ULTRAFAST ELECTRO-OPTIC SWITCHING IN LIQUID CRYSTALS

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ABSTRACT

We present the nanosecond electro-optic response of liquid crystals in the nematic and isotropic phases. The results demonstrate that in the isotropic phase (close to the phase transition), both the dielectrically positive and negative liquid crystals have larger field induced birefringence than in the nematic phase. However, a nematic mixture with negative dielectric anisotropy exhibits two advantages, namely, the field induced birefringence is weakly dependent on temperature, and the characteristic time of this nanosecond response does not depend on the electric field. The observed nanosecond response can benefit the ultrafast electro-optic applications.

Keywords: *Nanosecond switching, Order parameter, Nematic liquid crystal, Electric field*

1. INTRODUCTION

Nematic liquid crystal (NLC) has been widely used in the electro-optic devices, such as displays, because of its optic and electric anisotropies, the birefringence $\Delta n = n_e - n_o$ and the dielectric anisotropy $\Delta\varepsilon$, where n_e and n_o are the extraordinary and ordinary refractive indices, respectively. The long axes of the NLC molecules are on average aligned parallel to the optic axis, which is also known as the director $\hat{\mathbf{n}}$. Traditionally, the switching of a liquid crystalline electro-optic device is controlled by reorientation of the director by an external electric field. Although the switching-on time is controlled by the applied voltage and could be sufficiently fast, the relaxation time of the switching-off process is relatively slow, about several milliseconds. By realigning an NLC in a polymer network [1], the response time was reduced below milliseconds. However, ultrafast electro-optic applications require the response time in the nanosecond timescale.

Herein, we present a brief introduction of experimental methods and recent results for the nanosecond electro-optic response in liquid crystals (LC) in both nematic and isotropic phases [2-5].

2. THEORETICAL BACKGROUND AND EXPERIMENT METHOD

In order to achieve nanosecond electro-optic response of LCs in the nematic phase, we employ such geometries in which an electric field does not cause the reorientation of the director. Namely, we apply the electric field along the *x* axis (Fig.1) use the planar and homeotropic cells for NLCs with $\Delta\varepsilon < 0$ and $\Delta\varepsilon > 0$, respectively. In this case, the applied electric field modifies the degree of molecular order, called the order parameter (OP), and the spectrum of director fluctuations (SDF). The modification of the OP takes place on the timescale of nanoseconds, so we call this effect nanosecond electric modification of the order parameter (NEMOP). In the NLCs with $\Delta\varepsilon < 0$, both the *uniaxial* NEMOP and the *biaxial* NEMOP are observed [2].

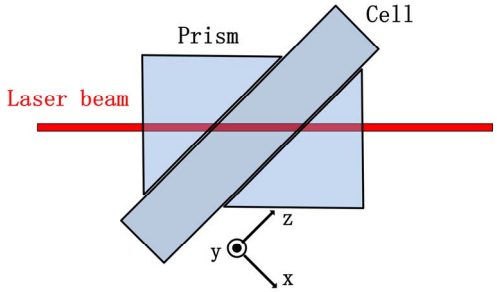

Fig. 1 Experimental geometry. The angle between the direction of a probing beam inside the LC and cell boundaries is $45°$. The electric field is applied along the x axis.

In the isotropic melt of an LC, the external electric field induces a uniaxial order of the molecules, see Fig. 2 (a) and (b). This effect is well known as the Kerr effect. In this case, the induced optic axis of the LC is along the applied electric field. The characteristic time of this isotropic-to-uniaxial phase is on the timescale of nanoseconds, at the temperature well above the nematic-isotropic transition temperature T_{NI}.

All the above-mentioned mechanisms change the optic properties of an LC, see Fig. 2, such as birefringence $\Delta n(E)$. In order to measure the optic response caused by the change of birefringence, we use a typical optical scheme, in which a laser beam passes through crossed polarizers with the cell and an optic

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compensator between them. The LC cell is sandwiched between two right angle prisms, Fig. 1. Some parasitic effects, which are not associated with the birefringence change, may also affect the intensity of the transmitted beam. Their influences are eliminated by using a two-setting scheme of the optical compensator that allows one to subtract these parasitic contributions from the intensity change caused by the birefringence change δn of the LC [3]. For an NLC with $\Delta\varepsilon < 0$, we choose the z axis along the rubbing direction of the planar cell, so that the contribution to the optic response from the modification of SDF is excluded. In this geometry, the optic response comes from the modification of the biaxial and uniaxial OPs [3]. Thus, we call it geometry BU.

