Fast Switching and Low Operating Vertical Alignment Liquid Crystal Display With 3-D Polymer Network for Flexible Display

Young Jin Lim, Hyo Joong Kim, Young Cheol Chae, G. Murali, Joong Hee Lee, Byung-June Mun, Dae Young Gwon, Gi-Dong Lee, and Seung Hee Lee

***Abstract*— Vertical alignment liquid crystal (LC) cell driven by in-plane field with 3-D polymer network exhibited no pooling mura under an external mechanical pressure; however, the operating voltage of the device was increased, because the polymer network hinders field-induced reorientation of LC. In this paper, we adopted a modified cell structure in which a counter electrode on top substrate of the conventional mode is existed, to improve upon this drawback. The proposed device in which the polymer network is formed in bulk of vertically aligned LC layer shows a very fast response time of 2 ms (rise + decay), 57% reduction in operating voltage, and also keeps image quality although the cell is curved.**

***Index Terms*— 3-D polymer network, fast response time, liquid crystal, low operating voltage, vertical alignment.**

I. Introduction

FLAT panel displays (FPDs) have been replacing CRTs over last two decades. More recently, such FPDs are requested to have more functional displays with free form factors and flexibility, such as curved, bendable, foldable, and circular-shaped display [1], [2]. Among FPDs, liquid crystal displays (LCDs) were main devices from small size to large-sized displays although the active matrix organic light emitting diodes (AMOLEDs) [3]–[5] rise up as a strong competitor. Theoretically, AMOLED with plastic substrate can be flexible and can have a free form factor, because it is self-emissive displays composed of thin films [6]–[8]. However, present commercialized LCDs use a fluid LC and in addition, the LC molecules are uniformly aligned like a single crystal having either homogeneous alignment, such as in-plane switching (IPS) [9], [10] and fringe-field switching [11]–[13] modes, or vertical alignment, such as multi-domain vertical alignment [14], [15] and patterned vertical alignment [16]–[19] modes by two substrates holding LCs. Therefore, bending or curving of the display will give a mechanical stress to the substrate and more worse situation arises from different stresses at two substrates, leading to misalignment between two substrates, and also will cause distortion of cell gap and uniform LC orientation associated with the fluidity of LC molecules.

Recently, we reported electro-optic characteristics of vertical alignment mode driven by in-plane electric field (VA-IPS) [20]–[22] using the bulk polymer network [23], in which the polymer network is formed in three dimensions so that the device shows no pooling mura even under an external mechanical pressure. However, polymer network in the VA-IPS device has a high driving voltage, because the bulk polymer network hinders the reorientation of the LCs and in addition, VA-IPS requires relatively high operation voltage to reorient LCs as the LC directors between electrodes try to reorient in opposite directions each other along the center lines between electrodes.

In this paper, we proposed the modified VA-IPS in which additional counter electrode is formed on top substrate [24], [25] so called fast switching-vertical alignment mode (FS-VA) [26]–[28] which reorients LC directors by both in-plane and oblique electric field under formed polymer network in a bulk LC layer. The proposed device shows faster response time and lower operating voltage even with the use of an LC with low magnitude of dielectric anisotropy. And also VA mode with polymer network using plastic substrate is fabricated to test its image quality change at bending stress. There is no pooling mura at all even though external pressure is applied to the device and kept a uniform bright state even if the device using plastic substrate is bent.

II. Switching Principle of the Proposed FS-VA Mode Before and After UV Curing

The normalized transmission (T/T_0) of light through the FS-VA cell in which vertically aligned uniaxial LC medium is

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Y. J. Lim, H. J. Kim, Y. C. Chae, G. Murali, J. H. Lee, and S. H. Lee are with the Department of BIN Convergence Technology and Department of Polymer-Nano Science and Technology, Applied Materials Institute for BIN Convergence, Chonbuk National University, Jeonju 54896, South Korea (e-mail: blueribbonyj@naver.com; kys5484@naver.com; wertrew651@naver.com; drmuraliphy@gmail.com; jhl@chonbuk.ac.kr; lsh1@chonbuk.ac.kr).

B.-J. Mun, D. Y. Gwon and G.-D. Lee are with the Department of Electronics Engineering, Dong-A University, Busan 49315, South Korea (e-mail: mbj1101@naver.com; eodud1213@naver.com; gdlee@dau.ac.kr).

