

# Fast Switching Liquid Crystals for Color-Sequential LCDs

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**Abstract**—High birefringence ( $0.3 < \Delta n < 0.4$ ) and relatively low-viscosity liquid crystal mixtures containing isothiocyanato tolane and isothiocyanato terphenyl liquid crystals are developed. A twisted-nematic (TN)  $1.6\text{-}\mu\text{m}$  thin cell for color-sequential liquid crystal display with  $\sim 1\text{-ms}$  response time is demonstrated.

**Index Terms**—Color sequential display, high-birefringence liquid crystals, liquid crystal display (LCD), response time.

## I. INTRODUCTION

HIGH-BIREFRINGENCE ( $\Delta n$ ) liquid crystals are attractive for improving the response time of a display device through cell-gap ( $d$ ) reduction [1]–[3]. In a  $90^\circ$  twisted-nematic (TN) cell, the Gooch–Tarry first minimum leads to the following equation [1]:

$$d\Delta n/\lambda = \sqrt{3}/2 \quad (1)$$

where  $\lambda$  is the wavelength. Meanwhile, the decay time is related to the cell gap and visco-elastic coefficient ( $\gamma_1/K_{22}$ ) as

$$\tau_{\text{off}} = \gamma_1 d^2 / (K_{22} \pi^2). \quad (2)$$

Fast response time is especially important for color-sequential liquid crystal displays (LCDs) using blinking backlight [2] or primary-color (RGB) light-emitting diodes (LEDs). [3], [4] In the RGB LED-backlit color-sequential LCDs, the pigment color filters can be eliminated, which not only reduces the LCD cost but also triples the device resolution. However, to avoid a color break, the  $LC$  response time (gray to gray) should be kept below 5 ms. Commercially available high- $\Delta n$  TFT-grade  $LC$  mixtures usually have  $\Delta n \sim 0.2$ . Under such a circumstance, to satisfy the Gooch–Tarry’s first minimum condition would require a cell gap of  $\sim 2.5\ \mu\text{m}$  [5]. The resultant response time would exceed 5 ms. Thus, there is an urgent need to develop high- $\Delta n$  and low-viscosity  $LC$  mixtures so that the cell gap can be suppressed to  $2\ \mu\text{m}$  or less. The objective here is to formulate a high- $\Delta n$  nematic mixture which will satisfy the Gooch–Tarry’s first minimum condition using a thin ( $< 2\ \mu\text{m}$ )  $LC$  cell.

High melting temperature, increased viscosity, and insufficient UV stability are the major concerns for the high- $\Delta n$   $LC$

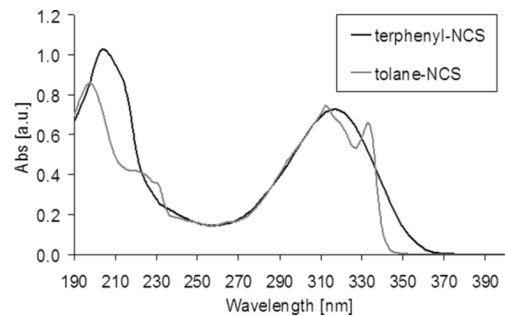


Fig. 1. UV absorption spectra of NCS-based tolane and terphenyl compounds.

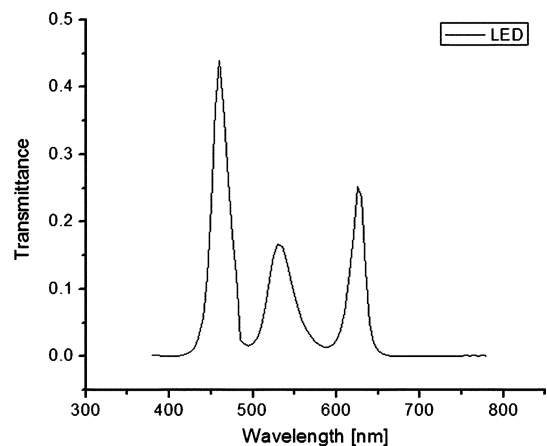


Fig. 2. Emission spectra of a typical RGB LED backlight.

