{\partial z}\right]^2 \\ & - \frac{1}{2}\varepsilon_0\Delta\varepsilon E^2(z,t)\sin 2\theta(z,t),\end{aligned} \tag{2}$$

respectively [2], where $\sigma(t)$ is an integration constant with respect to z, ε_o is the dielectric permittivity of vacuum, $E(z, t)$ is the z-component of the electric field, and

$$\begin{aligned}a(\theta) = {} & \alpha_1 \sin^2\theta(z,t)\cos^2\theta(z,t) \\ & + \frac{1}{2}[-\gamma_2\cos 2\theta(z,t) + \alpha_3 + \alpha_4 + \alpha_5],\end{aligned} \tag{3}$$

$$b(\theta) = \frac{1}{2}[\gamma_2 \cos 2\theta(z,t) - \gamma_1], \tag{4}$$

$$g(\theta) = K_{11}\sin^2\theta(z,t) + K_{33}\cos^2\theta(z,t), \tag{5}$$

where K_{11} and K_{33} are the splay and bend elastic constants of the NLC, respectively. $\gamma_1 = \alpha_3 - \alpha_2$ denotes the rotational viscosity and $\gamma_2 = \alpha_3 + \alpha_2$.

Discussion

In the absence of flow ($v_x = 0$), the angular momentum equation [Eq. (1)] becomes

$$\gamma_1 \frac{\partial\theta(z,t)}{\partial t} = g(\theta)\frac{\partial^2\theta(z,t)}{\partial z^2} + \frac{1}{2}\frac{dg(\theta)}{d\theta}\left[\frac{\partial\theta(z,t)}{\partial z}\right]^2 - \frac{1}{2}\varepsilon_0\Delta\varepsilon E^2(z,t)\sin 2\theta(z,t). \tag{6}$$

It is found from Eq. (6) that the director response is governed only by γ_1 among five independent Leslie viscosity coefficients and becomes faster with decreasing γ_1 in case where the flow effects on the director reorientation are negligible. This is the case of homogeneous NLC cells with positive dielectric anisotropy ($\Delta\varepsilon > 0$) [3]. However, the director reorientation in homeotropic NLC cells with $\Delta\varepsilon < 0$ is significantly influenced by the flow of NLCs [2,3], and hence, Eq. (6) can not be applied to the analysis of the director reorientation process in homeotropic NLC cells with $\Delta\varepsilon < 0$.

We have shown in our previous paper [2] that the appropriate boundary condition for fluid flow on the field-induced director response in homeotropic NLC cells with $\Delta\varepsilon < 0$ is the free-slip boundary condition, which means that NLC molecules move freely on the electrodes and which corresponds to $\sigma(t) = 0$ in Eq. (1). From Eq. (1) under the free-slip boundary condition and Eq. (2), we have

$$\gamma_1^*(\theta) \frac{\partial\theta(z,t)}{\partial t} = g(\theta)\frac{\partial^2\theta(z,t)}{\partial z^2} + \frac{1}{2}\frac{dg(\theta)}{d\theta}\left[\frac{\partial\theta(z,t)}{\partial z}\right]^2 - \frac{1}{2}\varepsilon_0\Delta\varepsilon E^2(z,t)\sin 2\theta(z,t), \tag{7}$$

which is identical with Eq. (6) except that γ_1 is replaced by

$$\gamma_1^*(\theta) = \gamma_1 - \frac{b^2(\theta)}{a(\theta)}. \tag{8}$$

We call $\gamma_1^*(\theta)$ the effective rotational viscosity, which is dependent of θ. It should be noted that $\gamma_1^*(\theta)$ contains five independent Leslie viscosity coefficients. The second term in Eq. (8) reflects the effects of flow. We find from Eq. (7) that the director response in homeotropic NLC cells with $\Delta\varepsilon < 0$ is governed by $\gamma_1^*(\theta)$ and becomes faster with decreasing $\gamma_1^*(\theta)$. Equation (8) has been also derived from the Ericksen-Leslie equations but under different conditions and sample geometry that the periodicity of flow velocity and director fields was taken into account in nuclear-magnetic-resonance tubes containing NLC polymers [12].

Figure 1 shows the dependence of $\gamma_1^*(\theta)$ on θ calculated using the values of the Leslie viscosity coefficients of 4-methoxybenzylidene-4′-*n*-butylaniline (MBBA) with $\Delta\varepsilon < 0$ at 293 K ($\alpha_1 = -0.0215$ Pa s, $\alpha_2 = -0.153$ Pa s, $\alpha_3 = -0.001$ Pa s, and

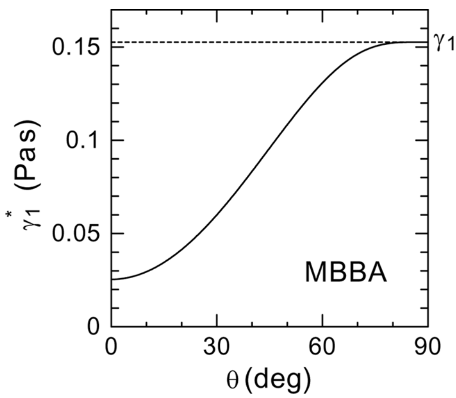

Figure 1. Dependence of an effective rotational viscosity γ_1^* of a homeotropic NLC cell on the polar angle of the director θ calculated using the Leslie viscosity coefficients of MBBA [13] with $\Delta\varepsilon < 0$.

