

Effects of three-dimensional polymer networks in vertical alignment liquid crystal display controlled by in-plane field

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Abstract: Polymer network in vertical alignment liquid crystal cell driven by in-plane field (VA-IPS) is formed in three dimensions to achieve fast response time and to keep the liquid crystal alignment even when an external pressure is applied to the cell. The network formed by UV irradiation to vertically aligned liquid crystal cell with reactive mesogen does not disturb a dark state while exhibiting very fast decaying response time less than 2ms in all grey scales and almost zero pooling mura. The proposed device has a strong potential to be applicable to field sequential display owing to super-fast response time and flexible display owing to polymer network in bulk which supports a gap between two substrates.

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References and links

1. R. A. Soref, "Field effects in nematic liquid crystals obtained with interdigital electrodes," *J. Appl. Phys.* **45**(12), 5466–5468 (1974).
2. M. Oh-e and K. Kondo, "Electro-optical characteristics and switching behavior of the in-plane switching mode," *Appl. Phys. Lett.* **67**(26), 3895–3897 (1995).
3. S. H. Lee, S. L. Lee, and H. Y. Kim, "Electro-optic characteristics and switching principle of a nematic liquid crystal cell controlled by fringe-field switching," *Appl. Phys. Lett.* **73**(20), 2881–2883 (1998).
4. S. H. Lee, S. S. Bhattacharyya, H. S. Jin, and K.-U. Jeong, "Devices and materials for high-performance mobile liquid crystal displays," *J. Mater. Chem.* **22**(24), 11893–11903 (2012).
5. K. Hanaoka, Y. Nakanishi, Y. Inoue, S. Tanuma, Y. Koike, and K. Okamoto, "A New MVA-LCD by Polymer Sustained Alignment Technology," *SID Symposium Digest of Technical Papers* **35**, 1200–2003 (2004).
6. S. G. Kim, S. M. Kim, Y. S. Kim, H. K. Lee, S. H. Lee, G.-D. Lee, J.-J. Lyu, and K. H. Kim, "Stabilization of the liquid crystal director in the patterned vertical alignment mode through formation of pretilt angle by reactive mesogen," *Appl. Phys. Lett.* **90**(26), 261910 (2007).
7. S. Suwa, T. Isozaki, Y. Inoue, M. Nakamura, M. Miyakawa, and T. Urabe, "Novel Field-induced Pre-tilt Alignment Technique Using a Photo-reactive Alignment Layer for VA LCD," *SID Symposium Digest of Technical Papers* **41**, 595–598 (2010).
8. C. W. Tang and S. A. Vanslyke, "Organic electroluminescent diodes," *Appl. Phys. Lett.* **51**(12), 913–915 (1987).
9. G. Rajeswaran, M. Itoh, M. Boroson, S. Barry, T. K. Hatwar, K. B. Kahen, K. Yoneda, R. Yokoyama, T. Yamada, N. Komiya, H. Kanno, and H. Takahashi, "Active Matrix Low Temperature Poly-Si TFT/OLED Full Color Display: Developmetn Stratus," *SID Int. Symp. Digest Tech. Papers* **31**, 974–977 (2000).
10. K. Mamenno, R. Nishikawa, K. Suzuki, S. Matsumoto, T. Yamaguchi, K. Yoneda, Y. Hamada, H. Kanno, Y. Nishio, H. Matsuoka, Y. Saito, S. Oima, N. Mpri, G. Rajeswaran, S. Mizukoshi, and T. K. Hatwar, "Development of 2.2-inch Full Color AM-OLED Display for Mobile Applications," *Proc. of the 9th International Display Workshops (Society for Information Display, Hiroshima, Japan)*, 235–238 (2002).
11. A. Sugimoto, H. Ochi, S. Fujimura, A. Yoshida, T. Miyadera, and M. Tsuchida, "Flexible OLED Displays Using Plastic Substrates," *IEEE J. Sel. Top. Quantum Electron.* **10**(1), 107–114 (2004).
12. T.-H. Han, Y. Lee, M.-R. Choi, S.-H. Woo, S.-H. Bae, B. H. Hong, J.-H. Ahn, and T.-W. Lee, "Extremely efficient flexible organic light-emitting diodes with modified graphene anode," *Nat. Photonics* **6**(2), 105–110 (2012).
13. Y. Chen, J. Au, P. Kazlas, A. Ritenour, H. Gates, and M. McCreary, "Electronic paper: Flexible active-matrix electric ink display," *Nature* **423**, 136 (2003).

