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Enhanced contrast ratio of homogeneously aligned liquid crystal displays by controlling the surface-anchoring strength

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Abstract
The dark state of homogeneously aligned liquid crystal displays (LCDs) associated with the in-plane switching of a LC director depends on their molecular ordering. We propose a new approach to reduce the light leakage in the dark state of homogeneously aligned LCDs. A very small amount of reactive mesogen (RM) is mixed with the LC material and polymerized at room temperature and also at a low temperature (−20 °C) to strengthen the surface-anchoring energy. The contrast ratio of the low-temperature cured cell is improved by about 50% over that of the pure LC cell and the room temperature cured RM-mixed LC cell due to an enhanced order parameter.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Nowadays liquid crystal displays (LCDs) are most commonly used in the display market due to several advantages such as light weight, low power consumption and high resolution. To develop LCDs into the new large-sized display market such as three-dimensional (3D) displays, a wide viewing angle, with fast response time and high image quality, is necessary. With the advance of different switching modes such as in-plane switching (IPS) [1–3], fringe-field switching (FFS) [4–6] and vertical alignment (VA) [7, 8] modes, high image quality has been achieved. Homogeneously aligned LCDs such as IPS and FFS modes are known to exhibit intrinsically wide viewing angle characteristics because of the in-plane rotation of the liquid crystal director but the contrast ratio (CR) of those modes are still not satisfactory. In general, the dark state is the most important aspect to determine the CR as well as the image quality [9]. So, to improve the CR, technologies have been developed continuously by improving the dark state.

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The normalized transmittance of homogeneously aligned LCDs with a uniaxial LC medium under crossed polarizers is given by

$$T/T_0 = \sin^2(2\varphi)\sin^2(\pi d\Delta n/\lambda) \quad (1)$$

where φ is the angle difference between the transmittance axis of the polarizer and the LC director, d is the cell gap, and Δn and λ are the birefringence of LC and incident wavelength, respectively. For completely dark state, it is required that φ becomes zero. However, it is difficult to have zero transmittance because the order parameter of LC molecules is not one, so there is a slight difference between the LC director and the transmittance axis of the polarizer, and also process margin. Consequently, this results in light leakage of dark state. The order parameter of a LC is defined as

$$S = \tfrac{1}{2}\langle 3\cos^2\theta - 1\rangle \quad (2)$$

where θ is the angle between the director and the long axis of individual molecule. In an isotropic liquid, the average of the cosine terms is zero, and therefore the order parameter is equal

