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Mingxia Gu
Kent State University - Kent Campus, gu@lci.kent.edu

Ivan I. Smalyukh
Kent State University - Kent Campus

Oleg Lavrentovich
Kent State University - Kent Campus, olavrent@kent.edu

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Directed vertical alignment liquid crystal display with fast switching

Mingxia Gu,[a)] Ivan I. Smalyukh, and Oleg D. Lavrentovich
Chemical Physics Interdisciplinary Program, Liquid Crystal Institute, Kent State University, Kent, Ohio 44242

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We describe a directed vertical alignment (VA) display mode based on a nematic liquid crystal (LC) doped with a chiral dopant and confined between two substrates, one of which is pretreated, say, by unidirectional rubbing or photoalignment. The design allows one to eliminate umbilical defects that appear during switching of the conventional VA cells and thus to obtain better contrast. Switching is ~30% faster than for VA cells when optimized concentration of a chiral dopant is added and LC molecules at one of the substrates are slightly tilted from the cell normal due to the unidirectional surface treatment. [DOI: 10.1063/1.2172299]

Liquid crystal displays (LCDs) have many advantages over other display technologies and are widely used nowadays. Various types of LCDs have been proposed, such as twisted nematic (TN), in-plane switching (IPS), and the patterned vertical alignment (PVA) mode, each with their advantages and disadvantages, see, for example, Ref. 1. The PVA mode is one of the best approaches in commercially available LCDs. In the OFF state, the molecules are normal to the two bounding plates thus the phase retardation of the cell is zero. An electric field applied to the bounding plates tilts the molecules and causes optical retardation; the material is of a negative dielectric anisotropy. Chevron-shaped patterned electrodes produce a fringe electric field with the in-plane component that directs the molecular tilt in the ON state. The resulting multifold symmetry of the director field gives an excellent viewing angle performance, high transmittance, and contrast ratio. Manufacturing does not require rubbing. However, the PVA mode is associated with the appearance and dynamics of defects of the director field in the ON state, which degrades the brightness and switching performance.

In this work, we first demonstrate that the defects are so-called umbilics,[2,3] i.e., pairs of point defects at the bounding plates, by using the three-dimensional (3D) visualization technique of the fluorescence confocal polarizing microscopy (FCPM).[4] We then propose a directed vertical alignment (DVA) mode that allows one to eliminate the umbilics. In the DVA cell, one of the substrates is treated (rubbing) to direct the molecular tilt in the azimuthal direction when the field is applied and thus to avoid the degeneracy of the director that causes the umbilics. In addition, the liquid crystal (LC) is doped with an optimized amount of a chiral agent that in combination with the alignment scheme produces fast response, high contrast and brightness. The DVA mode can also be utilized with the patterned chevron electrodes, in which case it preserves the wide viewing angle characteristic of the normal PVA mode and demonstrates enhanced brightness, faster switching and more stable electro-optic characteristics.

The homeotropic alignment in the vertical alignment (VA) mode is achieved by coating the glass plates with indium-tin oxide layers by a thin layer of the polyimide JALS-204 (JSR Micro). The substrates with patterned electrodes were provided by Samsung Electronics Corporation. In the DVA cell, one of the substrates is rubbed by a velvet cloth; it produces a small deviation of the director from the normal orientation in the OFF state, by less than 3°. The direction of rubbing in the patterned DVA (PDVA) cells was parallel to one of the sides of the chevron electrodes (and thus perpendicular to the other side). The other substrate in both DVA and PDVA cells is not rubbed. The cell gap d is ~8 μm as determined by using a spectrometer. The nematic host MLC-6609 is doped with the chiral agent CB15 (both purchased from Merck). The ratio of the cell gap d to the chiral pitch $p, d/p$, was chosen in the range of $0 < d/p < 0.6$ (in order to prevent the appearance of fingerprint textures) by using different concentrations of CB15. The mixtures are additionally doped with ~0.01 wt % of fluorescent dye BTBP (N, N′-Bis(2, 5-di-tertbutylphenyl)-3, 4, 9, 10-perylenedicarboximide) for the FCPM studies. The contrast ratio and brightness were measured by the Nikon MicroSpectroPhotometry (MSP) system, which is mounted on the Nikon microscope; light transmission between crossed polarizers is measured through a well-defined circular area with a diameter 0.3–2.0 mm.