14. M. Nishii, R. Sakurai, K. Sugie, Y. Masuda, and R. Hattori, "The Use of Transparent Conductive Polymer for Electrode Materials in Flexible Electronic Paper," *SID Symposium Digest of Technical Papers* **40**, 768–771 (2009).
15. R. Sakurai, S. Ohno, S.-I. Kita, Y. Masuda, and R. Hattori, "Color and Flexible Electronic Paper Display using QR-LPD® Technology," *SID Symposium Digest of Technical Papers* **37**, 1922–1925 (2006).
16. M. Kim, M. S. Kim, B. G. Kang, M.-K. Kim, S. Yoon, S. H. Lee, Z. Ge, L. Rao, S. Gauza, and S.-T. Wu, "Wall-shaped electrodes for reducing the operation voltage of polymer-stabilized blue phase liquid crystal displays," *J. Phys. D Appl. Phys.* **42**(23), 235502 (2009).
17. Z. Ge, S. Gauza, M. Jiao, H. Xianyu, and S.-T. Wu, "Electro-optics of polymer-stabilized blue phase liquid crystal displays," *Appl. Phys. Lett.* **94**(10), 101104 (2009).
18. K. Hanaoka, Y. Nakanishi, Y. Inoue, and S. Tanuma, Y., "A new MVA-LCD by polymer sustained alignment technology," *SID Symposium Digest* **35**, 1200–1203 (2004).
19. S. G. Kim, S. M. Kim, Y. S. Kim, H. K. Lee, S. H. Lee, G.-D. Lee, J.-J. Lyu, and K. H. Kim, "Stabilization of the liquid crystal director in the patterned vertical alignment mode through formation of pretilt angle by reactive mesogen," *Appl. Phys. Lett.* **90**(26), 261910 (2007).
20. V. Borshch, J.-Y. Hwang and L.-C. Chien, "Liquid crystal-directed polymer nanostructure for vertically-aligned nematic cells," *Proc. SPIE* **7618**, 76180V (2010).
21. S. H. Lee, H. Y. Kim, I. C. Park, B. G. Rho, J. S. Park, H. S. Park, and C. H. Lee, "Rubbing-free, vertically aligned nematic liquid crystal display controlled by in-plane field," *Appl. Phys. Lett.* **71**(19), 2851–2853 (1997).
22. H. Yoshida, Y. Nakanishi, T. Sasabayashi, Y. Tasaka, K. Okamoto, Y. Inoue, H. Sukenori, and T. Fujikawa, "Fast-Switching LCD with Multi-Domain Vertical Alignment Driven by an Oblique Electric Field," *SID Symposium Digest of Technical Papers* **31**, 334–337 (2000).
23. I. Y. Cho, S. M. Kim, S. J. Hwang, W. I. Kim, M. Y. Kim, J. H. Son, J. J. Ryu, K. H. Kim, and S. H. Lee, "New vertical alignment liquid crystal device with fast response time and small color shift," *Proc. of the 28th International Display Research Conference (Society for Information Display, Orlando, Florida, USA)*, 246–248 (2008).
24. S.-W. Kang, Y. E. Choi, B. H. Lee, J. H. Lee, S. Kundu, H.-S. Jin, Y. K. Yun, S. H. Lee, and L. Komitov, "Surface polymer-stabilised in-plane field driven vertical alignment liquid crystal device," *Liq. Cryst.* **41**(4), 552–557 (2014).
25. L. Komitov, G. Hegde, and S. H. Lee, "Fast liquid crystal light shutter," *SID Symposium Digest of Technical Papers* **42**, 1587–1589 (2011).
26. L. Komitov and G. Hegde, "Fast switching liquid crystal display modes," in *Proceedings of the SPIE Advances in Display Technology II Conference (SPIE, 2012)(San Francisco, California, USA)* (2012).
27. C. V. Rajaram, S. D. Hudson, and L. C. Chien, "Morphology of Polymer Stabilized Liquid Crystals," *Chem. Mater.* **7**(12), 2300–2308 (1995).
28. H. Wang, T. X. Wu, X. Zhu, and S.-T. Wu, "Correlations between liquid crystal director reorientation and optical response time of a homeotropic cell," *J. Appl. Phys.* **95**(10), 5502–5508 (2004).

