Submillisecond-Response Vertical-Aligned Liquid Crystal for Color Sequential Projection Displays

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Abstract—We developed a fluorinated, UV-stable, high birefringence and low viscosity liquid crystal mixture for projection displays. With this mixture in a thin-cell-gap LCOS, we can achieve submillisecond gray-to-gray response time at an elevated temperature, which enables color sequential projection displays with negligible color breakup.

Index Terms—Color breakup, liquid crystal on silicon (LCOS), projection.

I. INTRODUCTION

COLOR sequential projection display [1]–[3] requires only a single monochrome LCD panel so that the optical system is much easier than that using three panels. However, to suppress color breakup the LCD panel should have a fast response time, preferably less than 1 ms. To achieve submillisecond response time, several approaches have been proposed, such as thin vertical alignment (VA) liquid crystal on silicon (LCOS) cell [4], [5], mixed-mode twisted nematic (MTN) cell [6], ferroelectric cell [7], and polymer-stabilized blue phase (PSBP) cell [8], [9]. PSBP LC is emerging as a promising candidate for direct-view and projection displays because of its fast response time [10], [11] and alignment-layer-free features. However, high driving voltage and low transmittance for in-plane switching mode [9], and directional backlight for vertical-field switching [8] remain to be overcome before widespread applications can be realized.

VA LCOS has been widely used in projection displays because of its unprecedented contrast ratio [12]. However, fringing field degrades the contrast ratio and reduces the display brightness [13], [14]. A straightforward way to suppress fringing field effect is to reduce cell gap (d). Another advantage for using a thin cell is fast response time because the response time is proportional to d^2. A major challenge for the thin cell approach is the need of a high birefringence (Δn) and low viscosity LC. For a VA LCOS, the required $d\Delta n$ is ~165 nm (at $\lambda = 550$ nm) in order to achieve high reflectance at a low voltage (<5 V) [15].

Due to thermal effect from the employed arc or LED lamp, the LCOS panel is usually operated at 40 °C–50 °C. As the temperature increases, both visco-elastic coefficient and birefringence decrease. The latter vanishes at T_c (clearing point). Therefore,

high Δn and high T_c are particularly desirable. To realize the electro-optic effect of a VA cell, a large but negative dielectric anisotropy $(\Delta \varepsilon)$ LC is required. For active matrix LCDs, high resistivity is another important requirement for obtaining high voltage-holding-ratio (VHR > 98%) and avoiding image flickering. To achieve high resistivity, fluorinated LCs are commonly used [16]. However, some laterally difluoro high birefringence compounds are difficult to align, especially at elevated temperatures [17]. A poor LC alignment leads to a low contrast ratio.

UV stability is another critical issue for a high Δn LC due to its relatively long conjugation length. In an LCOS projector, the arc lamp is relatively bright. Although filters are used to block the unwanted UV and infrared lights from the lamp, residual UV contents could still decompose the LC materials if the molecular structures are not intrinsically stable.

In this paper, we formulated a fluorinated high Δn (0.191 at $\lambda = 550$ nm and $T = 50$ °C) and low viscosity negative $\Delta \varepsilon$ LC mixture and measured its physical properties. Between crossed polarizers, the light leakage of our VA cell is unnoticeable indicating the molecular alignment is excellent. Using our measured material parameters in a thin (d = 0.93 μm) VA LCOS, the simulated rise time is 0.26 ms and decay time is 0.40 ms at $T \sim 50$°C. We also tested the photo-stability of our mixture using a UV LED lamp ($\lambda \sim 385$ nm and intensity ~300 mW/cm^2) for 5 hours, and no sign of degradation was observed.