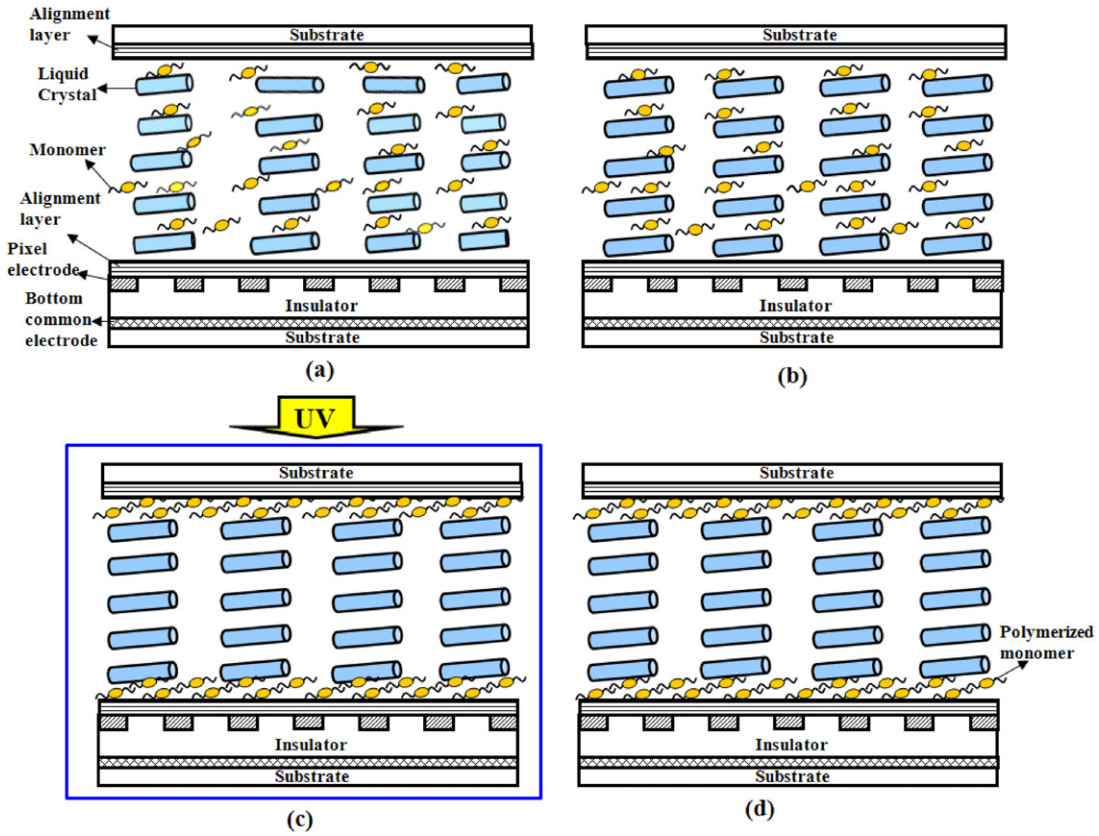

Figure 1. Schematic diagram of the fabrication processes for the proposed homogeneously aligned LC cell: (*a*) RM and LC are homogeneously aligned with imperfect alignment at room temperature, (*b*) LC as well as the RM are more perfectly aligned at a low temperature (−20 °C), (*c*) RMs diffuse to the surface and polymerization is induced under UV exposure and (*d*) even at room temperature, high-order parameter of LC orientation on the surface persists in the polymerized sample.

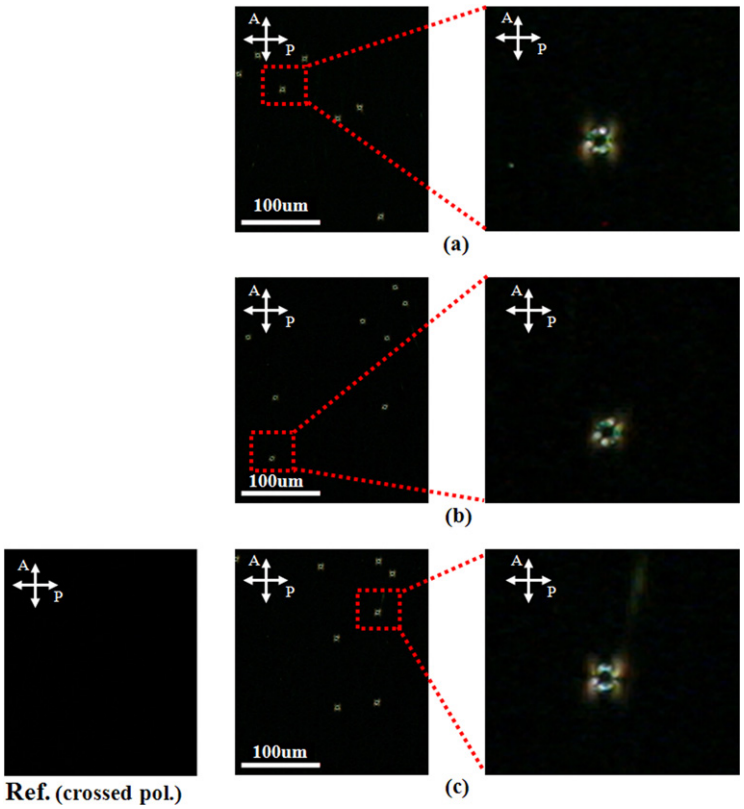

Figure 2. POM microphotographs between crossed polarizers at the dark state of the pure LC cell (*a*) and the cured RM-mixed LC cells at low (*b*) and room (*c*) temperatures when compared with the crossed polarizers without the LC cell.