When the voltage U is applied to a VA cell, the defects with four dark brushes appear, Fig. 1(a), and then slowly annihilate with time (seconds to minutes). FCPM shows that they are umbilics caused by degeneracy of the director tilt, Figs. 1(b) and 1(c), rather than singular disclinations observed in homeotropic cholesteric cells with large d/p.[5] This degeneracy can be lifted by a unidirectional treatment of at least one of the substrates, for example, by rubbing or photoalignment.[1,6,7] The defects are then completely eliminated in a wide range of U, Figs. 1(d)–1(f). As the result, the brightness of the ON state is enhanced and the contrast ratio (determined by the ratio of light intensity transmitted in the ON state to that in the OFF state, not normalized for reflections) reaches 3000, as determined using the microscope with MSP and crossed polarizers. The contrast ratio for a VA cell measured using the same method and under the same condition is about 1000. In addition, absence of umbilics stabilizes light transmission as a function of time. For example, the intensity variations measured in a circular area with a diameter $D = 1.9$ mm during the first 60 s after the field is applied are about ±8% for the normal VA mode and less than ±1% for the DVA mode.

a)Electronic mail: gu@lci.kent.edu

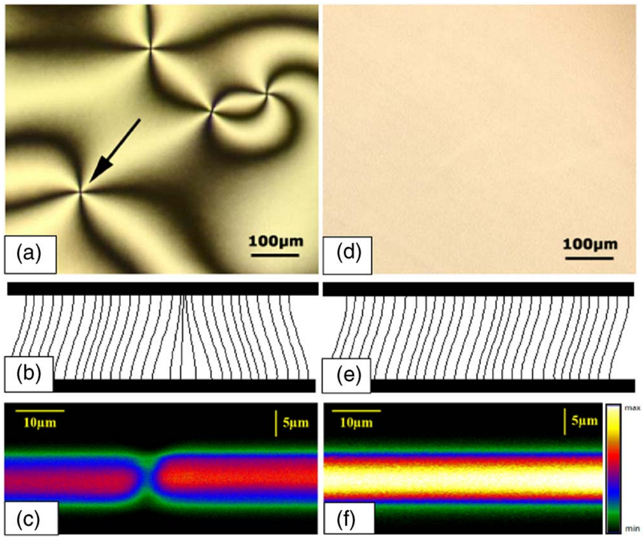

FIG. 1. Effect of rubbing of one plate on the director configurations in the VA cell: (a) Polarizing microscope texture, (b) director configuration of a VA cell with azimuthally degenerated homeotropic alignment at nonrubbed substrates, and (c) a FCPM image of the vertical cross section; (d)–(f) show the corresponding pictures for a rubbed VA cell. The cells are driven by pulses of 4.5 Vrms at 1 KHz. The arrow in (a) indicates an umbilics defect.

The above VA mode as well as its patterned version, PVA, can be further improved by twisting the nematic matrix. As described previously,[8–12] a twisted structure increases contrast and brightness of the VA and PVA modes, but at the expense of a longer response time. For the DVA mode, we found experimentally that all the parameters, including the response time, Fig. 2(a), can be optimized by choosing the appropriate value(s) of d/p. There is an optimum value of d/p at which the response time is minimized, $d/p \approx 0.23$ in Fig. 2(a). We tested various DVA cells with different gaps while keeping $d/p \approx 0.23$, and compared their performance with the normal VA cells, Fig. 2(b). The total response time of the DVA is improved by more than 20% as compared to the normal VA. For both the DVA and the normal VA, the response time is proportional to d^2, at least in the range of thicknesses $\sim$3–12 μm studied, as expected.[9] We also performed measurements for a PDVA cell with $d/p \approx 0.23$ and a normal PVA cell. The response time behavior of the PDVA as a function of d/p is similar to that of the DVA cell. The rise, decay and total response time normalized by d^2 for the PVA mode are $\tau_{\text{rise}}/d^2 \approx 1.39$ ms/μm^2, $\tau_{\text{decay}}/d^2 \approx 0.88$ ms/μm^2, and $\tau_{\text{total}}/d^2 \approx 2.27$ ms/μm^2, while for the PDVA cell with $d/p \approx 0.23$, they are generally smaller: $\tau_{\text{rise}}/d^2 \approx 0.87$ ms/μm^2, $\tau_{\text{decay}}/d^2 \approx 0.87$ ms/μm^2, and $\tau_{\text{total}}/d^2 \approx 1.74$ ms/μm^2, respectively. The response time shown in Fig. 2 is measured using voltage pulses of a constant amplitude, and it can be further shortened by overshooting driving schemes.[10] The fast switching is an advantage of the DVA over the inverse TN mode[11] and the homeotropic to twisted-planar (HTP) mode,[12] in which both homeotropic substrates are rubbed. Note also that the total in-plane twist ϕ in the DVA depends on U, $2\pi(K_2 d/K_3 p) < \phi(U) < 2\pi(d/p)$ (Ref. 13) (K_2 and K_3 are the twist and bend Frank elastic constants, respectively), and at high voltages reaches $2\pi d/p \approx 90°$, i.e., becomes the same as in the inverse TN and HTP modes where $\phi = 90°$ barely depends on U and is set by unidirectional treatment of both substrates.

