Display Technology Letters

Submillisecond Gray-Level Response Time of a Polymer-Stabilized Blue-Phase Liquid Crystal

Kuan-Ming Chen, Sebastian Gauza, Haiqing Xianyu, and Shin-Tson Wu

***Abstract*—The gray-to-gray response time of a polymer-stabilized blue-phase liquid crystal is investigated. As the voltage increases, rise time decreases gradually but decay time remains unchanged. A set of analytical equations is used to fit the measured results, and an acceptable agreement is obtained.**

***Index Terms*—Blue phase liquid crystal, color sequential display, gray-to-gray (GTG) response time.**

I. Introduction

BLUE-PHASE liquid crystal display (BP-LCD) [1]–[3] is emerging rapidly because it exhibits following attractive features. 1) It does not require any LC alignment layer, such as polyimide, which not only simplifies the manufacturing processes but also reduces the cost. 2) Its response time is in the submillisecond range, which enables color-sequential displays if an RGB LED backlight is used. The elimination of color filters improves the optical efficiency by $\sim 3X$ and triples the device resolution. 3) The dark state of a blue-phase LCD is optically isotropic so that its viewing angle is wide and symmetric [4]. The commonly used optical compensation films could be removed, depending on the applications. 4) The transmittance is insensitive to the cell gap as long as it exceeds 2–3 μm [5]. This cell gap insensitivity is particularly beneficial for large-panel LCDs from manufacturing yield viewpoint.

For TV applications, the majority of displayed images are in gray levels. Therefore, gray-to-gray (GTG) response time is fundamentally important. In nematic LCDs, GTG response time has been well explored [6]. However, almost all the previous BPLC studies focus on black-to-white transition; very little GTG response time information has been reported. The operation principles of nematic and BP LCs are different in twofold: 1) Nematic LC is based on anisotropic-to-anisotropic LC director reorientation, but BPLC is based on Kerr-effect- induced isotropic-to-anisotropic transition. 2) Nematic LC has a threshold voltage, but BPLC does not. In this paper, we report the GTG response time of a polymer-stabilized (PS) BPLC.

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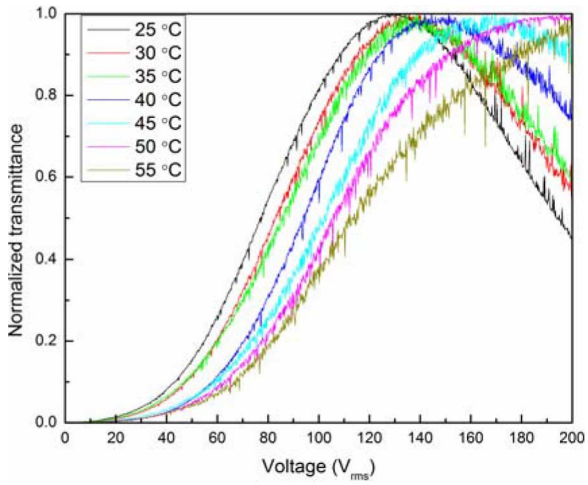

Fig. 1. Voltage dependent normalized transmittance of the PS-BPLC in an IPS cell from 25 °C to 55 °C. $\lambda = 632.8$ nm. Polarizers are crossed.

II. Experiment

High birefringence cyanates were used for mixture formulation. In order to induce blue phase structure, a mixture with birefringence of 0.27 °C and 100 °C clearing temperature was mixed with chiral agents of CB15 and R-1011, both from Merck. Mixture was further doped with reactive monomer RM257 and EHA acrylic ester. The BPLC mixture was filled into an in-plane-switching (IPS) cell. The cell gap was controlled at ~ 13 μm. The top substrate was a plain glass and the bottom glass substrate was coated with zigzag ITO (indium tin oxide) electrodes. The electrode width is 5 μm and electrode spacing is 10 μm. During the optical measurement process, the PS-BPLC cell was placed between two crossed polarizers. A 10-mW CW He-Ne laser ($\lambda = 633$ nm) was used as the probing light source.

III. Result and Discussions

First we measured the temperature effect on the voltage- dependent transmittance (VT) curves. Results are shown in Fig. 1.

TABLE I
MEASURED RESPONSE TIMES OF A PS-BPLC CELL BETWEEN DIFFERENT GRAY LEVELS.