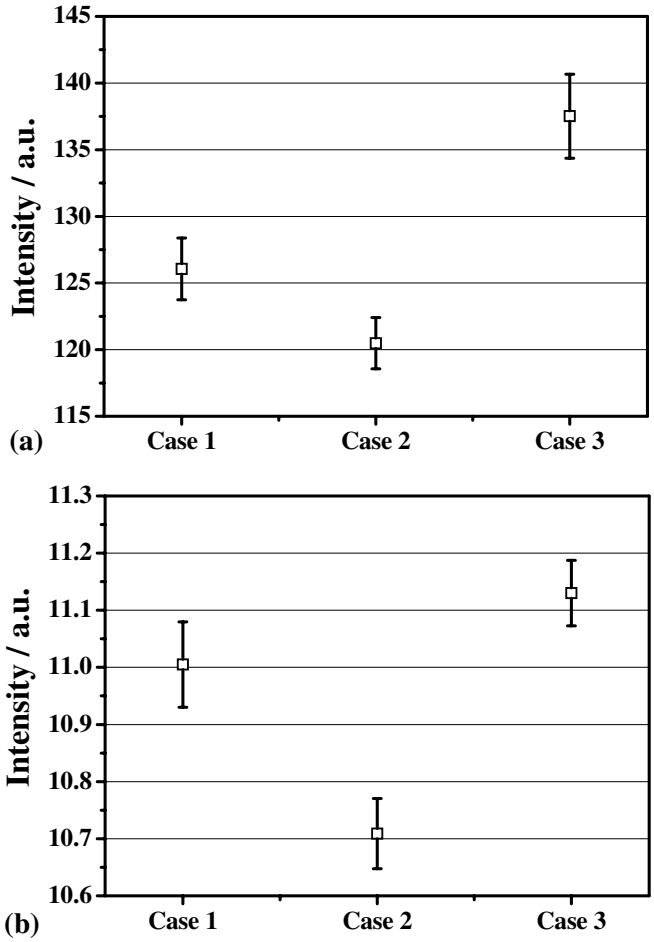

Figure 3. Measured intensity value from the POM image of the dark state in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell) in the (*a*) whole area and (*b*) light leakage around the spacer using the i-solution program.

to zero. For a perfect crystal, the order parameter is evaluated to be one. Typical values of the order parameter of a LC range between 0.3 and 0.9, with the exact value being a function of temperature, as a result of kinetic molecular motion. We can expect a better dark state if the LC molecules can be aligned with a larger value of order parameter.

On the basis of this argument, in this paper, we have proposed an advanced method for improving dark state and consequently enhancing CR by surface modification using reactive mesogen (RM) [10] without any complicated driving method. The UV polymerization of LC and RM mixture at a low temperature (−20 °C) increases the surface-anchoring energy as well as the order parameter of LC molecules at the surface.

2. Experimental

For the experiment, we chose a FFS cell with an electrode width of 4 μm, electrode distance of 6 μm and cell gap of 4 μm. The rubbing process was in the horizontal direction to align the LC director at an angle of 83° with respect to the horizontal component of the fringe field. We used a LC

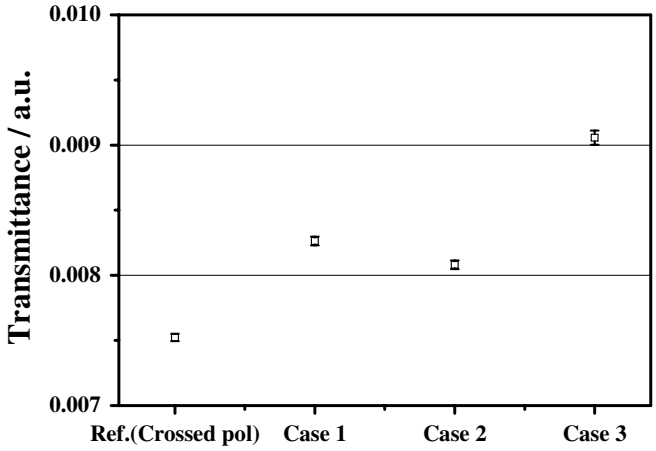

Figure 4. Measured transmittance of dark state in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell) using the optic measurement machine (LCD-1000S).