1. Introduction

Nowadays, performance of image quality of the liquid crystal display (LCD) is rapidly improving by applying the advanced LC modes such as in-plane switching (IPS) [1, 2], fringe field switching (FFS) [3, 4], and multi-domain vertical alignment (MVA) including polymer stabilization at surface [5–7]. Nevertheless, LCD is recently challenged by organic light-emitting diode (OLED) display [8–10], especially flexible OLED [11, 12] and also electronic paper-like display [13–15] utilizing plastic substrates. Now the question arises whether flexible LCDs, with plastic substrates, can successfully be made. At present, all commercialized LCDs utilize a nematic liquid crystal (LC) orientated uniformly over large area. Therefore, although plastic film is used in LCDs, applying external pressure to the display or bending the display would deteriorate the displayed image quality because of distortion of cell gap and uniform LC orientation associated with the fluidity of LCs. In addition, high speed LCD modes such as blue phase LCD [16, 17] which provide several μ s or less than few ms response time in all grey levels, have to be developed for displaying perfect moving images, and also three-dimensional and field sequential color LCDs.

In LCD-televisions, LCDs with MVA type is still popular because of rubbing-free process and high contrast ratio at normal direction and recently surface polymer-stabilization by adding small amount of RM less than 1 wt% into LC is performed to improve rising response time of the device [18–20]. All conventional devices use a LC with negative dielectric anisotropy of which the rotational viscosity is higher than the one of a LC with positive dielectric anisotropy. As one of solutions to overcome such the problem, VA mode driven by in-plane field (named VA-IPS) [21–24] and fringe-field [25, 26] using a LC with positive dielectric anisotropy exhibiting very fast response time are reported. However, the device also

exhibits pooling mura by distortion of LC molecules when an external pressure is applied to the display so that all proposed VA modes are not suitable for flexible displays.

In this paper, we investigated the electro-optic characteristics of the VA-IPS cell with polymer network created in the LC bulk. This device shows no pooling mura under an external mechanical pressure while showing faster decay response time due to the polymer network.

2. Switching principle of the VA-IPS mode with polymer network in bulk

The normalized transmission of light through the VA-IPS cell in which vertically aligned uniaxial LC medium is driven by in-plane electric field under crossed polarizer is given by

$$T/T_0 = \sin^2(2\psi(V)) \sin^2(\pi d \Delta n_{\text{eff}}(V)/\lambda) \quad (1)$$

where ψ is a voltage-dependent angle between the transmission axes of the crossed polarizer and the LC director, d is a cell gap, Δn_{eff} is the voltage-induced effective birefringence of LC, and λ is the wavelength of the incident light.

Figure 1 shows structure of the proposed VA-IPS cell in which interdigitated pixel electrodes exist only on bottom substrate and polymer network is generated in the LC bulk. In general, a bulk polymer network stabilized VA device shows fast response time but low transmission and low contrast ratio due to the light scattering effect [27]. One interesting viewpoint of the proposed device is that the existence of polymer network does not disturb much the orientation of vertical alignment and also the refractive index mismatch between polymer and ordinary refractive index of LC is minimized because the polymer is made of reactive mesogens with its ordinary refractive index similar to that of the LC and its optic axis in vertical direction. Consequently the cell still appears to be black in the field-off state even with polymer network in bulk LC. When the voltage is applied, the in-plane field is generated by the in-plane electrodes, reorient the LC molecules along the field direction with $\psi = 45^\circ$ so that the cell appears white. Unlike conventional VA-IPS cell in which straight form of disclination lines exists between two electrodes, the polydomain type of LC textures without forming a line shape of disclination line is expected to appear in the on-state due to the polymer network (see Fig. 1).