		Rise time (μs)							
Fall time (μs)		T0	T10	T20	T40	T60	T80	T90	T100
	T0	X	370.6	208.4	57.6	58.6	57.4	57.6	56.9
	T10	282.2	X	526.0	162.2	121.9	122.4	100.2	57.8
	T20	262.5	307.1	X	300.4	271.4	227.5	156.2	56.6
	T40	341.0	279.8	208.6	X	342.7	357.7	296.6	31.6
	T60	376.8	259.8	197.7	253.8	X	247.9	350.9	251.4
	T80	337.4	313.9	283.7	343.3	202.9	X	185.6	367.3
	T90	381.4	258.1	191.4	223.5	259.0	172.2	X	273.5
	T100	367.5	376.0	344.0	372.8	149.5	321.4	347.9	X

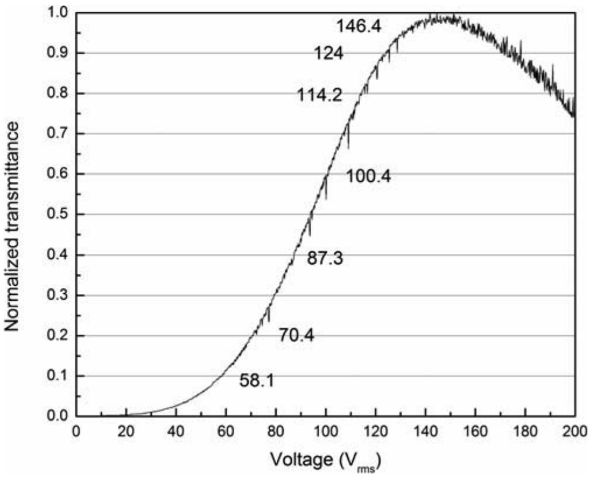

Fig. 2. Corresponding voltages of the eight gray levels in a polymer-stabilized BPLC cell at 40°C.

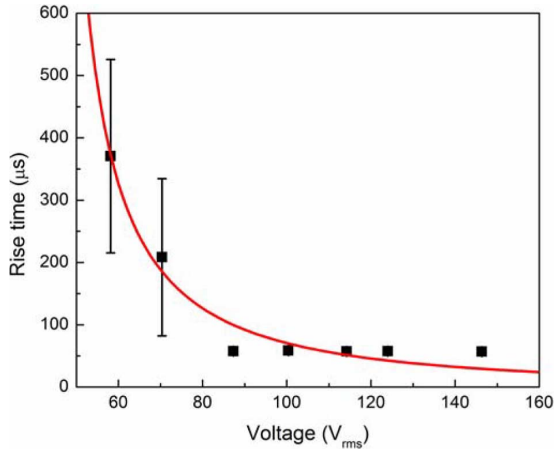

Fig. 3. Measured rise time of the PS-PBLC cell from T0 to each gray level. Black solid squares are measured data and red line is the fitting curve.

Here we normalize the transmittance to that of two open polarizers, which is $\sim 34\%$. From Fig. 1, as the temperature increases the VT curve shifts to the right side because of the decreased birefringence. For the GTG measurements, we fixed the temperature at 40 °C.

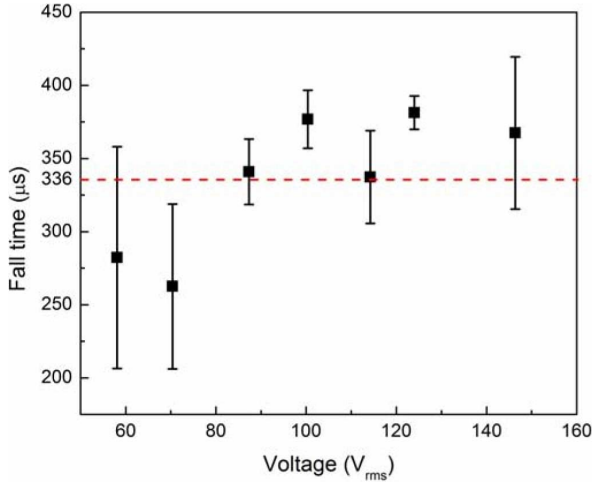

Fig. 4. Measured decay time of the PS-PBLC cell from each gray level to T0. Black solid squares are the measured results and dashed red lines stand for average fall time, which is 335.5 μs.

One of the major attractions of BPLC is its submillisecond response time [7]–[10]. In the past, most of blue-phase LC materials exist in a fairly narrow temperature range so that the temperature control should be very precise. Here, our PS-BPLC exhibits a fairly wide operating temperature range (from below 25 °C to 55 °C), as shown in Fig. 1.

To measure the GTG response time, we divide the VT curve into 8 gray levels (by convenience) with their corresponding voltages indicated in Fig. 2. From Fig. 2, T10 (10% normalized transmittance) occurs at 58.1 V_{rms}, T20 at 70.4 V_{rms}, etc. The measured rise time (from 10% to 90% of the peak signal) and fall time (from 90% to 10% of the peak signal) between each gray level are listed in Table I. Here, the upper triangle represents the rise time between two corresponding gray levels, while the lower triangle is for the fall time. Most of the rise time and fall time between gray levels is under 400 μs, and the total response time $(\text{rise} + \text{fall})$ is < 1 ms.