II. EXPERIMENT

In experiment, we formulated a negative $\Delta \varepsilon$ LC mixture (VA- host) with two lateral difluoro-terphenyl homologs [17]. Its physical properties are: $\Delta n = 0.235$ (at $\lambda = 633$ nm and $T \sim 23$ °C), $\Delta \varepsilon = -1.8$ and $T_c \sim 112.3$ °C. A small $\Delta \varepsilon$ leads to a high driving voltage. To increase $\Delta \varepsilon$ while keeping low viscosity, we doped 40 wt% of lateral difluoro alkoxy-biphenyls, -cyclohexane phenyls, -cyclohexane biphenyls [16] into the VA host. For convenience, we name this mixture as VA-N1. An excellent dark state was achieved in the entire nematic range. The measured T_c for VA-N1 is 93.2 °C. The dielectric anisotropy was determined by measuring the capacitance of a homogeneous cell and a homeotropic LC cell [18] and the measured results are $\Delta \varepsilon = -3.74$ at 23 °C and -2.91 at 50°C.

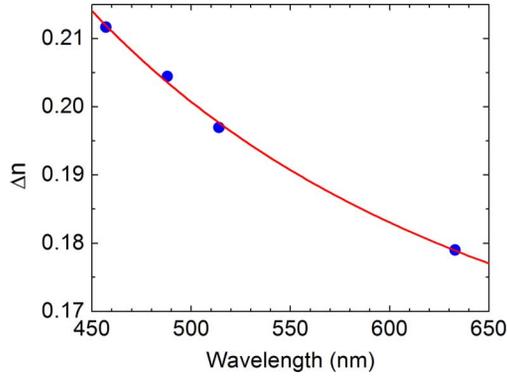### A. Temperature Dependent Birefringence

Birefringence was measured through phase retardation of a VA cell sandwiched between two crossed polarizers [19]. The VA cell has strong anchoring energy and cell gap $d \sim 5$ μm. A 1 kHz square-wave AC voltage signal was applied to the LC cell. A He–Ne laser ($\lambda = 633$ nm) and a tunable Argon ion laser ($\lambda = 457$ nm, 488 nm or 514 nm) were used as the light sources. The temperature dependent Δn of VA-N1 was measured from
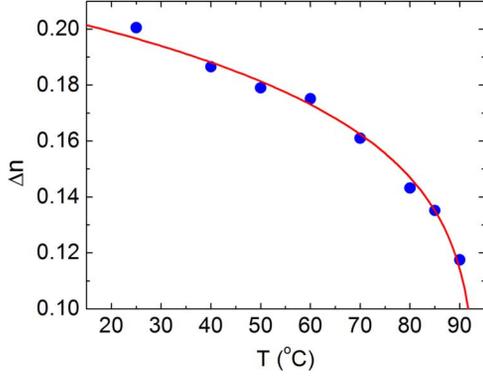
Fig. 1. Temperature dependent Δn of VA-N1 at $\lambda = 633$ nm.

Fig. 2. Wavelength dependent Δn of VA-N1 at $T = 50°$C.

25 °C to 90 °C. Results are plotted in Fig. 1, where blue dots represent the measured data and red solid line is the fitting curve using Haller's semi-empirical equation [20]:

$$\Delta n = \Delta n_0 (1 - T/T_c)^\beta \qquad (1)$$

where Δn_0 is the extrapolated birefringence at $T = 0$ K and β is a material constant. Through fitting, we obtained $\Delta n_0 = 0.265$ and $\beta = 0.177$.

B. Birefringence Dispersion

To investigate the electro-optical performances at RGB colors, we measured the birefringence dispersion at 50 °C, which is the intended operation temperature for an LCOS projector. Results are shown in Fig. 2; here dots are the measured data and solid line represents fitting results using extended Cauchy equation [21], [22]:

$$\Delta n = A + B/\lambda^2 + C/\lambda^4 \qquad (2)$$

where A, B, and C are Cauchy coefficients. From fitting we obtained $A = 0.142$, $B = 1.52$E4 nm^2, and $C = -1.11$E8 nm^4. With these parameters and through (2), the birefringence at any wavelength can be calculated. For example, we find $\Delta n = 0.191$ at $\lambda = 550$ nm and 50 °C. Thus, for a VA LCOS we need $d = 0.93$ μm to achieve ~100% reflectance (normalized to polarizers) at a relatively low operating voltage (<5 V). Although challenging, ferroelectric LCOS with $d \sim 0.8$ μm has been commercialized.
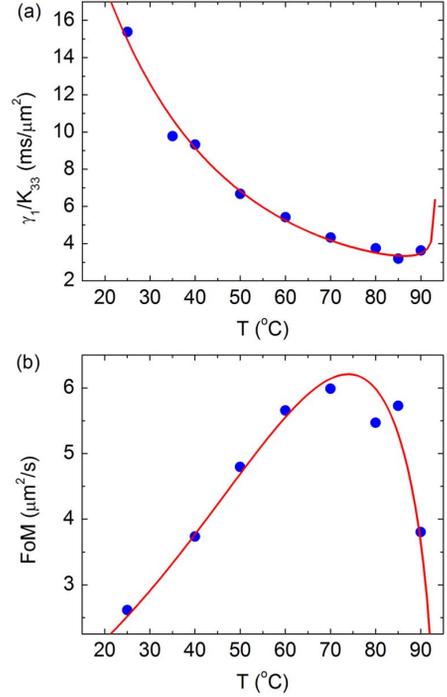
Fig. 3. Temperature dependent (a) γ_1/K_{33} and (b) FoM of VA-N1.

C. Visco-Elastic Constant and FoM

From the relaxation time measurement of the LC cell, the visco-elastic coefficient (γ_1/K_{33}) can be obtained [18]. We measured γ_1/K_{33} at different temperatures and fitted the experimental results by (3), as shown in Fig. 3(a):

$$\frac{\gamma_1}{K_{33}} = \frac{a \cdot \exp(E/K_B T)}{(1 - T/T_c)^\beta} \qquad (3)$$

where a is a proportionality constant, E is the activation energy of the LC mixture, and K_B is the Boltzmann constant. Here the activation energy is 286.9 meV. The overall performance of the LC was evaluated based on the FoM defined as $(\Delta n)^2/(\gamma_1/K_{33})$, which is commonly used to compare the performance of a LC mixture because it is independent of the cell gap employed. Since K_{33} and γ_1 are temperature dependent, we can rewrite *FoM* as follows [23]:

$$\text{FoM} = b(\Delta n_o)^2 \left(1 - \frac{T}{T_c}\right)^{3\beta} \exp\left(\frac{-E}{K_B T}\right) \qquad (4)$$

where b is a proportionality constant. Fig. 3(b) depicts the measured data and fitting curve based on (4). At room temperature, the FoM of VA-N1 is ~2.6 μm^2/s, and it increases to 4.8 μm^2/s at 50 °C. As the temperature increases, visco-elastic coefficient decreases more quickly than birefringence initially, resulting in an increased FoM. As T approaches T_c, Δn decreases more quickly than γ_1/K_{33} leading to a sharply declined FoM, as Fig. 3(b) depicts.

III. SIMULATION RESULTS FOR VA LCOS

The electro-optical characteristics of a VA-LCOS are calculated using a commercial LCD simulator DIMOS 2.0. In simulation, we used $d = 0.93$ μm, $\Delta n = 0.191$ at $\lambda = 550$ nm, and $\gamma_1/K_{33} \sim 6.7$ms/μm^2 at $T = 50$ °C. The initial pretilt

TABLE I
CACULATED GTG RESPONSE TIME (UNIT: MS) OF THE REFLECTIVE VA CELL

		Rise Time (ms)							
		1	2	3	4	5	6	7	8
Decay time (ms)	1		2.36	1.75	1.39	1.13	0.91	0.69	0.26
	2	0.34		1.31	1.13	0.95	0.79	0.60	0.22
	3	0.33	1.33			0.88	0.73	0.56	0.20
	4	0.34	1.19	1.03		0.83	0.69	0.53	0.18
	5	0.34	1.10	1.01	0.91		0.68	0.53	0.17
	6	0.35	1.04	0.98	0.88	0.78		0.53	0.16
	7	0.37	1.01	0.96	0.88	0.79	0.68		0.15
	8	0.40	1.01	0.97	0.90	0.83	0.74	0.63	