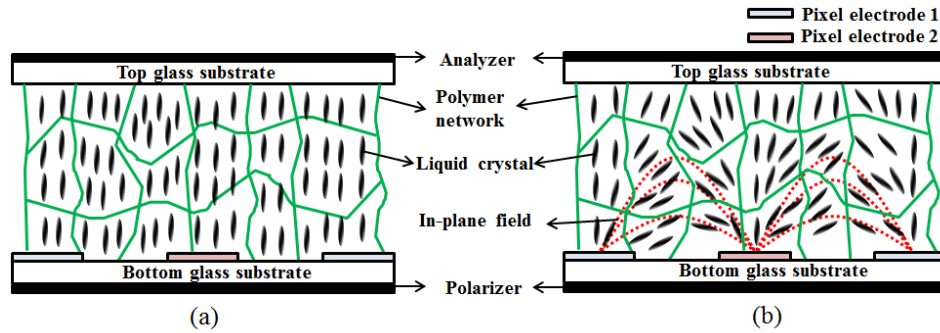


Fig. 1. Schematic cell structure of the VA-IPS cell with polymer network in (a) off- and (b) on-states. The existence of polymer network in bulk does not disturb vertical LC orientation and the in-plane field induces LC reorientation.

3. Experimental results and discussion

To fabricate a VA-IPS cell with polymer network in the LC bulk state, the glass substrate without electrode and the other glass with interdigitated electrodes, made of aluminum (Al) with electrode width (w) of $4 \mu\text{m}$ and distance (l) of $10 \mu\text{m}$ between electrodes were assembled in a cell with conventional sandwich geometry. The cell gap was fixed to be $4.75 \mu\text{m}$ using a plastic ball spacer. On the inner surface of both substrates was deposited alignment layer (AL60702 from JSR) promoting vertical alignment (VA). Nematic LC from

Merck, with dielectric anisotropy ($\Delta\epsilon$) of 7.4 at 1 KHz and birefringence (Δn) of 0.088 at 589 nm, was used. In the LC was dissolved 2 wt% of UV curable reactive mesogen (RM) (RM-257 from Merck) and photoinitiator (Igracure 651 from Ciba) of 0.1 wt%. The LC mixture was filled in the cell at room temperature by capillary force. Once the LC mixture adopted vertical alignment in the initial field-off state, the experimental cell was exposed to the UV light (Lightning cure, HAMAMATSU) with 18 mW/cm² for 40 min, which caused polymerization of the RMs forming a polymer network in the LC bulk. It should be noted here that the cell after UV illumination appeared in field-off state fully transparent, i. e. without exhibiting visible light scattering. The absence of light scattering indicates that the network fibers are with preferred orientation along the cell substrate normal, since there is no any mismatching of the ordinary (n_o) indices of LC and RM 257.

Figure 2 shows polarizing optical macroscopic (POM, Nikon ECLIPSE E600, Japan) images at different applied voltage before and after UV curing. For comparison, POM images before and after UV curing were observed at the same light incidence because the polymer network might disturb LC orientation in some of areas of the cell and also cause scattering by refractive index mismatch between polymer network and LC. The dark states of the both cells were calculated using an image analyzer i-solutionTM (IMT i-Solution Inc.), and the leakage transmittance before and after UV curing was 9.02 and 9.06, respectively, showing the presence of a clear dark state. The results imply that the formed polymer network after UV curing did not affect much the vertical alignment of LC and also the scattering by refractive index mismatching between the polymer and LC is minimal. As the applied voltage increases above Freedericksz transition, the transmittance starts to appear between electrodes, as shown in Fig. 2. Before UV curing, the transmittance starts from electrode edge and extends to the center between electrodes as the applied voltage increases. In the cell, the disclination lines existed in a straight form until the transmittance reached maximum (see Fig. 2(a)). Interestingly, after UV curing the cell, the cell showed totally different LC texture in the field-on state. The straight line shape of disclinations did not appear anymore, instead, irregular disclination lines with zigzag shape appeared between electrodes and a polydomain-like texture was found to be formed. In addition, after formation of the polymer network, the disclination lines almost disappeared at very high applied voltage, showing better transmittance (see Fig. 2(b)). Another noticeable thing is that the device shows bluish white color before UV curing but shows yellowish white color after UV curing, indicating effective retardation of the proposed VA-IPS cell in on-state becomes larger after UV curing because more LC molecules tilt down along the higher intensity of electric field than that of UV curing.