material (Merck) with positive dielectric anisotropy ($\Delta\varepsilon$ = +5.2 at 1 kHz) and with elastic constant K_{11} = 13.2 pN, K_{22} = 6.5 pN, K_{33} = 18.3 pN at 20 °C. The material has a clearing temperature 92.5 °C with a nematic phase down to −40 °C. The LC was mixed with RM (RM 257, Merck) in the weight ratio of 99.9 : 0.1 and a photoinitiator (Irgacure 651, Merck) with 1 wt% compared with RM. The mixture was loaded into two different FFS cells. One cell was UV cured (365 nm) at room temperature (27 °C) and the other one at a low temperature (−20 °C) for 30 min with an intensity of 30 mW cm^{-2}.

Figure 1 shows the schematic diagram of the processes for fabricating the proposed cell with a defined ordering of the LC at the substrate surfaces [11–14]. Initially, the RM molecules are also aligned homogeneously along the LC layer due to the use of rubbed homogeneous alignment layers on both substrates, as shown in figure 1(*a*). Next, at a low temperature (−20 °C) achieved using liquid nitrogen, the RM and the LC molecules could be more perfectly aligned towards the LC director making the value of order parameter higher than that observed in the room temperature case, as shown in figure 1(*b*). Under this condition the cell was exposed to UV light (365 nm, 30 mW cm^{-2}, 30 min). As a result the monomers were polymerized through a photo-induced monomer diffusion process while maintaining a higher order parameter than that at room temperature, as depicted in figure 1(*c*). Consequently, for this cell the LCs in the bulk relax to the original homogeneous state at room temperature while the surfaces have perfect orientation along the director, which is depicted in figure 1(*d*). After fabrication of the sample, light leakage of the dark state was observed using a polarizing optical microscope (POM) Nikon DXM1200 with crossed polarizers in transmittance mode. The optical transmittance was calculated using an image analyser i-solution (*i*MTechnoloy) and also with LCD-1000S (Otsuka Electonics, Korea). Electro-optic measurements, e.g. voltage–transmittance (V–T) and response time, were carried out with LCMS-200 (Sesim photonics technology). The capacitance in IPS geometry was measured using an LCR meter (Agilent technologies).

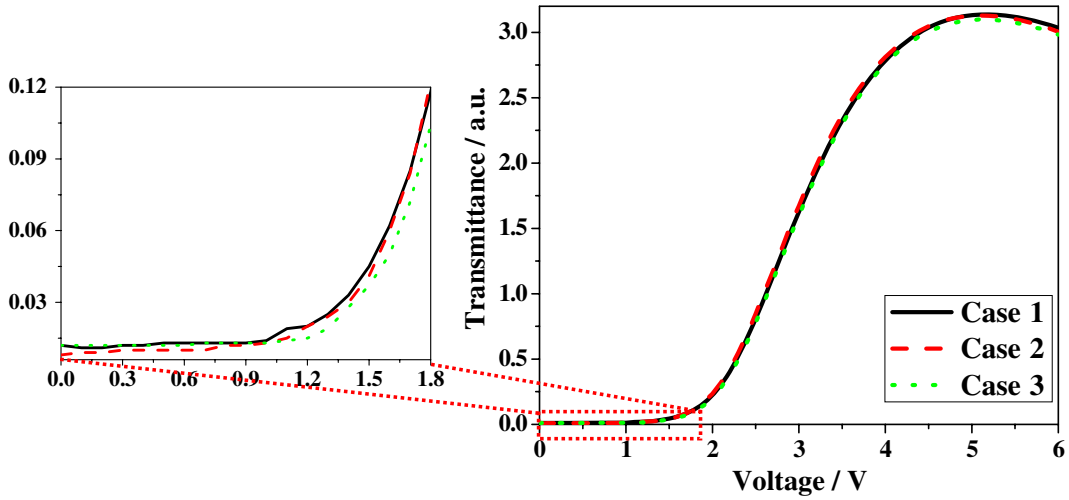

Figure 5. Measured voltage-dependent transmittance curves in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell).