materials. Some isothiocyanato tolanes and terphenyls [6] have been found to exhibit high  $\Delta n$ , modest rotational viscosity, and large dielectric anisotropy. Fig. 1 shows the measured absorption spectra of the two compounds employed [7], while Fig. 2 refers to the typical emission spectra of the RGB LED backlights. From Fig. 2, there is no UV content in the RGB LEDs. As a result, the concern for UV-induced photostability for high- $\Delta n$  LCs is greatly relieved. A detailed studies of photo and thermal stability of some  $LC$  compounds can be found in [7] and [8]

The  $\Delta n$  in the range of 0.30–0.40 enables a  $1.2\text{--}1.6\text{-}\mu\text{m}$  cell gap to be used for achieving less than 2-ms response time so that a color-sequential LCD without a color break can be realized. Although such a thin cell is presently still challenging to fabricate for large-size panels, it is stretchable for small-size LCDs, e.g., cell phones and PDAs. The  $90^\circ$  TN cell was chosen because of its simplicity, low production cost, and efficient white-light modulation. This device concept can also be extended to TN-based notebook computers where the viewing angle may not be a critical issue.

## II. EXPERIMENTAL TECHNIQUES

All of the electrooptic measurements were carried out using  $1.6\text{-}\mu\text{m}$  TN cells with ITO electrodes coated in the inner sides

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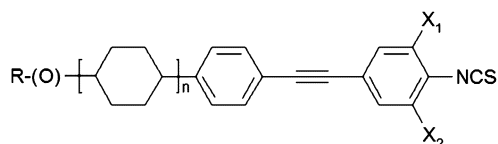


Fig. 3. Structure I.

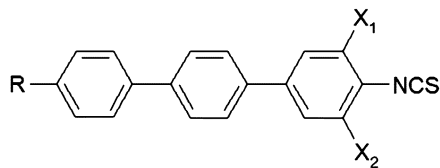


Fig. 4. Structure II.

of the glass substrates. A thin polyimide layer was overcoated on ITO electrodes, baked, and rubbed to form a  $90^\circ$  TN cell. A small pretilt angle of  $2^\circ$  was introduced. A linearly polarized He-Ne laser with  $\lambda = 633$  nm was used as the light source for the electrooptic measurements. The temperature of the TN cell was stabilized and controlled by a Linkam heating/cooling system (LTS 350 with temperature programmer THMS). The electrooptical response time was determined by measuring the 10%–90% transmittance change. The absorption spectra of the pure LC compounds were measured by a spectrophotometer from hexane solutions.

### III. EXPERIMENTAL RESULTS

Tolane and terphenyl liquid crystals exhibit a reasonably high  $\Delta n$ , low viscosity, and good chemical, photo, and thermal stability. Despite these advantages, alkyl and alkoxy-tolanes are known to have limited mesomorphic performance [9]. Similar properties are also found in isothiocyanates [6]. Therefore, coupling tolane or terphenyl rigid core and NCS terminal group would lead to a high birefringence and large dielectric anisotropy while preserving a relatively low viscosity compared with that of cyano analogues. Terphenyl and tolane isothiocyanates exhibit a high birefringence, however, most NCS compounds are smectics and not suitable for nematic mixtures. Lateral substitution is necessary to suppress the smectic phase and, in the meantime, lower the melting temperatures [10], [11]. Low melting temperature is particularly important for display applications.

The tolane (structure I) and terphenyl (structure II) we used for formulating high-birefringence LC mixtures are given in Figs. 3 and 4, where R is up to five carbons alkyl chain,  $n = 0, 1$ , and  $X_1$  and  $X_2$  are laterally substituted fluorine or hydrogen. Detailed properties of different homologues can be found in [6]–[11]. Using these compounds, we have prepared several eutectic mixtures with birefringence ranging from 0.30 to 0.40 in the visible spectral region.