Figure 3 shows the measured voltage-dependent transmittance (V-T) curves and response times of the experimental VA-IPS cell before and after UV curing process, using the measuring equipment LCMS-200 (Sesim Photonics Technology Inc, Korea) in which halogen lamp of 100W is used and the beam shape of an incident light is a circle with a diameter of 3 mm. As shown in Fig. 3(a), the cell with polymer network exhibits higher transmittance in field-on state than that without polymer network, which is consistent with observed textures under POM. However, the threshold and operating voltage became much higher. This is due to the polymer network, formed in the LC bulk after UV curing, resulting in a substantial increase of the solid surface/liquid crystal interface, which in its turn leads to increase of the cell operation voltages. In addition, light leakage in a dark state was slightly increased after UV curing, indicating thus that there exists some level of depolarization of the incident light by the polymer network. Such deterioration of the dark quality was resulting in a decrease of the contrast ratio at normal viewing direction. Overall, V-T curve is shifted to the right after UV curing, implying that reorientation of LC molecules are strongly affected by polymer network. As seen in Fig. 3(a), the slope of the of the V-T curve decreased also substantially. This indicates the increased impact of the solid surface/liquid crystal anchoring on the electro-optic response of the cell due to the polymer network in LC bulk.

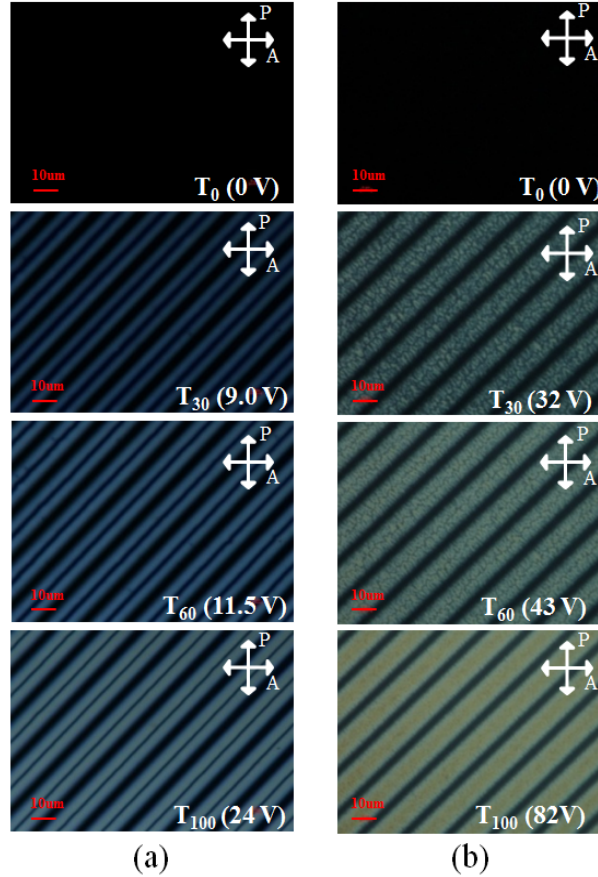


Fig. 2. Polarizing optical macroscopic images at different applied voltages: (a) before and (b) after UV curing. Here, T indicates transmittance and the number in a subscript indicates relative value of the maximum transmittance.

