A Vertically-Aligned LCOS with Submillisecond Response Time

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Abstract

We demonstrated a TFT-grade fluorinated , UV-stable, high birefringence and low viscosity negative Δε LC mixture and characterized its physical properties. With this mixture in a thin-cell-gap LCOS, we can achieve submillisecond response time at an elevated temperature, which enables color sequential projection displays without noticeable color breakup.

Author Keywords

liquid crystal on silicon (LCOS); projection; birefringence; color sequential; submillisecond

1. 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 display applications 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]. A straightforward way to suppress fringing field 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. If the response time is below 1 ms, then color sequential display becomes feasible because the color breakup problem can be minimized. 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 λ=550 nm) [14] in order to achieve high reflectance at a low voltage.

Due to thermal effect from the employed arc or LED lamp, the LCOS panel is usually operated at ~50˚C. As the temperature rises, 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. Some laterally difluoro high Δn compounds are difficult to align, especially at elevated temperatures [15]. A poor LC alignment leads to a low contrast ratio.

In this paper, we developed a TFT-grade high Δn (0.195 at λ=550nm and T=50˚C) and low viscosity negative $\Delta\varepsilon$ LC mixture and characterized its physical properties. Between crossed polarizers, the light leakage of our VA cell is unnoticeable indicating an excellent alignment. Using our measured material parameters in a thin (d=0.93μm) VA LCOS, the simulated rise time is 0.38 ms and decay time is 0.42 ms at T~50°C.

2. Material Properties

In experiment, we formulated a negative Δε LC mixture (VA-host) with two lateral difluoro-terphenyl homologs [15]. Its physical properties are: Δn=0.235 (at λ=633nm and T~23˚C), $\Delta\varepsilon$= ī 1.8 and T_c~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 [17] and the measured results are $\Delta\varepsilon$ = ī 3.74 at 23 ˚C and -2.91 at 50˚C.

Birefringence was measured through phase retardation of a VA cell sandwiched between two crossed polarizers. The VA cell has strong anchoring and d~5 μm. A 1 kHz square-wave AC voltage signal was applied to the LC cell. A He-Ne laser (λ = 633 nm) and a tunable Argon ion laser were used as the probing light sources. The Δn of VA-N1 was measured at different temperatures from 25°C to 90°C. Results are plotted in Fig. 1. The black dots represent the measured data and the blue solid line is the fitting curve using Haller's semi-empirical equation [18]:

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

where the fitting parameters are Δn_0=0.265 and β=0.177.

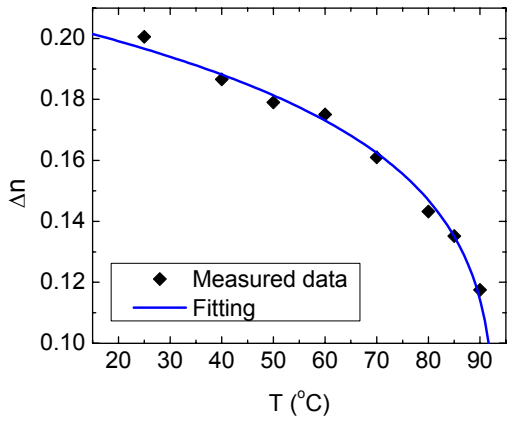

Figure 1. Temperature dependent Δn of VA-N1 at λ=633 nm. Dots are measured data and solid line is the fitting with Eq. (1).

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To investigate the electro-optical performances at different wavelengths, we measured the birefringence dispersion at 50˚C; the intended operation temperature for LCOS. Results are shown in Fig. 2; here dots are the measured data and solid line represents fitting results using extended Cauchy equation [19]:

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

where A, B, and C are Cauchy coefficients. From fitting we obtained A=0.142, B=-1.52E4 nm^2 and C=-1.11E8 nm^4. With these parameters, the birefringence at any wavelength can be calculated. For example, we find Δn=0.191 at λ=550 nm and 50˚C. Thus, for a VA LCOS we only need d=0.93 μm to achieve 100% reflectance (normalized to polarizers) at a relatively low operating voltage (<5V). Although challenging, ferroelectric LCOS with d~0.8 μm has been commercialized.

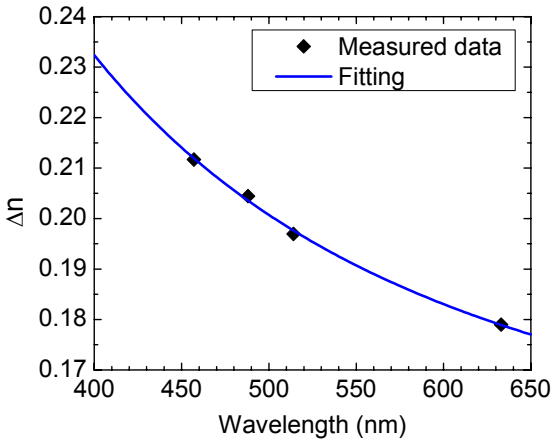

Figure 2. Birefringence dispersion of VA-N1 at 50 ˚C. Dots are the measured data and solid line represents the fitting results according to Eq. (2).