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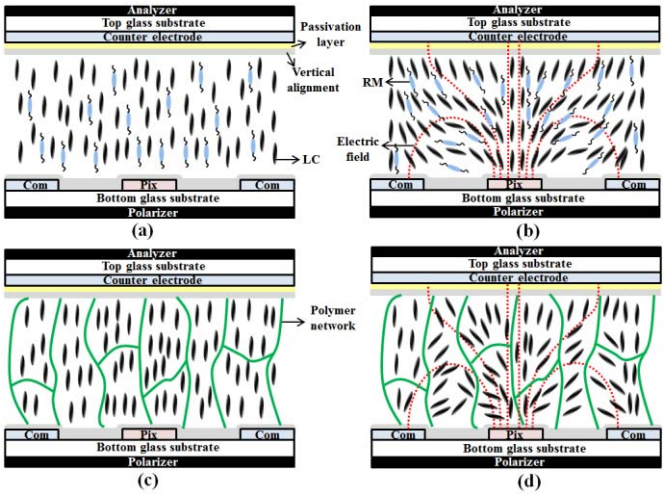

Fig. 1. Schematic of the operating principle of FS-VA mode for (a) and (c) OFF-state and (b) and (d) on-state before and after UV curing.

driven by both in-plane and oblique electric field under crossed polarizer is given by

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

where ψ is an angle between the transmission axes of the crossed polarizers and the projection of the LC director onto the xy- plane, d is a cell gap, Δn is the voltage-induced birefringence of LC (that is, induced retardation $R = d\Delta n = \int_0^d \Delta n(z)dz$), and λ is the wavelength of an incident light.

Fig. 1 shows the schematic of the operating principle of the FS-VA mode for OFF- and ON-states before and after UV curing. The pixel and common electrodes exist on the bottom substrate in an interdigitated form with electrode width and distance between electrodes and the additional counter electrode exist on the top substrate in plane form. In both before and after UV curing states, initial LC molecules are vertically aligned in the OFF state and so $R = 0$, and thus, it is in a dark state. When a voltage is applied, the combination of an in-plane field and an oblique electric field is generated by the in-plane electrodes and the counter electrode, so that it reorients the LC molecules along the field direction with $\psi = 45°$. Here, because ψ is fixed by 45° owing to the fixed directions of crossed polarizers and applied electric fields, the transmittance in a bright state (gray level) would be determined as

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

Unlike conventional VA-IPS mode in which straight form of disclination lines exists between two bottom electrodes, two domains and poly-domain of LC textures without forming a line shape of disclination line are expected to appear in the ON-state due to the effect of asymmetric oblique electric field between the counter and pixel electrodes before UV curing [see Fig. 1(b)] and polymer network after UV curing [see Fig. 1(d)], respectively.

III. Experimental Results and Discussion

For comparison study, we fabricate VA-IPS cell without counter electrode and FS-VA cell with counter electrode on top substrate. In the FS-VA cell, a passivation layer with thickness of 0.12 μm is coated on the counter electrode. Both cells have interdigitated electrodes made of indium–tin–oxide with electrode width (w) of 4 μm and distance (l) of 4 μm between electrodes. Cell gaps were fixed to be 4 μm using a plastic ball spacer. The LC mixture with positive dielectric anisotropy ($\Delta\varepsilon = 7.4$) and birefringence ($\Delta n = 0.088$ at 589 nm and 20 °C) is used. The reactive mesogen (RM) used in this paper is RM 257 (Merck, Darmstadt, Germany). In the LC was dissolved 2 wt% of UV curable RM and photoinitiator (Igracure 651 from Ciba) of 0.1 wt% due to the sufficiency of RM to form polymer network [12]. The experimental cell was exposed to the UV light (Lightning cure, HAMA MATSU) with 18 mW/cm^2 for 40 min, which caused the polymerization of the RM 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.

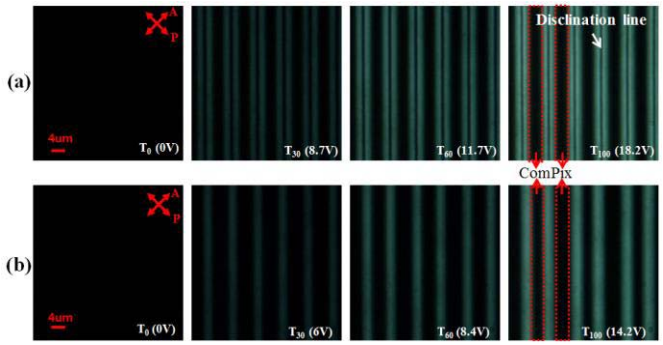

Fig. 2. POM images at different applied voltages. (a) VA-IPS cell. and (b) FS-VA cell before UV curing. Here, T indicates transmittance and the number in a subscript indicates relative value of the maximum transmittance.