Figure 3(b) shows the measured response time characteristics of the experimental VA-IPS cell in eight gray levels by applying a 60 Hz square wave AC voltage before and after UV curing process. Here, the applied voltages for each gray scale were different before and after UV curing. Normally, the rise (τ_{on}) and decay (τ_{off}) time of VA cell is given as [28]

$$\begin{aligned}\tau_{on} &= \tau_{off} / [(V/V_{th})^2 - 1] \\ \tau_{off} &= \gamma d^2 / \pi^2 K_3\end{aligned}\quad (2)$$

where V is applied voltage, V_{th} is the threshold voltage, d is the LC cell gap, γ is the rotational viscosity, and K_3 is the bend elastic constant. In the case of τ_{on} , the VA-IPS cell after UV curing reacted superiorly faster than that before UV curing because higher voltages were applied, that is, V is much higher than V_{th} in the cell with polymer network. The average τ_{off} of the VA-IPS cell after UV curing is also much faster than that before UV curing; the decay time in the VA-IPS cell after UV curing was approximately 76% faster. This is due to the polymer network in the LC bulk resulting in an increase of the impact of the solid surface/liquid crystal interactions on the switching process of the LC molecules by the applied electric field. On the other hand the existence of the polymer network also reduces the effective d greatly. Now, in order to find out the origin of higher operating voltage and faster decaying response time obtained in the cell with polymer network, scanning electron microscopy (SEM) images of top and bottom substrate of the cell with polymer network were investigated. The SEM images of the substrates' inner surface are shown in Fig. 4. For these

experiments, top and bottom substrates were detached carefully and the LC was washed using a mixed solvent of hexane and dichlorobenzene.

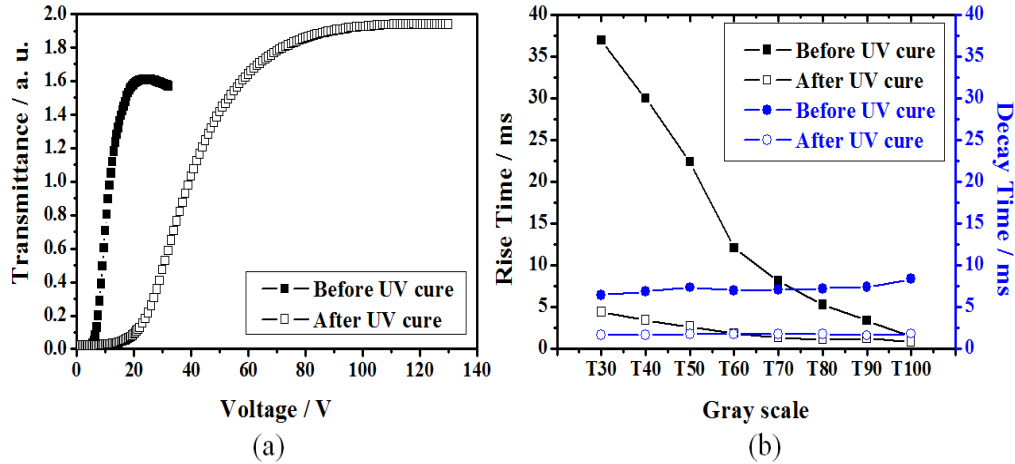


Fig. 3. Measured (a) V-T curves and (b) response times of the proposed VA-IPS cell before and after UV curing of RM.