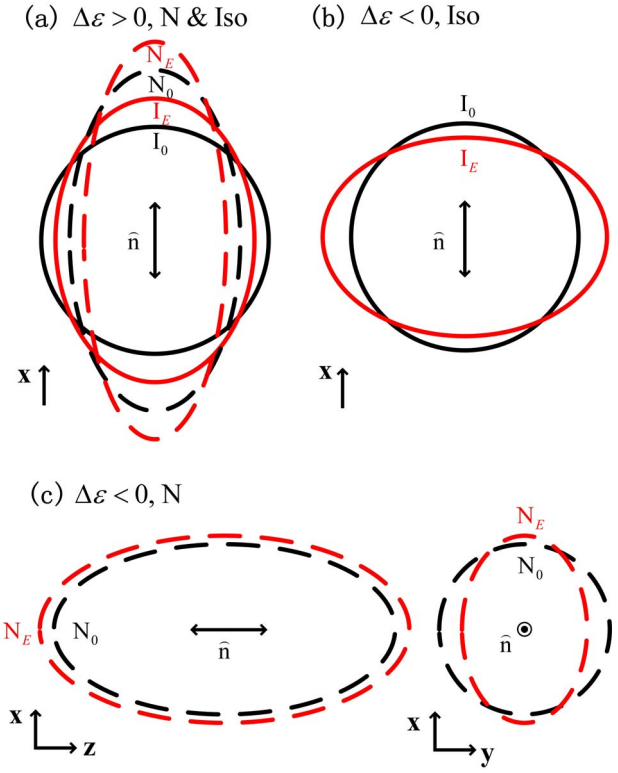

Fig. 2. Electric modification of OPs of LCs with $\Delta\varepsilon > 0$ (a) and $\Delta\varepsilon < 0$ (b and c). The circle I_0 and the ellipse N_0 represent the field-free state of the isotropic and nematic phases, respectively. The ellipses I_E and N_E correspond to the field-on states of the isotropic and nematic phases, respectively.

The field-induced birefringence can be calculated from the Fresnel equation [3, 5]. The field-induced birefringence δn_{BU}, δn_H, and δn_{iso} correspond to the NLCs with $\Delta\varepsilon < 0$, $\Delta\varepsilon > 0$, and their isotropic phase, respectively.

$$\delta n_{BU} = \frac{n_o/n_e + 1 + n_e/n_o}{6\sqrt{n_e^2 + n_o^2}}\left(\delta\tilde{\varepsilon}_u + \frac{3}{2}\delta\tilde{\varepsilon}_b\right), \qquad (1)$$

$$\delta n_H = \frac{\delta\tilde{\varepsilon}_u + 3\delta\tilde{\varepsilon}_f}{3} \left(\frac{n_e^2 n_o^2 - 2n_e^4 + 2n_o^4 + 2n_e^3\sqrt{2n_e^2 - n_o^2}}{2n_e^3 n_o\sqrt{4n_e^2 - 2n_o^2}}\right), \qquad (2)$$

and $$\delta n_{iso} = \frac{\sqrt{2}\delta\tilde{\varepsilon}_u}{4n_{iso}}, \qquad (3)$$

where $\delta\tilde{\varepsilon}_b$, $\delta\tilde{\varepsilon}_u$, and $\delta\tilde{\varepsilon}_f$ denote the contributions of optic properties originating from the changes of the biaxial OP, uniaxial OP, and SDF, respectively.

3. EXPERIMENTAL RESULTS

When an external electric field is applied, the birefringence of an LC changes $\delta n = \Delta n_{E>0} - \Delta n_{E=0}$. For both positive and negative dielectric LCs, this optic response occurs on the timescale of nanoseconds, Fig. 3.

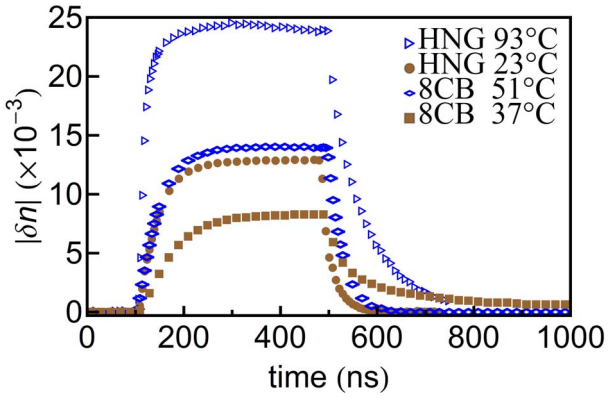

Fig. 3. Dynamics of field-induced birefringence of HNG715600-100 (HNG, $E = 1.3\times10^8$ V/m) and 8CB ($E = 6.5\times10^7$ V/m) in the nematic (23°C and 37°C) and isotropic (51°C and 93°C) phases.