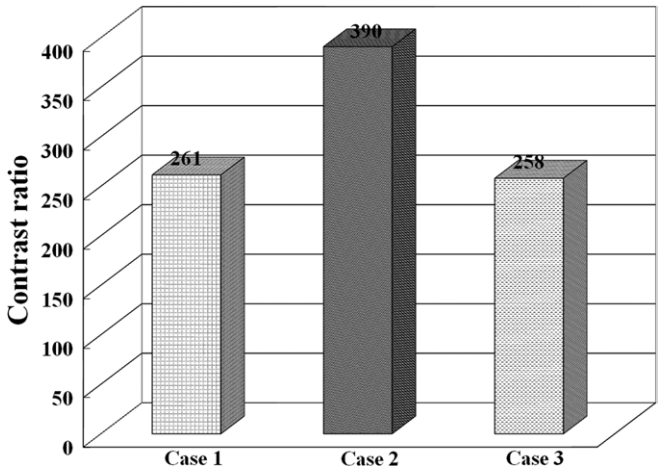

Figure 6. Measured CR value in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell).

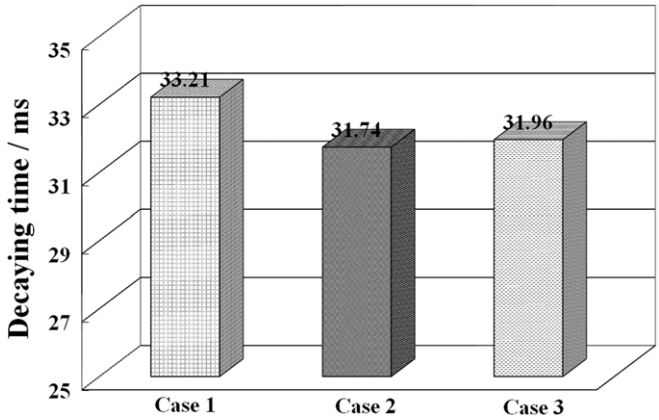

Figure 7. Measured decaying time in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell).

3. Results and discussion

Polymer-stabilized IPS LC cells were previously investigated by Escuti *et al* [15]. However, the doping amount of RM was in the range 0.5–2 wt%. With this approach, the response time was improved by forming polymer networks not only on the surface but also in bulk LC. High density of polymer networks in the bulk can create light leakage in the dark state because of light scattering due to the refractive index mismatch between the LC and the polymer. Therefore, keeping the monomer ratio very low enough to control the surface-anchoring strength or pretilt angle [12, 16] is highly important in the proposed technology and thus RM doping amount of 0.1 wt% into LC is chosen.

Figure 2 shows the POM images in the dark state of the pure LC (case 1) and low-temperature (case 2) and room temperature (case 3) UV-cured RM-mixed LC cells. As indicated in figures 2(*a*)–(*c*), in all the cases similar good dark states can be observed in the whole image; it is hard to find a difference between each case. However, when the highlighted areas of figures 2(*a*)–(*c*) are enlarged, it is noticed that the light leakage around the spacer of case 2 is smaller than that of cases 1 and 3.

We have calculated the intensities of the dark states using the i-solution program in each case and compared the results in figure 3. From the figure we confirm that the dark state of case 2 both in the whole area (figure 3(*a*)) and around the area of a spacer (figure 3(*b*)) is better than that of cases 1 and 3. To confirm the calculated results, light leakage of each case was measured using an optical transmittance measurement machine, LCD-1000S, as revealed in figure 4. The results show the same trend as in figure 3. From these results we can conclude that due to the enhanced surface-anchoring energy, LC ordering improved by the polymerization of RM in a low-temperature environment and as a result the light leakage caused by the spacer was reduced, so a better dark state was realized.