Figs. 3–6 show the measured rise time and decay time between T0, T10 and other gray levels. The solid lines in Figs. 3 and 5 represent fittings with following equations [11], [12]:

$$\tau_{off} = \frac{\gamma_1}{E_c^2 \varepsilon_0 \Delta\varepsilon} \tag{1}$$

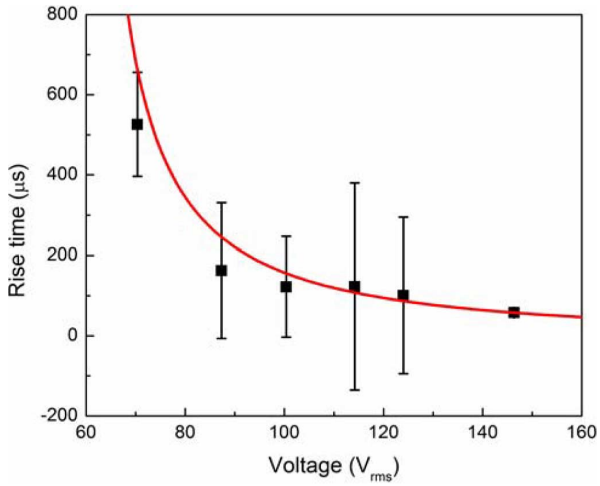

Fig. 5. Measured rise time of the PS-PBLC cell from T10 to higher gray levels. The black solid squares are the measured results and red is the fitting curve.

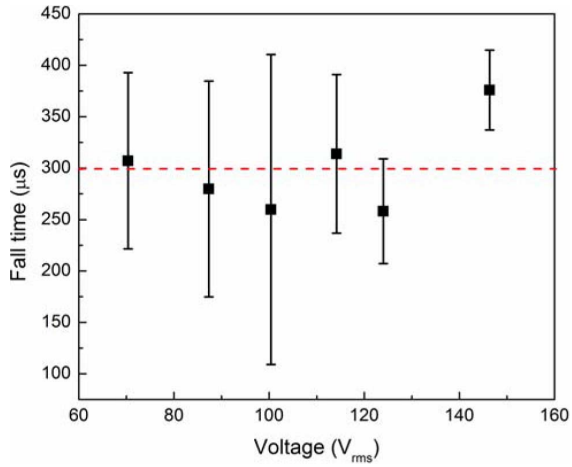

Fig. 6. Measured fall time of the PS-PBLC cell from higher gray levels to T10. The black solid squares are the measured results. The dashed red lines denote the average value of the measured result, which is 299.1 μs.

$$\tau_{on} = \frac{\tau_{off}}{\left(\frac{V}{V_c}\right)^2 - 1}. \tag{2}$$

Here, γ_1 is the rotational viscosity, E_c is the critical field and V_c critical voltage for unwinding the pitches, and $\Delta\epsilon$ is the dielectric anisotropy of the BPLC. Due to the fast response time of the BPLC sample, ripples appear during the transient signal-on state. For some of the states, these signal-on state oscillations affect the response time readings from the digital oscilloscope so that the error bars are larger.

From (1), the fall time of the BPLC stays constant and the rise time is dependent on the ratio of V/V_c. We fitted the experimental data shown in Fig. 3 with (1) and (2) by setting critical voltage and decay time as adjustable parameters, and found that $V_c = 42.8V_{\rm rms}$, and $\tau_{\rm off} = 315.9$ μs. The obtained decay time agrees within 6% with the average decay time (336 μs) of the measured data shown in Fig. 4. That is equivalent to say, we actually only need one fitting parameter which is V_c.

For the response time between other gray levels, the rise time equation can be modified by replacing the critical voltage with the final gray level voltage V_b (or called bias voltage) as [13]:

$$\tau_{on} = \frac{\tau_{off}}{\left(\frac{V}{V_b}\right)^2 - 1}. \tag{3}$$

Fig. 5 depicts the rise time from T10 to other higher gray levels. The measured rise time is fitted by (3) with $V_b = 58.1V_{\rm rms}$ (this is the T10 voltage taken from Fig. 2) and the only adjustable parameter is the fall time τ_{off}. The fitting curve follows well with the measured data. The fitted fall time is 308.3 μs, which is also in good agreement with the average fall time (299.1 μs) shown in Fig. 6.

As shown in (2) and (3), the rise time would be slower if the applied voltage is in the vicinity of critical voltage. To speed up the turn-on process, we could apply an overdrive voltage [14], similar to nematic LCDs, for overcoming the slow rise time. Also from (1)–(3), temperature has an important effect on the GTG response time mainly thru rotational viscosity. As the temperature increases, rotational viscosity decreases exponentially.

IV. Conclusion

The gray-level response time of a BPLC cell is studied. The measured results fit well with the analytical equations. The rise time is shortened as the applied voltage increases, while the decay time remains basically constant. The fast turn-on and turn-off times make BPLC a strong contender for color sequential displays provided that the operating voltage can be reduced. Parallel efforts for reducing operating voltage are undertaken actively.

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