Fig. 2 shows polarizing optical macroscopic (POM, Nikon ECLIPSE E600, Japan) images at different applied voltage in both VA-IPS and FS-VA cells before UV curing. For comparison, POM images of VA-IPS and FS-VA cells were observed at the same light incidence. In the OFF state, the both cells show the presence of a clear dark state, because the LC molecules are vertically aligned with excellent uniformity. The spatially averaged values of pixel brightness in POM images in 8-b gray scale of VA-IPS and FS-VA cells using an image analyzer i-solution (IMT i-Solution Inc.,) are 0.16 and 0.17, respectively. In the VA-IPS cell, the transmittance starts from both the edges of electrodes by the reorientation of LCs to the right and left directions along the symmetric in-plane field between electrodes and extends to the center so that the straight shape of disclination line appears between two electrodes in a white state [see Fig. 2(a)]. Meanwhile, the FS-VA does not show the straight shape of disclination line, because the LC molecules tilt downward in one direction between two electrodes due to the effect of asymmetric oblique electric field between the top electrode and the pixel electrode in a white state [see Fig. 2(b)].

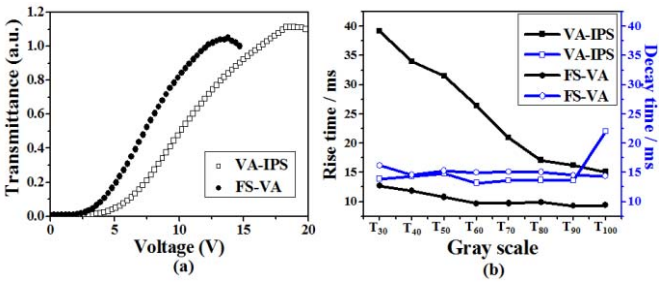

Fig. 3. Measured (a) V—T curves and (b) response times of the VA-IPS and FS-VA cells before UV curing.

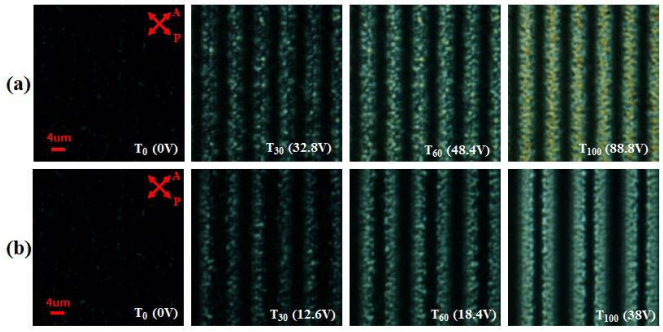

Fig. 4. POM images at different applied voltages. (a) VA-IPS cell. and (b) FS-VA cell after UV curing. Here, T indicates transmittance and the number in a subscript indicates relative value of the maximum transmittance.

Fig. 3 shows the measured voltage-dependent transmittance (V–T) curves and response times of the VA-IPS and FS-VA cells before UV curing process, using the measuring equipment LCMS-200 (Sesim Photonics Technology Inc., South Korea) in which halogen lamp of 100 W 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 FS-VA mode has lower operating voltage by 4.5 V than that of the VA-IPS mode, because LC can be tilted to one direction without collision between LC molecules due to oblique electric field. In the case of response times, rise times of FS-VA mode are much faster than those of the VA-IPS mode although less voltage is applied to the LC in the FS-VA mode; however, the decay times of both modes are about the same each other, as shown in Fig. 3(b). The average rise time in the FS-VA cell before UV curing is approximately 40% faster.