Figure 5 demonstrates the room temperature measurement of voltage-dependent transmittance (V–T) curves of pure LC cells and RM-mixed LC cells polymerized at different temperatures. In order to understand the dependence clearly,

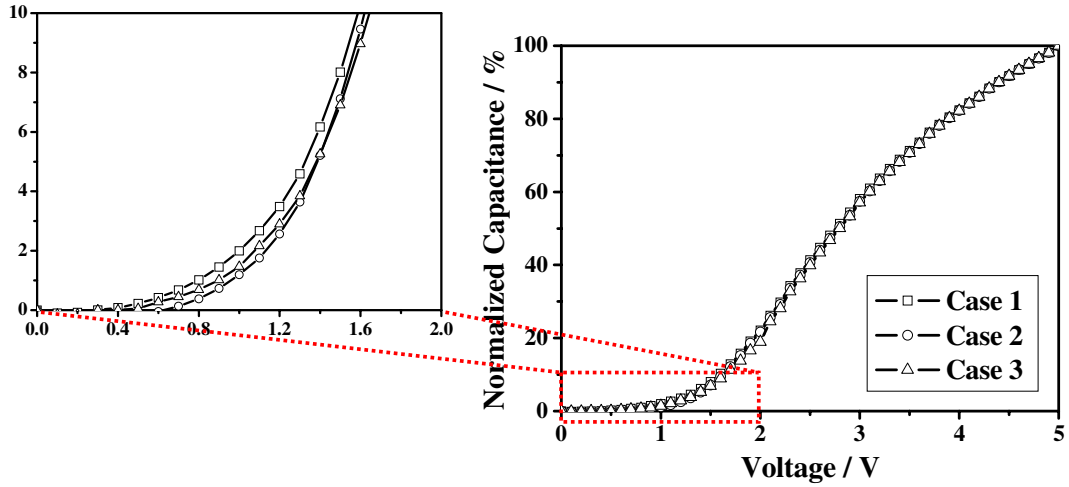

Figure 8. Measured capacitance–voltage curves in each case (case 1: the pure LC, case 2: low-temperature UV-cured RM-mixed LC cell, case 3: room temperature UV-cured RM-mixed LC cell) using the capacitance measurement machine (LCR meter).

the low-voltage highlighted area is enlarged in the figure. As expected it is observed that the transmittance of case 2 is smaller than that of cases 1 and 3 in the area below the threshold voltage. However, we have calculated the CR for all the cases. Although the difference in transmittance level is very small for all the three cases, but the CR of case 2 increases by about 33% compared with the other cases, as shown in figure 6.

Normally, the decaying time of homogeneously aligned LCDs is dependent on the cell gap d, rotational viscosity γ_1 and twist elastic constant K_{22} as follows [17]:

$$\tau_{\text{decay}} = \frac{\gamma 1 d^2}{K_{22}\pi^2}. \tag{3}$$

Here this mathematical relation is derived on the assumption that the surface-anchoring energy is very strong ($W \to \infty$). However, W is virtually finite; taking this into account the modified decaying time has the following form [18]:

$$\tau'_{\text{decay}} = \frac{\gamma 1}{K_{22}\pi^2}\left(d^2 + \frac{4dK_{22}}{W}\right). \tag{4}$$

From equation (4), it is clear that larger value of W has an important role in reducing the LC response time. Figure 7 shows the decaying time of pure LC cells and RM-mixed LC cells polymerized at different temperatures. The decaying times of both RM-mixed LC cells improved by about 4.43% compared with the pure LC cell, which comes from the strong W because of the polymerized RM on the surface. Consequently, in our processing method, W can be improved without any transmittance loss and mismatching of retardation values between the LC and the polymerized RM network.

To reconfirm the effect of surface-anchoring energy, capacitance–voltage (C–V) measurement of each case was carried out in IPS geometry using an electronic measurement machine, LCR meter, as revealed in figure 8. All the cases apparently show almost the same changes in capacitance with increasing voltage and about the same threshold voltage (V_{th}) at which the capacitance starts to change. However, in a larger scale near V_{th} as shown in figure 8 the C–V graph for case 2, i.e. the case in which we have polymerized the sample at a low temperature, shows the largest V_{th} and steepest C–V change among the three cases. The implicit dependence of V_{th} and W is given by [19]

$$\xi_{\text{C}} = -\frac{\xi_E^{\text{th}}}{\tan \xi_E^{\text{th}}} \tag{5}$$

where $\xi_E^{\text{th}} = V(d/D)(\varepsilon_0 \cdot \Delta\varepsilon/K_{22})^{1/2}$ is the dimensionless electric field, and $\xi_C = Wd/K_{22}$ is the anchoring parameter on the surface. Equation (5) gives V_{th} as a function of surface-anchoring strength of the LC (W), cell thickness (d) and the distance between the interdigitated electrodes (D). With this dependence we can describe the effect of the increase in V_{th} for strong anchoring. Thus, it is quite clear from figure 8 that W is enhanced by the polymerization process of mixing RM at room temperature and the value of W is the highest for the case of polymerization at a low temperature.