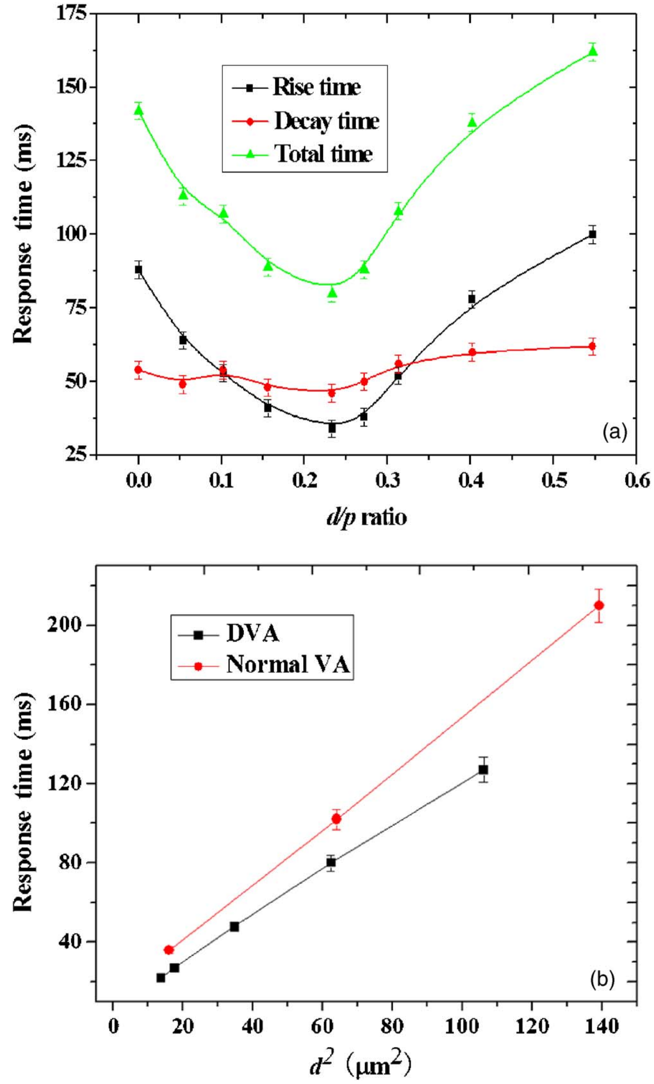

FIG. 2. (a) Response time of the DVA cells as a function of d/p; (b) response time vs d^2 for unrubbed VA cells with $d/p = 0$ and for DVA cells with $d/p \approx 0.23$. The measurements were performed using a He-Ne laser light with the wavelength $\lambda = 633$ nm.

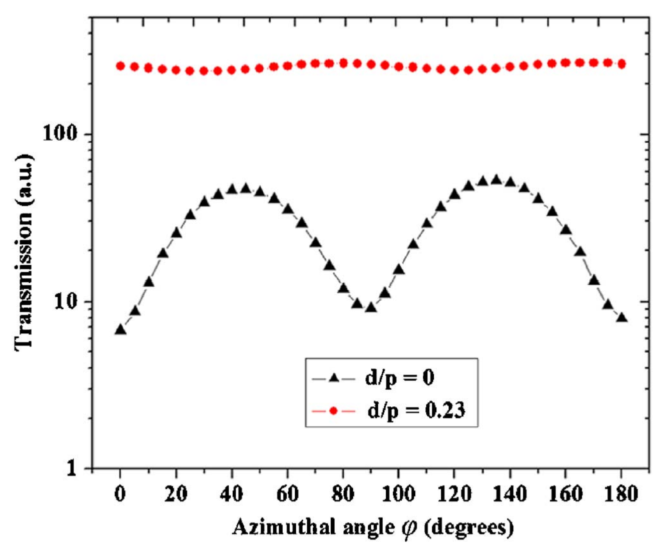

FIG. 3. Light transmission as a function of the azimuthal angle φ for DVA cells with $d/p = 0$ and $d/p \approx 0.23$ under $U = 6$ Vrms at 1 KHz. The measurements were performed using a monochromatic light with the wavelength $\lambda = 546$ nm.

