Alignment layer effects on thin liquid crystal cells

Meizi Jiao, Zhibing Ge, Qiong Song, and Shin-Tson Wu[a)]
College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816, USA

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Factors affecting the thin cell performance of a liquid crystal cell are analyzed. Examples based on vertically aligned thin cells are given to illustrate these effects. When the cell gap is below ~2 μm, the liquid crystal alignment material, layer thickness, and anchoring energy all play important roles. The first two factors affect the threshold and on-state voltage, while the last one affects the operating voltage and response time. Three reflective liquid crystal cells are studied experimentally. Good agreement between experiment and theory is obtained.
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Fast response time is critically important for reducing the motion blurs of liquid crystal display televisions (LCD TVs) and the color breakup of color sequential LCDs. To shorten response time, thin cell gap is a straightforward approach because the liquid crystal (LC) response time is proportional to the LC layer thickness (d) as $\tau_o \sim d^x$, where the exponent x is dependent on the surface anchoring energy. It varies between 2 and 1 from strong to weak anchoring.[1–3] For transmissive LCD TVs,[4] a typical cell gap is 3.5 μm and the trend is to go thinner. In color-sequential projection displays using a single reflective liquid crystal on silicon (LCOS) panel,[5] color breakup would be negligible if the LC response time can be reduced to ~1 ms.[6] A typical cell gap for LCOS is 2 μm, in which color breakup is still noticeable. There is a strong need to use a thinner cell gap for achieving a faster response time.

As the LC cell gap is reduced, several factors such as the alignment layer thickness and surface roughness which are negligible in thick cells become important. A typical polyimide (PI) alignment layer is about 100 nm thick and there are two such layers in a LC cell. The dielectric property of these PI layers would shield a portion of the applied electric field in a thin cell, which results in an increased threshold voltage and on-state voltage. The anchoring energy of these alignment layers would affect the dynamics of the LC response. Moreover, the surface roughness of these alignment layers would reduce the effective birefringence (Δn) of the LC layer.[7]

In this letter, we analyze the factors affecting the performances of thin LC cells in both transmissive mode and reflective mode. To demonstrate the key impact, we use a vertical alignment (VA) cell[8,9] as an example. We focus our analyses on the alignment layer's dielectric and anchoring energy effects on the operating voltage and response time. In experiment, the voltage-dependent reflectance of three thin VA LCOS cells was measured. Parameters of alignment layer thickness, pretilt angle,[10,11] anchoring energy, and effective Δn were extracted. Good agreement between the experiment and theoretical model is obtained.

In a LC cell, part of the applied voltage is shielded by the alignment layers, e.g., PI or SiO_x, due to their dielectric properties. To analyze the voltage shielding effect, a LC cell can be treated as three capacitors (two alignment layers and one LC layer) in series.[12] The relationship between the effective voltage on the LC layer (V_{LC}) and the applied voltage (V_{AP}) is derived as follows:

$$V_{LC} = \frac{V_{AP}}{\left(1 + \frac{2\varepsilon_{LC} d_{AL}}{\varepsilon_{AL} d_{LC}}\right)}, \qquad (1)$$

where ε_{LC} is the effective dielectric constant of the LC layer at a given voltage, ε_{AL} is the dielectric constant of the alignment layer, and d_{AL} and d_{LC} are the thicknesses of alignment layer and LC layer, respectively. Equation (1) indicates that V_{LC} is smaller than V_{AP} because of the voltage shielding effect of the alignment layers. For a thick cell where $d_{LC} \gg d_{AL}$, Eq. (1) is reduced to $V_{LC} \sim V_{AP}$, which means that the dielectric shielding effect is negligible. However, for a thin cell, the dielectric shielding effect would be apparent.

Figures 1(a) and 1(b) show the calculated voltage-dependent transmittance (VT) and reflectance (VR) curves of some thin VA cells at wavelength $\lambda = 550$ nm and room temperature. Here, we assume that the anchoring is strong and the pretilt angle is 2°. For the transmissive cell, we assume that the alignment layers are polyimide with $d_{AL} \sim 80$ nm and $\varepsilon_{AL} = 3.4$. For the reflective cell, we assume that the alignment layers are SiO_2 with $d_{AL} \sim 120$ nm and $\varepsilon_{AL} = 3.9$. To keep the on-state voltage below ~6 V_{rms} for low power consumption, we choose $d_{LC}\Delta n = 360$ nm for the transmissive mode and $d_{LC}\Delta n = 180$ nm for the reflective mode. All the other physical properties of the LC material are taken the same as Merck MLC-6608. The reference curves in Fig. 1 represent the cells without considering the alignment layer effect. From Fig. 1, the voltage shielding effect remains small for thick cells but gradually becomes evident when the cell gap is below 2 μm. If we take ~50% transmittance or reflectance as an example, for the 2 μm transmissive cell, there is an ~0.4 V_{rms} voltage drop across the PI layers, while for the 1 μm reflective cell, the shielded voltage by the SiO_2 layers is increased to ~1.1 V_{rms}. In a reflective cell, the cell gap is thinner so that the voltage shielding effect is more evident.