$\alpha_4 + \alpha_5 = 0.217$ Pa s) [13]. We see that $\gamma_1^*(\theta)$ is much smaller than γ_1 at smaller values of θ. $\gamma_1^*(\theta)$ becomes larger with increasing θ and eventually is equal to γ_1. The result in Figure 1 shows that the director in homeotropic NLC cells with $\Delta\varepsilon < 0$ responses quickly at the initial stage of the director reorientation process. This is consistent with our earlier findings that the electric-field-induced director rotation in homeotropic NLC cells with $\Delta\varepsilon < 0$ is accelerated by fluid flow under the free-slip boundary condition at the initial stage of the director reorientation process and the flow velocity becomes smaller as the director rotates [3]. It is important to note that fast response in VA-NLC displays is understood from the polar-angle dependence of $\gamma_1^*(\theta)$.

We have shown that the complete set of the Leslie viscosity coefficients is determined from the analysis of transient current induced by step-voltage application to VA-NLC cells [14]. We have also shown that the director reorientation in VA-NLC cells subject to external electric field is not solely determined by γ_1 (other Leslie viscosity coefficients control the director reorientation as well) [15]. The polar-angle dependence of $\gamma_1^*(\theta)$ as shown in Figure 1, calculated from the complete set of the Leslie viscosity coefficients, may give us information concerning the response speed of director reorientation in VA-NLC cells. Such information would be valuable for the development of new NLC materials with $\Delta\varepsilon < 0$.

Conclusions

We have derived the effective rotational viscosity $\gamma_1^*(\theta)$ of homeotropic NLC cells with $\Delta\varepsilon < 0$ from the Ericksen-Leslie equations for coupled director orientation and fluid flow under the free-slip boundary condition. $\gamma_1^*(\theta)$ contains five Leslie viscosity coefficients. It is found that the response time of homeotropic NLC cells with $\Delta\varepsilon < 0$ reduces with decreasing $\gamma_1^*(\theta)$. We note that $\gamma_1^*(\theta)$ becomes much smaller than γ_1 as θ decreases. $\gamma_1^*(\theta)$ is an important quantity for understanding faster electrooptic response in VA-NLC displays and for the development of new NLC materials with $\Delta\varepsilon < 0$.

References

[1] Klasen, M., Bremer, M., & Tarumi, K. (2000). *Jpn. J. Appl. Phys.*, *39*, L1180.
[2] Iwata, Y., Naito, H., Inoue, M., Ichinose, H., Klasen-Memmer, M., & Tarumi, K. (2004). *Jpn. J. Appl. Phys.*, *43*, L1588.
[3] Iwata, Y., Naito, H., Inoue, M., Ichinose, H., Klasen-Memmer, M., & Tarumi, K. (2008). *Jpn. J. Appl. Phys.*, *47*, 8230.
[4] Ericksen, J. L. (1960). *Arch. Ration. Mech. Anal.*, *4*, 231.
[5] Leslie, F. M. (1966). *Q. J. Mech. Appl. Math.*, *19*, 357.
[6] Chandrasekhar, S. (1992). *Liquid Crystals*, 2nd ed., Cambridge University Press: Cambridge.
[7] De Gennes, P. G. & Prost, J. (1993). *The Physics of Liquid Crystals*, 2nd ed. Oxford University Press: Oxford.
[8] Kleman, M. & Lavrentovich, O. D. (2003). *Soft Matter Physics: An Introduction*, Springer-Verlag: New York.
[9] Naito, H., Yoshida, K., Okuda, M., & Sugimura, A. (1993). *J. Appl. Phys.*, *73*, 1119.
[10] Imai, M., Naito, H., Okuda, M., & Sugimura, A. (1994). *Jpn. J. Appl. Phys.*, *33*, L119.
[11] Imai, M., Naito, H., Okuda, M., & Sugimura, A. (1995). *Jpn. J. Appl. Phys.*, *34*, 3170.
[12] Martins, A. F., Esnault, P., & Volino, F. (1986). *Phys. Rev. Lett.*, *57*, 1745.
[13] Kneppe, H., Schneider, F., & Sharma, N. K. (1982). *J. Chem. Phys.*, *77*, 3203.
[14] Iwata, Y., Naito, H., Inoue, M., Ichinose, H., Klasen-Memmer, M., & Tarumi, K. (2008). *Thin Solid Films*, *517*, 1421.
[15] Iwata, Y., Naito, H., Inoue, M., Ichinose, H., Klasen-Memmer, M., & Tarumi, K. (2008). *Thin Solid Films*, *517*, 1417.