4. Summary

In this paper, we have proposed a new method to improve the dark state in homogeneously aligned liquid crystal cells by mixing a very small amount of RM and polymerizing it at a low temperature. The cured RM at low temperature enhances the surface-anchoring energy, as well as the order parameter of the LC alignment, and thus, the dark state of the proposed RM-mixed LC cell cured at a low temperature becomes better than that of the pure LC cell and RM-mixed LC cell cured at room temperature. The polymerized RM network on the surface strengthens the surface-anchoring energy, and consequently the decaying time is reduced for the polymerized samples.

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References

[1] Oh-e M and Kondo K 1997 *Japan. J. Appl. Phys.* **36** 6798
[2] Satake T, Nishioka T, Saito T and Kurata T 2001 *Japan. J. Appl. Phys.* **40** 195
[3] Hong H-K and Seo C-R 2004 *Japan. J. Appl. Phys.* **43** 7639
[4] Lee S H, Lee S L and Kim H Y 1998 *Appl. Phys. Lett.* **73** 2881
[5] Hong S H, Park I C, Kim H Y and Lee S H 2000 *Japan. J. Appl. Phys.* **39** L527
[6] Lim Y J, Shin S J, Cho N H, Bhattacharyya S S, Park K H, Lee J H, Kim B K and Lee S H 2011 *Opt. Express* **19** 8085
[7] Takeda A, Kataoka S, Sasaki T, Chida H, Tsuda H, Ohmuro K, Koike Y, Sasabayashi T and Okamoto K 1998 *SID Int. Symp. Digest Tech. Papers* **29** 1077
[8] Jisaki M and Yamaguchi H 2001*Proc. 8th Int. Display Workshop (Society for Information Display, Nagoya, Japan)* p 133
[9] Song I S, Won H K, Kim D S, Soh H-S, Kim W Y and Lee S H 2004 *Japan. J. Appl. Phys.* **43** 4242
[10] Broer D J, Finkelman H and Kondo K 1988 *Makromol. Chem.* **189** 185
[11] Hanaoka K, Nakanishi Y, Inoue Y, Tanuma S, Koike Y and Okamoto K 2004 *SID Int. Symp. Digest Tech. Papers* **35** 1200
[12] Kim S G, Kim S M, Kim Y S, Lee H K, Lee S H, Lee G-D, Lyu J-J and Kim K H 2007 *Appl. Phys. Lett.* **90** 261910
[13] Lim Y J, Chin M H, Kim J H, Her J H, Jin H S, Kim B K and Lee S H 2009 *J. Phys. D: Appl. Phys.* **42** 145412
[14] Suwa S, Isozaki T, Inoue Y, Nakamura M, Miyakawa M and Urabe T 2010 *SID Int. Symp. Digest Tech. Papers* **41** 595
[15] Escuti M J, Bowley C C, Zumer S and Crawford G 1999 *SID Int. Symp. Digest Tech. Papers* **30** 32
[16] Lee S H, Kim S M and Wu S -T 2009 *J. Soc. Inform. Disp.* **17** 551
[17] Yang D-K and Wu S-T 2006 *Fundamentals of Liquid Crystal Devices* (New York: Wiley) p 206 chapter 8.3
[18] Nie X, Lu R, Xianyu H, Wu T X and Wu S-T 2007 *J. Appl. Phys.* **101** 103110
[19] Andrienko D, Barbet F, Bormann D, Kurioz Y, Kwon S-B, Reznikov Y and Warenghem M 2000 *Liq. Cryst.* **27** 365