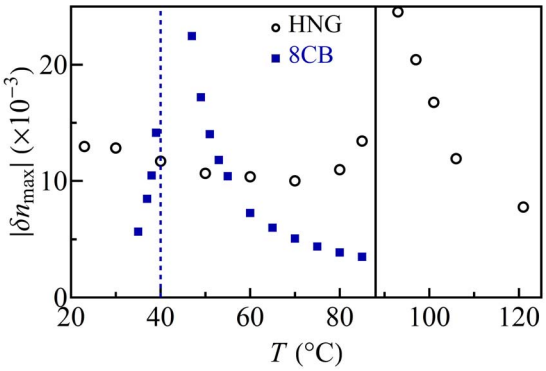

Fig. 4. Amplitude of δn for HNG (open circles) and 8CB (filled squares) as function of temperature at the fields $E = 1.3\times10^8$ V/m and 6.5×10^7 V/m, respectively. The vertical lines show the T_{NI} of HNG (solid line) and 8CB (dashed line).

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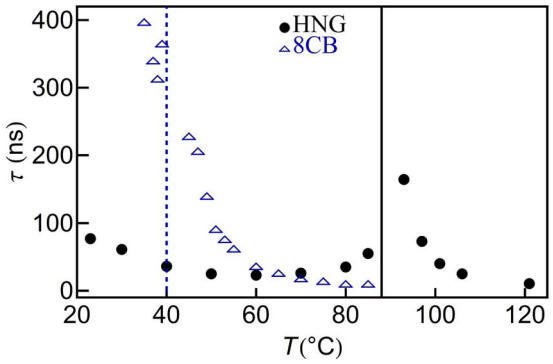

Fig. 5. Temperature dependences of characteristic time of HNG and 8CB at the electric fields $E = 1.3\times10^8$ V/m and 6.5×10^7 V/m, respectively. The vertical lines show the T_{NI} of HNG (solid line) and 8CB (dashed line).

3.1 Electric-optic response of NLCs with $\Delta\varepsilon < 0$

We observed the NEMOP effect in 13 nematic materials with $\Delta\varepsilon < 0$ in geometry BU [4]. It turns out that the NEMOP response can be enhanced by choosing the NLCs with larger dielectric anisotropy and with higher filed-free birefringence. The field-induced birefringence δn on the order of 0.01 was obtained at the room temperature in the mixture, HNG715600-100 (HNG, $\Delta\varepsilon = -12.2$, $T_{NI} = 88$°C, purchased from Jiangsu Hecheng Display Technology). The characteristic response time is nanoseconds or tens of nanoseconds at both the switch-on and switch-off process, as expected. The response times do not depend on the electric field, as expected.

The field-induced birefringence of HNG in the isotropic phase close to T_{NI} is generally larger than that in the nematic phase, Fig. 3 and 4. It can be explained by the fact that, the field-free order parameter of the isotropic state is zero so the electric field can induce a relatively large OP. In the isotropic phase far away from T_{NI}, the characteristic times $\tau = \mathrm{Max}[\tau_{on}, \tau_{off}]$ of HNG are several nanoseconds, Fig.5.

The field-induced birefringence of HNG in both studied phases shows a quadratic dependence on the electric field when a low electric field is applied. At strong electric fields, the field-induced birefringence grows slower than E^2, as expected from the higher order terms in the Landau-de Gennes model [5].

3.2 Electric-optic response of NLCs with $\Delta\varepsilon > 0$

In the isotropic phase close to T_{NI}, the LC 8CB ($\Delta\varepsilon = 7.6$, $T_{NI} = 40$°C, purchased from Merck) exhibits larger δn than in the nematic phase, see Fig.3. The relatively slow relaxation process of 8CB in the nematic phase is caused by the contribution from the modification of SDF. The field-induced birefringence of 8CB strongly depends on the temperature in the nematic and isotropic phases, Fig. 4. Close to the phase transition, the characteristic time of 8CB is larger, Fig. 5. The field induced birefringence grows faster than E^2 at strong electric fields, as expected [5].

4. CONCLUSION AND DISCUSSION

We briefly introduced our experimental methods and recent results. The designed incident geometries were used to measure the optic response associated with nanosecond field-induced birefringence in both the nematic and isotropic phases. We succeeded in observing the optic response on the timescale of nanoseconds for a variety of materials with positive and negative dielectric anisotropies. The nematic mixture HNG with a negative dielectric anisotropy and a broad nematic temperature range has more potential for the electro-optic applications, because the field-induced birefringence weakly depends on the temperature and the response time is independent on the electric field.

ACKNOWLEDGMENTS

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