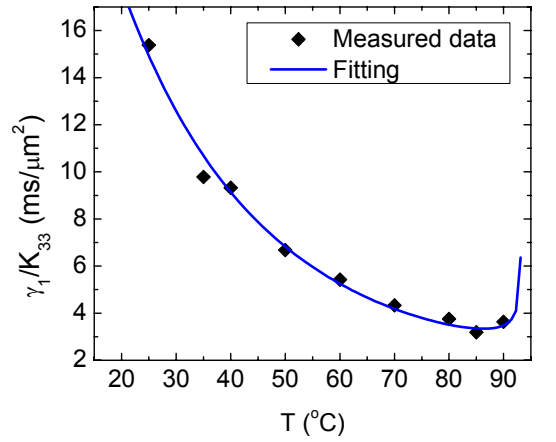

Figure 3. Temperature dependent visco-elastic coefficient of VA-N1. Dots are measured data, and solid line is the fitting with Eq. (3)

From the relaxation time measurement of the LC cell, the visco-elastic coefficient (γ_1/K_{33}) can be obtained [20]. We measured γ_1/K_{33} at different temperatures and fitted the experimental results with Eq. (3):

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

where a is a proportionality constant, E is the activation energy of the LC mixture, and K_B is the Boltzmann constant. Results are shown in Fig. 3. From fitting, we obtained E=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 [17]:

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

where b is a proportionality constant. Figure 4 depicts the measured FoM and fitting curve based on Eq. (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. 4 depicts.

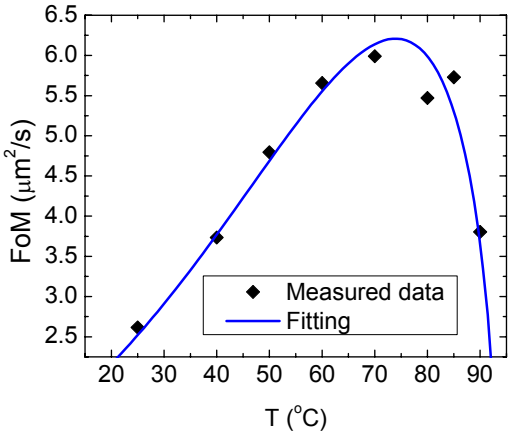

Figure 4. Temperature dependent *FoM* of VA-N1. Dots are the measured data, and solid line is the fitting with Eq. (4).

3. Simulation results for VA LCOS

The electro-optical characteristics of a VA-LCOS are calculated using a commercial LCD simulator DIMOS.2D. In simulation, we used d=0.93 μm, Δn=0.191 at λ=550 nm, and γ_1/K_{33} ~6.7 ms/μm^2 at T=50˚C. The initial pretilt 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. Figure 5 shows the normalized voltage-dependent reflectance (VR) curve. The on-state voltage occurs at V_{on}=4.83V for λ=550 nm. The dispersion is relatively large for high birefringence LCs. As shown in Fig. 2, Δn=0.214, 0.191, 0.177 at λ=450nm, 550nm and

650nm, respectively. Therefore, the peak transmittance for RGB colors occurs at different voltages because of their different phase retardations. Thus, three gamma curves are needed for driving the RGB colors.

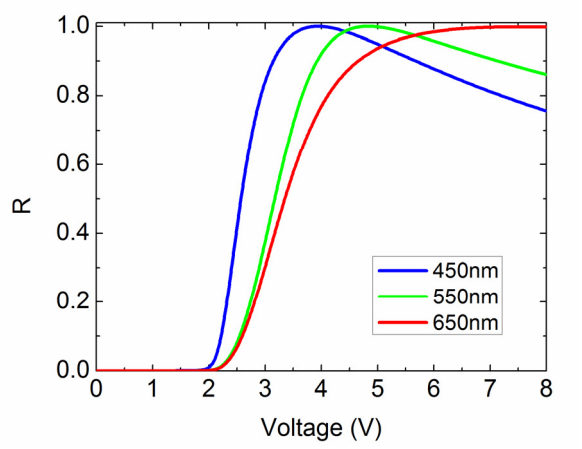

Figure 5. Simulated VR curve for RGB colors of a VA LCOS. d= 0.93 μm, T=50°C.

Both rise time and decay time are calculated between 10% and 90% reflectance change. From the simulation we find the rise time is 0.26 ms and decay time is 0.40 ms. We also calculated the gray-to-gray (GTG) response times of the VA LCOS [21]. 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. 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. With such a fast response time, image blur and color breakup would 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} [22]. For example, if the application is at room temperature, then from Fig. 3 the estimated response time would be ~2.3X slower than that at 50°C. To shorten response time, overdrive and undershoot voltage method can be applied [23]. 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 of the insufficient phase retardation (<1π).

4. 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 [24]. To investigate UV stability, we exposed our VA-N1 cell (ITO glass substrates) with a UV LED lamp (λ~385nm and light intensity ~300mW/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.

5. 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 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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7. References

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