Fig. 4 shows POM images while increasing voltages from dark to white states in VA-IPS and FS-VA cells after UV curing. The dark state of both the cells with the calculated values of 1.54 and 1.58, respectively, is higher light leakage than those before UV curing;, however, there are still showing a perfect dark state. Interestingly, both VA-IPS and FS-VA devices show quite different LC textures in the voltage-ON state compared with those without UV exposure. The straight line shape of disclination lines in the VA-IPS mode does not appear anymore, instead, irregular zigzag shape of disclination lines appear between electrodes. In addition, the disclination lines almost disappear at very high applied voltage, showing better transmittance [see Fig. 4(a)]. Even in the case of FS-VA mode, the transmittance occurs in the same region before UV exposure, but the transmittance appears with some

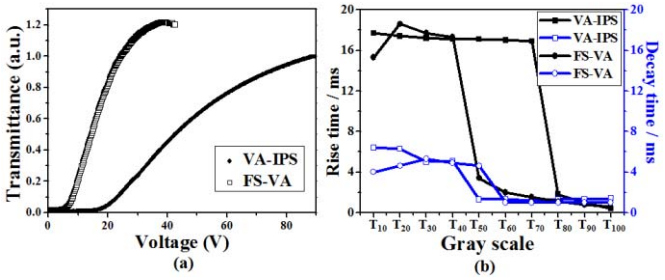

Fig. 5. Measured (a) V—T curves and (b) response times of the VA-IPS and FS-VA cells after UV curing.

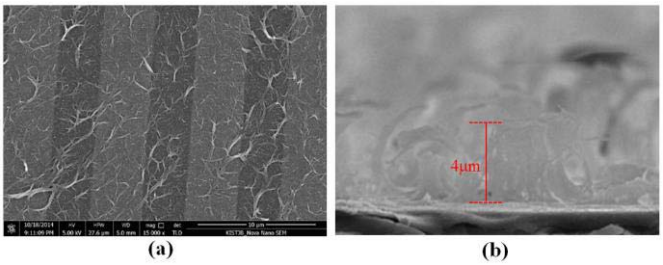

Fig. 6. SEM images of polymer network of the experimental FS-VA cell after UV curing. (a) Top view and (b) side view of polymer network on bottom substrate.

irregular textures which are associated with polymer network [see Fig. 4(b)].

Fig. 5 shows the measured V-–T curves and response times of VA-IPS and FS-VA cells after UV curing. Both threshold and operating voltages of VA-IPS and the FS-VA cells after UV curing is increased as compared with before UV curing, due to the hindrance effect of LC reorientation by a bulk polymer network. However, the operating voltage of FS-VA cell (38 V) exhibits much lower than VA-IPS device (88.8 V). This is due to occurred oblique electric field by additional counter electrode on top substrate. The operating voltage of a VA device is proportional to $(1/\Delta\varepsilon)^{1/2}$ so that if we use an LC with $\Delta\varepsilon = 40$, it can be reduced to about 16 V. The response time of the VA-IPS and the FS-VA after UV curing is 2 ms (rise + decay time), faster than that before UV curing because higher operating voltage than before UV curing is applied for rise time and the polymer network in the LC bulk resulting in an increase of the impact of the solid surface/LC interactions and reduced cell gap effect results in a fast decay time.

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 bottom substrate of the cell with polymer network were investigated. The SEM images of the substrates' inner surface are shown in Fig. 6. For these experiments, top and bottom substrates were detached carefully and the LC was washed using a mixed solvent of hexane of 80% and dichloromethane of 20%. The SEM image of bottom substrate indicates that irregular polydomain type of polymer network is formed, as shown in Fig. 6(a). The height of the polymer network like fiber is 4 μm, the intervals between the fibers are very narrow [see Fig. 6(b)] such that the effective cell gap is reduced, which explains faster decay time.

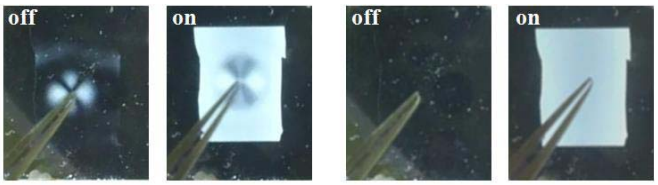

Fig. 7. Macroscopic images in off and on states of the proposed FS-VA cell exhibiting clearly comparable pooling effect under an external mechanical pressure. (a) Before UV curing. (b) After UV curing.

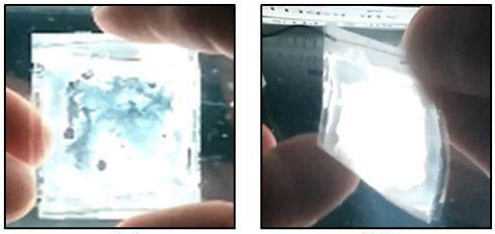

Fig. 8. Macroscopic image of VA mode using plastic substrate in ON-state when the substrate is deformed. (a) Before UV curing. (b) After UV curing.