The top view of SEM image of top substrate indicates that irregular polydomain type of polymer network is formed with various intervals from over $1\ \mu\text{m}$ to less than $8\ \mu\text{m}$ between polymer walls (fibres) (see Fig. 4(a)). The magnified image of one of polymer walls indicates that the height of the polymer wall is $3.51\ \mu\text{m}$ (lower than a cell gap; possibly broken when the cell is opened), and the interval between the walls is $1.84\ \mu\text{m}$ such that the effective cell gap is reduced, which explains faster decay time. Besides the polymer walls, also additional polymer layer, with irregular surface topography, is formed on vertical alignment layer (see Fig. 4(b)). The polymer network of the bottom substrate was found to be quite different from that of the top substrate, in which the polymer grain is formed only in between electrodes with their height of about $3.37\ \mu\text{m}$, as shown in Fig. 4(c) and 4(d). In the experiments, UV light was exposed to the bottom substrate with insertion of reflective mirror above top substrate. Since the electrodes Al blocks an incident UV light, the polymer grains are formed only in between electrode. However, the UV light that passes through the cell reflects again from the mirror and passes through the cell again so that the polydomain type of polymer network is expected to be formed on top substrate. Consequently it seems that the difference between the structures of the polymer networks on the top and on the bottom substrate inner surface, mainly comes from the UV exposure condition, i.e. the UV light is first hitting the substrate bearing the opaque interdigitated electrode structure. Another reason might be the not uniform distribution of the RM upon a non-uniform UV light illumination. There is obviously a relationship between V-T curve, polydomain texture of LC, and irregular shape of disclination lines. The structure of polymer network of top substrate suggests a polydomain type of LC texture and the irregular grain shape of polymer network on bottom substrate explains irregular shape of disclination lines in the field-on state. Further, the existence of polymer network increases an operating voltage due to the increased area of the solid surface/liquid crystal interface which in fact increases the solid surface/liquid crystal resulting in faster decay response time. As one of proving tips on the effects of polymer network, a 10 wt% of RM was tested. As can be seen in Fig. 5, quite good level of dark state is achieved but the transmittance does not occur even after applying of 80 V, indicating clearly that the voltage-induced birefringence is greatly reduced with this high amount of RM doping. The SEM images on top substrate show that a totally different shape of polymer network is formed, that is, a smooth type of polymer structure with its thickness of over $1\ \mu\text{m}$ is formed without showing existence of large holes or domains in the polymer network structure. This proves again that the polymer network hinders the LC reorientation along the field. Overall,

the obtained results indicated that the optimization of RM content and UV curing conditions is very critical for obtaining good electro-optic performance of VA-IPS cell with polymer network created in the LC bulk.

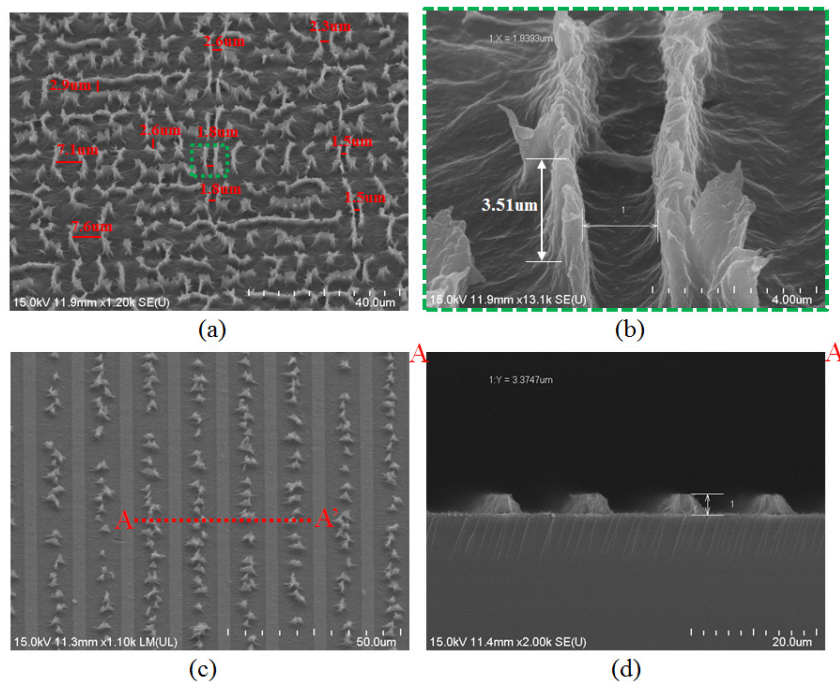


Fig. 4. SEM images of polymer network of the experimental cell after UV curing: (a) top view of polymer network on top substrate and (b) high magnification in green dotted area of Fig. 4(a) and (c) top view of polymer network on bottom substrate and (d) high magnification along the cross-section A-A' of Fig. 4(c).