The mixture (designated as LC-1) with  $\Delta n = 0.37$  was chosen for experimental studies. Its physical properties are listed in Table I. Fig. 5 shows the measured voltage-dependent transmittance curves of the  $1.6\text{-}\mu\text{m}$  TN cell at  $\lambda = 633$  nm and four temperatures:  $T = 25^\circ\text{C}$ ,  $35^\circ\text{C}$ ,  $45^\circ\text{C}$ , and  $50^\circ\text{C}$ .

The threshold voltage is about  $1 V_{\text{rms}}$  and the dark state voltage is  $\sim 2.5 V_{\text{rms}}$ . The low operating voltage results from the relatively large  $\Delta\epsilon$  of the LC-1 mixture. As the temperature

TABLE I  
PHYSICAL AND ELECTROOPTIC PROPERTIES OF THE INVESTIGATED MIXTURES

LC Mix	$T_{\text{MP}}$ [°C]	$T_c$ [°C]	$V_{\text{TH}}$ [ $V_{\text{rms}}$ ]	$\epsilon_{\parallel}$	$\epsilon_{\perp}$	$\Delta\epsilon$	$\Delta n$	$\gamma_1/K_{11}$ [ $\text{ms}/\mu\text{m}^2$ ]
LC-1	<30	100	1.4	20.9	4.7	16.2	0.37	12.5

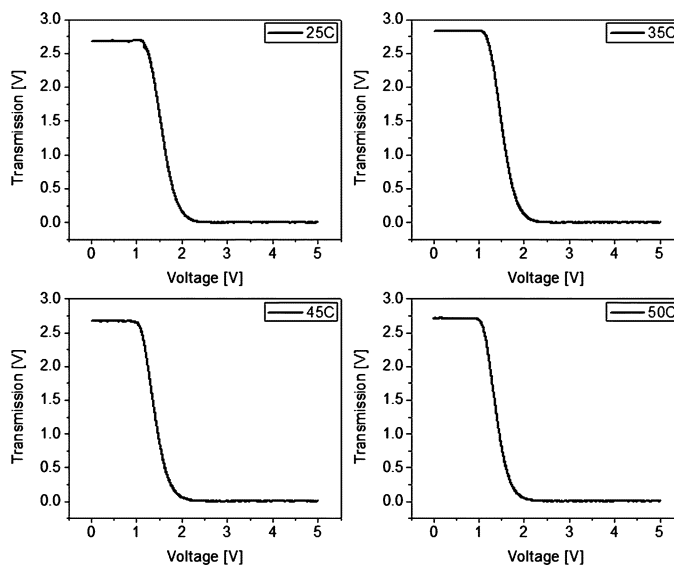


Fig. 5. Voltage-dependent transmittance of the  $1.6\text{-}\mu\text{m}$  TN cell filled with the LC-1 mixture.  $\lambda = 633$  nm.

TABLE II  
MEASURED RISE AND DECAY TIMES OF THE  $1.6\text{-}\mu\text{m}$  TN LC CELL

Temperature [°C]	Rise Time [ms]	Decay Time [ms]	Total [ms]
25	0.07	1.71	1.78
35	0.04	1.14	1.18
45	0.03	0.94	0.97
50	0.03	0.69	0.72

increases, both threshold voltage and dark state voltage slightly decrease.

Fig. 6 shows the measured response time of the  $1.6\text{-}\mu\text{m}$  cell at  $25^\circ\text{C}$ ,  $35^\circ\text{C}$ ,  $45^\circ\text{C}$ , and  $50^\circ\text{C}$ . To reduce rise time, an overdrive voltage was applied. [12]–[14] This overdrive method has been commonly used in order to shorten the rise time at different gray levels.

Table II summarizes the measured rise and decay times at the specified temperatures. The fast rise time results from the overdrive voltage, but the decay time is independent of the overdrive voltage. The decay time of the  $1.6\text{-}\mu\text{m}$  TN cell at  $25^\circ\text{C}$  is 1.71 ms. As the temperature increases, both rise time and decay time decrease.