As the voltage exceeds a threshold, the LC directors are reoriented by the electric fields. Taking a VA cell as an example, the value of ε_{LC} gradually increases from $\varepsilon_{\parallel}$ to $\varepsilon_{\perp}$ as the applied voltage increases. Accordingly, the shielded voltage keeps on increasing. Such a voltage shift increases the power consumption but has no benefit to the response time.

[a)]Electronic mail: swu@mail.ucf.edu.

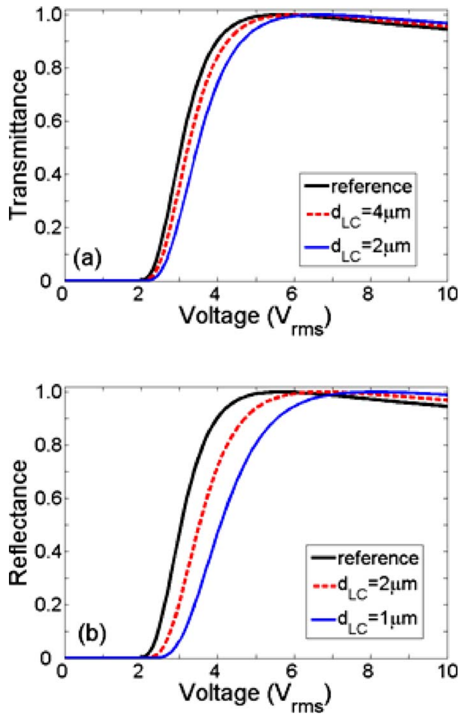

FIG. 1. (Color online) Cell gap dependent (a) VT and (b) VR curves. Reference curves do not consider the voltage shielding effects of the LC alignment layers. Other curves are for different thickness cells taking the voltage shielding effect into account.

This is because at a certain gray level, although the ratio of $V_{\mathrm{AP}}/V_{\mathrm{th}}$ increases, the $V_{\mathrm{LC}}/V_{\mathrm{th}}$ ratio remains the same. To minimize the voltage shielding effect, a thin alignment layer such as photoalignment whose alignment layer is only a few nanometers[13,14] is particularly attractive for thin cell applications.

It is commonly known that LC directors are much easier to be reoriented by an electric field under a weaker anchoring.[2,3] As the anchoring energy decreases, both threshold voltage and on-state voltage decrease. This phenomenon manifests further in thin cells. Figure 2 shows the VT curves for a 4 μm cell and a 2 μm cell under strong ($W\sim\infty$) and medium ($W=10^{-4}$ J/m^2) anchoring conditions. The alignment layers and LC material properties are the same as those in Fig. 1(a). With anchoring energy changing from strong to medium, for the 4 μm cell, the ~50% transmittance voltage is decreased by ~0.5 V_{rms}. However, for the 2 μm cell this

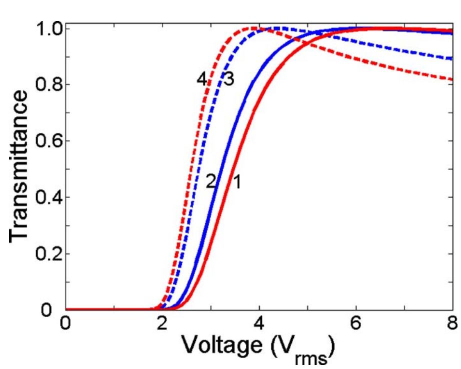

FIG. 2. (Color online) VT curves of a 4 μm cell and a 2 μm cell (but with the same $d\Delta n$) under strong anchoring ($W\sim\infty$) and medium anchoring ($W=10^{-4}$ J/m^2). Curve 1: $d=2$ μm, $W\sim\infty$; curve 2: $d=4$ μm, $W\sim\infty$; curve 3: $d=4$ μm, $W=10^{-4}$ J/m^2; curve 4: $d=2$ μm, $W=10^{-4}$ J/m^2.