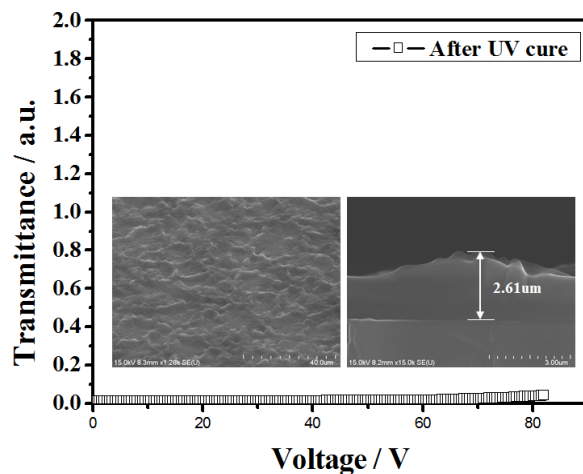


Fig. 5. Measured voltage-dependent transmittance curve in the VA-IPS cell after UV curing when the RM concentration is 10 wt%. The insets are SEM images of top and side views of polymer structure on top substrate. The SEM images show a polymer lump is formed with its thickness 2.6 μm .

According to the polymer structures in Fig. 4, the cell gap is also maintained by polymer network in addition to the ball spacer so that reorientation of LC director under external mechanical pressure to the cell (called pooling effect) can be minimized in our experimental cell. To prove reduced pooling effect, an external pressure is applied to two cells, as presented in Fig. 6. The normal VA-IPS cell, without polymer network, showed pooling effect clearly under the external pressure because the vertically aligned LC molecules tilt down to random directions upon the pressure (see Fig. 6(a)). However, the proposed VA-IPS cell with polymer network does not show any pooling effect at all when the same pressure is applied to the cell owing to the polymer network which supports top and bottom substrates and prevent any LC flow in the cell due to the mechanical pressure (see Fig. 6(b))

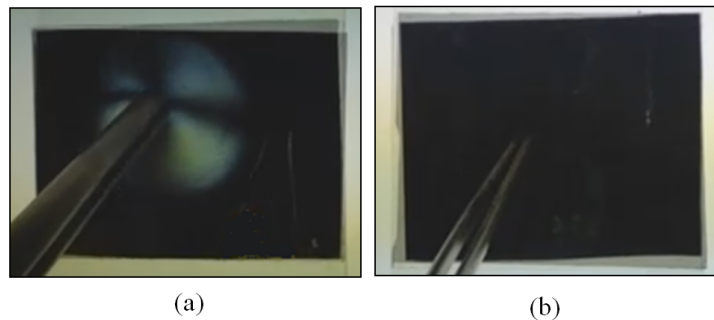


Fig. 6. Macroscopic images of (a) normal VA-IPS cell and (b) proposed VA-IPS cell exhibiting clearly comparable pooling effect under an external mechanical pressure.

The VA-IPS cell, with polymer network in the LC bulk, shows very fast response times and excellent durability under mechanical pressure, which is suitable to bendable or flexible display or field-sequential flexible display. Nevertheless, the operating voltage (V_{op}) seems to be too high in the proposed cell. V_{op} and response times are in trade-off relationship to some levels because loose polymer network would reduce V_{op} but the impact of the solid surface/liquid crystals interactions on the switching process of the LC will be reduced. As known, V_{op} is proportional to $l/d (K_3/\epsilon_0\Delta\epsilon)^{1/2}$ where K_3 is bend elastic constant. Therefore, further optimization of the cell and LC parameters is required to reduce V_{op} as well as further optimization of RM, its concentration and illumination conditions are required to have a proper polymer structure and thus to be able to obtain desirable operation characteristic of the LC cell.

4. Summary

We fabricated and studied VA-IPS cell with a polymer network created in the LC bulk. The proposed device still exhibits a good level of a dark state and very fast decaying response time less than 2 ms in all grey levels, which makes it good candidate for field-sequential LCDs. Another unique characteristic of the VA-IPS cell, containing a polymer network, is that, unlike conventional all LC devices which exhibit severe deformation of the LC orientation under an external mechanical pressure, this cell does not show any pooling mura upon applied pressure, suggesting thus that the polymer network in the LC bulk is a suitable approach for bendable as well as for flexible LCDs.

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