In an LCD TV, the polarizer employed absorbs a significant amount of the backlight. The absorbed light is converted to heat, which, in turn, increases the panel's temperature. It is quite common that the LCD panel temperature could reach  $\sim 40^\circ\text{C}$ . At this temperature, the total response time is about 1 ms, as shown in Table II.

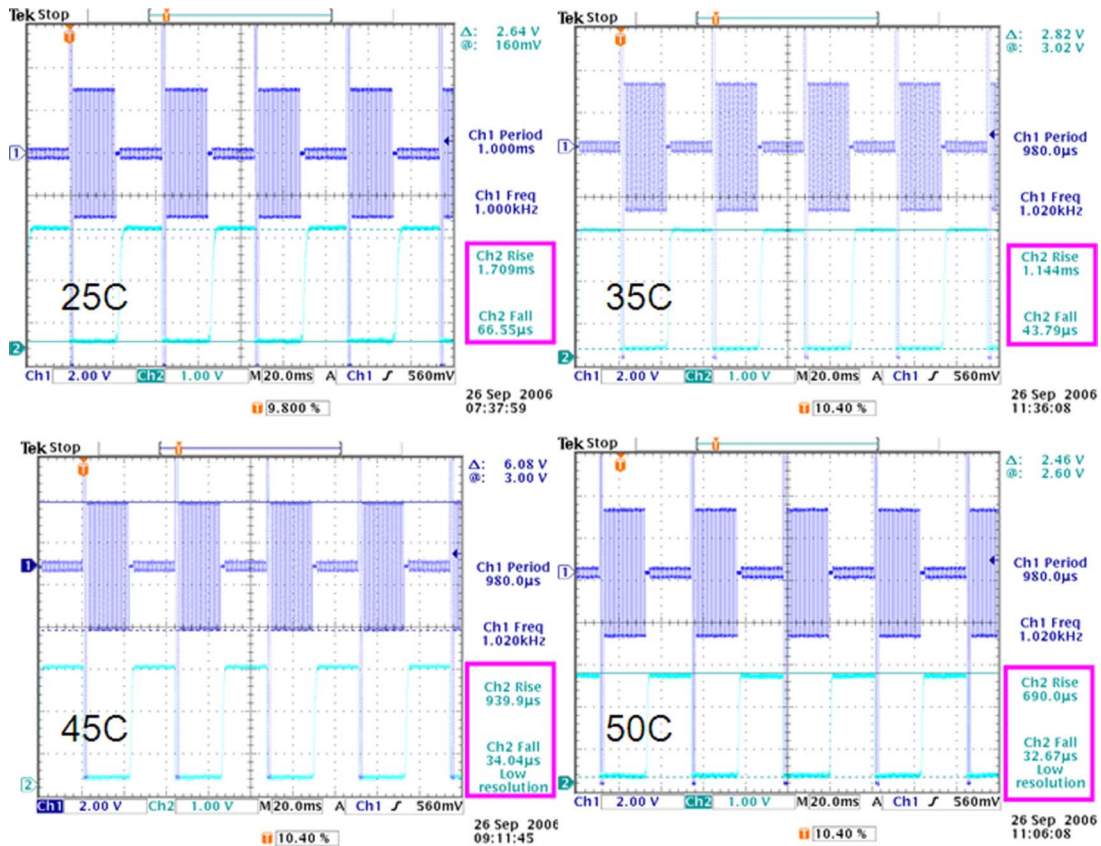


Fig. 6. Measured response of the 1.6- $\mu\text{m}$  TN cell at different temperatures.

#### IV. CONCLUSION

A high-birefringence, relatively low-viscosity, and wide-nematic-range LC mixture was successfully formulated. Using a 1.6- $\mu\text{m}$  TN cell, the response time of less than 2 ms was obtained. This material enables color-sequential LCDs using RGB LED backlights. Although fabricating such a thin cell gap remains technologically challenging, it is doable for small-size LCD panels, such as cell phones and PDAs. In small panels, the cell-gap uniformity is easier to control.

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