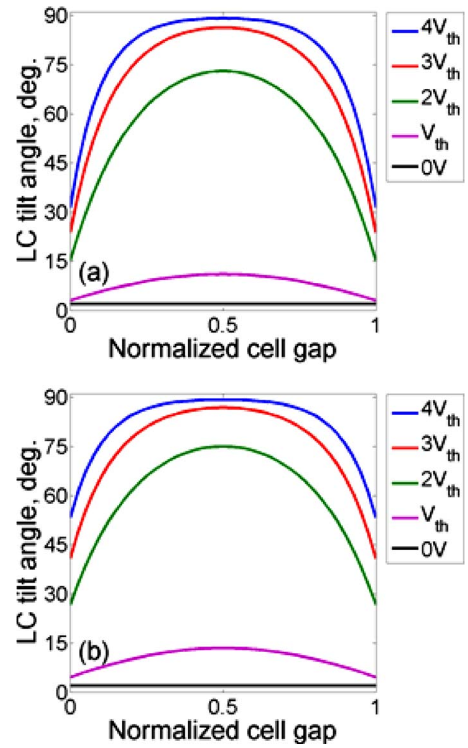

FIG. 3. (Color online) Simulated LC tilt angle distribution under medium anchoring energy $W=10^{-4}$ J/m^2. (a) $d=4$ μm and (b) $d=2$ μm. In both cases, $d\Delta n=360$ nm. Besides Δn, all other parameters are taken from MLC-6608.

~50% transmittance voltage is reduced by ~0.9 V_{rms}. That is to say, the anchoring energy effect is more sensitive to thin cells than thick cells.

The physical mechanism of this phenomenon is investigated. Figures 3(a) and 3(b) show the simulated LC tilt angle distributions of a 4 μm cell and a 2 μm cell with anchoring energy $W=10^{-4}$ J/m^2. Under the same medium anchoring and same voltage, the LC directors at the boundary layers of thin cells tilt more heavily than those of thick cells. The distribution of LCs is a result of the balance between the elastic energy, electric energy, and surface energy.[15] Let us divide the LC layer into two boundary layers and one bulk layer in between. For the bulk layer in a thin cell, under the same voltage, the electric field is stronger due to the smaller cell gap, but the anchoring effect is also stronger because the bulk layer is closer to the alignment layers. As a result, the middle layer's tilt angle is more or less the same between the thin and thick cells. Indeed, this is the case shown in Figs. 3(a) and 3(b). However, for the two boundary layers, the corresponding electric field is stronger in a thin cell than in a thick cell under the same applied voltage but their anchoring strength remains almost the same. Therefore, the LC tilt angle near the surface boundaries is larger in a thin cell than in a thick cell, as shown in Fig. 3. In other words, it takes a lower voltage for a thinner cell to achieve the same transmittance than a thicker cell, as shown in Fig. 2. Please note that the $d_{\mathrm{LC}}\Delta n$ of the cells remains the same, i.e., a thinner cell would require a higher Δn.

Anchoring energy effect on the LC director's response time can be described as follows:[3]

$$\tau_o = \frac{\gamma_1}{K\pi^2}\left(d^2 + \frac{4dK}{W} + \frac{4K^2}{W^2}\right),$$

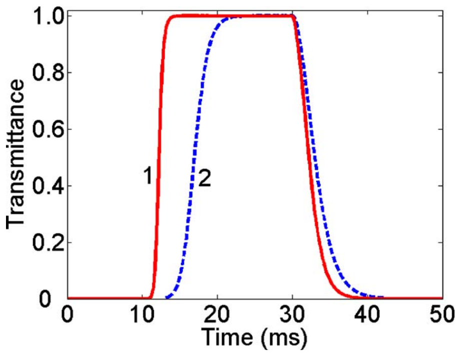

FIG. 4. (Color online) Comparison of the response time for a 2 μm transmissive cell under different anchoring energies. The voltage is applied from 0 to that corresponding to the first transmission maximum shown in Fig. 2. Curve 1: $W\sim\infty$; curve 2: $W=10^{-4}$ J/m^2.

$$\tau_{\text{rise}} = \frac{\tau_o}{\left|(V/V_{\text{th}})^2 - 1\right|}. \qquad (2)$$

From Eq. (2), for a given LC material and cell gap, the decay time (τ_o) becomes longer for a weaker anchoring energy. However, the rise time (τ_{rise}) also depends on the voltage switching ratio, defined as V/V_{th}. Although a weaker energy lowers the threshold voltage, it also lowers the on-state voltage. Thus, its overall effect depends on the operating conditions. Figure 4 shows the response time for the 2 μm cell mentioned above under different anchoring energies. The voltage is applied from 0 to that corresponding to the transmission peak shown in Fig. 2, i.e., $V=6.6$ V_{rms} for strong anchoring ($W\sim\infty$) and $V=3.9$ V_{rms} for medium anchoring ($W=10^{-4}$ J/m^2). As the anchoring energy is decreased from strong to medium, the (rise, decay) time is increased from [1.2 ms, 3.8 ms] to [3.9 ms, 5.0 ms], respectively. The total response time (rise+decay) is increased by ~78%. From Eq. (2), the longer decay time results from the weaker restoring force, but the longer rise time results also from a smaller voltage switching ratio. Although the threshold voltage is decreased under weak anchoring, the on-state voltage decreases even further. Thus, to achieve fast response time using a thin cell, a strong anchoring is preferred.