According to the polymer structures in Fig. 6, 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 the cell before and after UV curing, as presented in Fig. 7. The OFF and ON state of the cell before UV curing, 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. 7(a)]. The pooling effect at ON state is little less than at OFF state, because LC molecules already tilt down between pixel and common electrodes on bottom substrate by applied voltage. However, the OFF and ON state of the cell after UV curing 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. 7(b)].

Fig. 8 represents the macroscopic images of VA cell in ON-state before and after UV is exposed when the substrate is deformed. Here, all conditions are the same as to the previous experiment, but this VA device is made with plane IZO electrode on the top and bottom electrode with polycarbonate plastic film. Under mechanical deformation, the LC arrangements as well as the image are disturbed before UV curing [see Fig. 8(a)], but they are not disturbed after UV curing while keeping an excellent uniformity in a white state [see Fig. 8(b)], confirming an excellent cell gap is kept in the PS-VA cell.

IV. Conclusion

We fabricated and studied the proposed FS-VA cell with bulk polymer network for a possible use of flexible LCDs. The proposed FS-VA device with polymer network in a bulk LC layer solves a high operating voltage of the conventional VA-IPS device while keeping a fast response time and no pooling and bending mura although the cell is deformed by mechanical pressure. This opens a possibility for the prepared device to be applicable in flexible displays.

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Young Jin Lim received the Ph.D. degree from the Department of Polymer-Nano Science and Technology, Chonbuk National University, Jeonju, South Korea, in 2010.

She is currently a Research Assistant Professor with the Department of BIN Fusion Technology, Chonbuk National University. Her current research interests include developing high-performance LCDs, 2-D/3-D switchable LC lens, and orientation and interaction of the LC with nanosolids.

Hyo Joong Kim received the B.S. degree in polymer-nano science and technology from Chonbuk National University, Jeonju, South Korea, in 2015, where he is currently pursuing the master's degree with the Department of BIN Fusion Technology.

His current research interests include liquid crystal device and photoalignment.

Young Cheol Chae received the B.S. degree in polymer-nano science and technology from Chonbuk National University, Jeonju, South Korea, in 2015, where he is currently pursuing the master's degree with the Department of BIN Fusion Technology.

His current research interests include liquid crystal device, transparent electrode, and quantum dot.

G. Murali received the Ph.D. degree from the Department of Physics, Sri Venkateswara University, Tirupati, India, in 2014.

He joined the Group of Prof. S. H. Lee at the Department of BIN Convergence Technology, Chonbuk National University, Jeonju, South Korea, in 2014. His current research interests include the design and synthesis of luminescent nanomaterials for applications in optoelectronic and advanced energy devices.

Joong Hee Lee received the Ph.D. degree from the Department of Mechanical Engineering, University of Minnesota, Minneapolis, MN, USA, in 1995.

Since 1996, he has been a Professor with the Department of Polymer-Nano Science and Technology, and the Department of BIN Convergence Technology, Chonbuk National University, Jeonju, South Korea. His current research interests include the preparation and applications of functional nanocomposites.

Byung-June Mun received the Ph.D. degree from the Department of Electronics Engineering, Dong-A University, Busan, South Korea, in 2015.

Since 2016, he has been a Post-Doctoral Fellow with the Brain Korea 21 Plus, Dong-A University. His current research interests include developing high-performance LCDs, design for the optical configuration of the polarizers and retarders, 2-D/3-D switchable lens, photo-alignment method, and nanoencapsulation technology for LCDs.

Dae Young Gwon received the B.S. degree from the Department of Electronics Engineering, Dong-A University, Busan, South Korea, in 2015, where he is currently pursuing the master's degree with the Department of Electronics Engineering.

His current research interests include physics of liquid crystals and nanoencapsulation technology for LCDs.

Gi-Dong Lee received the Ph.D. degree from the Department of Electronics, Pusan National University, Busan, South Korea, in 2000.

Since 2004, he has been a Professor with the Department of Electronics Engineering, Dong-A University, Busan. His current research interests include LC director modeling and LC optics.

Seung Hee Lee received the Ph.D. degree from the Department of Physics, Kent State University, Kent, OH, USA, in 1994.

Since 2001, he has been a Professor with the Department of Polymer-Nano Science and Technology, and the Department of BIN Convergence Technology, Chonbuk National University, Jeonju, South Korea. His current research interests include functional electronic materials and its application to electro-optic devices.