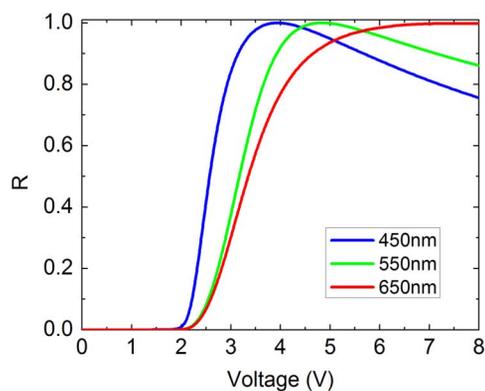Fig. 4. Simulated VR curves of a VA LCOS. $d = 0.93 \, \mu$m, $\lambda = 550$ nm.

angle is 88° and the azimuthal angle is 45° w.r.t. the optic axis of the polarizing beam splitter (PBS). A reflector is placed on the inner surface of the VA cell. Fig. 4 shows the normalized voltage-dependent reflectance (VR) curves for RGB colors. For the green light, the on-state voltage occurs at 4.83 V. The birefringence dispersion is relatively large for high birefringence LCs. As shown in Fig. 2, Δn $= 0.214, 0.191, 0.177$ at $\lambda = 450$ nm, 550 nm and 650 nm, respectively. From Fig. 4, the peak transmittance for RGB colors occur at different voltages. Thus, three gamma curves are needed for driving the RGB frames.

We also calculated the gray-to-gray (GTG) response times of the VA LCOS, and results are summarized in Table I. Taking green color as an example, the VR curve was uniformly divided into eight gray levels (1–8) and the response time between every two gray levels was calculated. Here both rise time and decay time are calculated between 10% and 90% reflectance change. From Table I, we find the rise time is 0.26 ms and decay time is 0.40 ms between gray levels 1 and 8. The average GTG rise time is 0.75 ms and the decay time is 0.79 ms. With such a fast response time, image blur and color breakup can be greatly suppressed.

The estimated operation temperature range for the proposed color sequential VA-LCOS is from 20 °C to 70 °C. As the operation temperature decreases, the response time would be slower because of the increased γ_1/K_{33} [24]. For example, if the application is at room temperature, then from Fig. 3(a) the estimated response time would be $\sim 2.3\times$ slower than that at 50 °C. To shorten response time, overdrive and undershoot voltage method can be applied [25], [26]. On the other hand, if the operation temperature exceeds 70 °C, then the birefringence decreases noticeably as Fig. 1 depicts. As a result, the optical efficiency will decline because the phase retardation is less than 1π.

IV. UV STABILITY

As mentioned above, UV stability is an important concern for an arc-lamp-based LCOS projector. UV light could damage the polyimide alignment layers and the LC material [27]. To investigate UV stability, we exposed our VA-N1 cell (ITO glass substrates) with a UV LED lamp ($\lambda \sim 385$ nm and light intensity ~ 300 mW/cm^2) for five hours. After UV exposure, VA-N1 shows no sign of degradation: clearing point, dark state, threshold voltage, and electro-optic properties remain unchanged within the experimental error.

For a high pressure Mercury arc lamp, the emission spectrum contains some harmful UV components in the 380–400 nm range. Therefore, a UV filter with cutoff wavelength ~ 420 nm is commonly employed. With such a UV filter, our LC mixture should have an excellent stability. For a typical RGB LED backlight unit, its UV content is negligible.

V. CONCLUSION

Our fluorinated high birefringence, low viscosity and negative $\Delta\varepsilon$ LC mixture enables a VA LCOS to achieve high contrast ratio, low voltage, and submillisecond GTG response time at an elevated temperature. Such a fast response time enables color sequential display using a single monochrome LCD panel. As a result, the optical system is greatly simplified. Moreover, good UV stability makes this LC mixture practical for projection displays. A thin cell gap (0.93 μm) also helps to suppress fringing field effect. Although making a sub-micron cell gap is technically challenging, it has been done in ferroelectric LCOS devices.

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