To validate the above analysis, we investigated the VR curves of three LCOS cells with $d_{\text{LC}}\sim 2.4$ μm. The LC employed is MLC-6608 whose physical properties are listed as follows: $K_{11}=16.7$ pN, $K_{33}=18.1$ pN, $\varepsilon_{\parallel}=3.6$, $\varepsilon_{\perp}=7.8$, $\gamma_1=0.186$ Pa s, $n_o=1.475$, and $n_e=1.558$. All the data were measured at 25 °C and $\lambda=633$ nm. Figure 5 shows the experimental data and fitting curves. The extracted parameters are listed as follows: alignment layer (SiO_x) thickness ~(200 ± 20) nm, pretilt angle ~5 ± 1°, anchoring energy $W\sim(1.8\pm0.3)\times10^{-4}$ J/m^2, and effective Δn ~0.063 ± 0.02. The effective Δn is lowered by ~24% from the original value because of the defects and surface roughness of the alignment layers.[7] Comparing the difference between the solid line and dashed lines, which represent the theoretical calculations with and without considering the voltage shielding effect, respectively, we find a good agreement between the experiment and theory.

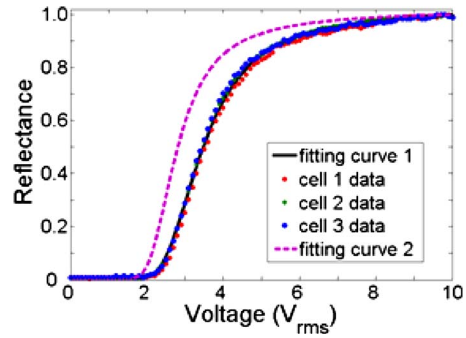

FIG. 5. (Color online) Experimental data (dots) and fitting curves of three LCOS cells. Fitting curve 1 includes the voltage shielding effect, while fitting curve 2 does not.

In conclusion, the alignment layer's voltage shielding effect and anchoring energy effect on the electro-optical response of VA LCDs with the thin cell gap are analyzed theoretically. Simulated examples are given to illustrate the influence. For the alignment layers presently in use, namely, ~80 nm polyimide and ~120 nm SiO_2, we found that the threshold voltage and on-state voltage are both increased evidently when the cell gap is below ~2 μm. Response time of thin cells is significantly slowed down under weak anchoring.

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[1]E. Jakeman and E. P. Raynes, Phys. Lett. **39A**, 69 (1975).
[2]J. Nehring, A. R. Kmetz, and T. J. Scheffer, J. Appl. Phys. **47**, 850 (1976).
[3]X. Nie, R. Lu, H. Xianyu, T. X. Wu, and S. T. Wu, J. Appl. Phys. **101**, 103110 (2007).
[4]J. J. Lyu, J. Sohn, H. Y. Kim, and S. H. Lee, J. Disp. Technol. **3**, 404 (2007).
[5]D. Armitage, I. Underwood, and S. T. Wu, *Introduction to Microdisplay* (Wiley, New York, 2006).
[6]M. Ogata, K. Ukai, and T. Kawai, J. Disp. Technol. **1**, 314 (2005).
[7]S. T. Wu and U. Efron, Appl. Phys. Lett. **48**, 624 (1986).
[8]M. F. Schiekel and K. Fahrenschon, Appl. Phys. Lett. **19**, 391 (1971).
[9]H. Wang, T. X. Wu, X. Zhu, and S. T. Wu, J. Appl. Phys. **95**, 5502 (2004).
[10]T. J. Scheffer and J. Nehring, J. Appl. Phys. **48**, 1783 (1977).
[11]X. Nie, H. Xiangyu, R. Lu, T. X. Wu, and S. T. Wu, J. Disp. Technol. **3**, 280 (2007).
[12]H. Seiberle and M. Schadt, Mol. Cryst. Liq. Cryst. Sci. Technol., Sect. A **239**, 229 (1994).
[13]M. Schadt, K. Schmitt, V. Kozenkov, and V. G. Chigrinov, Jpn. J. Appl. Phys., Part 1 **31**, 2155 (1992).
[14]H. S. Kwok, V. G. Chigrinov, H. Takada, and H. Takatsu, J. Disp. Technol. **1**, 41 (2005).
[15]D. K. Yang and S. T. Wu, *Fundamentals of Liquid Crystal Devices* (Wiley, New York, 2006).