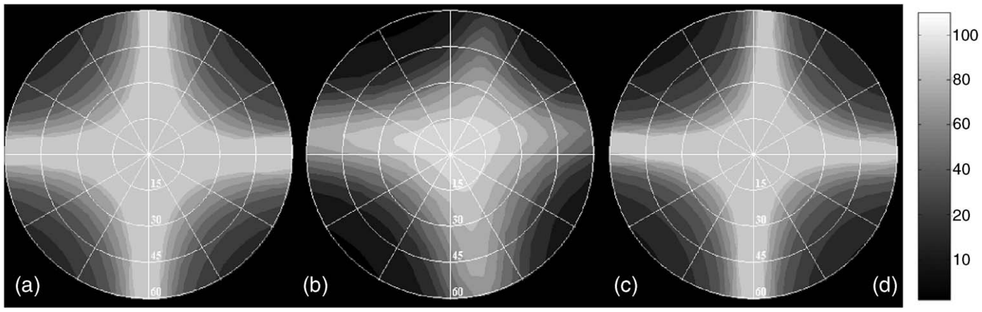

FIG. 4. Iso-contrast plots for viewing angle performance of (a) a normal PVA cell ($d/p=0, d\approx 4$ μm), (b) a DVA cell ($d/p\approx 0.23, d\approx 4$ μm), and (c) a PDVA cell ($d/p\approx 0.23, d\approx 8$ μm); the relative intensity scale bar is shown in (d). The measurements were performed using white achromatic light.

The twisted structure also helps one to reduce the azimuthal angular dependence of the light transmission between crossed polarizers (the azimuthal angle φ is defined as the angle between the rubbing direction and the polarization of incoming light). The effect is illustrated in Fig. 3 where we compare the light transmission versus φ for the DVA cells with $d/p=0$ and $d/p\approx 0.23$. Besides the ratio d/p, one also needs to optimize the birefringence Δn of the LC and/or the corresponding thickness d. This optimization would depend on the voltage used to drive the cells. Our computer simulations based on Jones Matrix Method[14,15] demonstrate that for a certain Δn, there is a well-defined cell gap d for which the azimuthal angular dependence of transmission, brightness, and contrast are optimized; the optimum value of Δnd is around 0.66 μm for $d/p\approx 0.23$.

To characterize the viewing angle, we attached crossed plastic polarizers to the outer sides of the glass plates. The polar and azimuthal angles that define the orientation of the cell normal with respect to the incident beam (achromatic light) are controlled with an accuracy better than 0.1°. Figure 4 shows the viewing angle performance of the PVA, DVA and PDVA cells measured under the same conditions; the data represent the contrast ratio for different polar and azimuthal angles. Note that the values of contrast ratio, especially off-axis, for all cells in Fig. 4 can be further increased by using high quality polarizers with better extinction coefficients and off-axis polarization quality. A multidomain PVA cell gives a much better viewing angle performance, Fig. 4(a), as compared to a mono-domain DVA cell, Fig. 4(b). However, viewing angle characteristics of the multidomain PDVA mode, Fig. 4(c), is comparable to those of the PVA, although at present still slightly worse than in the PVA. The cell parameters could be further optimized and the compensation films[1,16] could be employed to further improve the viewing angle performances of both DVA and PDVA. Note that the rubbing direction in this work was chosen to be along one of the directions of the chevron electrodes, because in the ON state, the effect of the fringe field on the twisted director is maximized to improve the viewing angle. Other configurations are possible, too.

In conclusion, we have demonstrated the DVA mode, in which the appearance of defects-umbilics during the switching process is eliminated. As the result, the display shows stable electro-optic characteristics, enhanced brightness and fast switching. The approach can be used as a nonpatterned DVA mode when the viewing angle is not important, or as the PDVA mode when it is important. In the latter case, the umbilics are eliminated, but not the wall defects, caused by the fringe electric field and associated with the opposite directions of the director field on the opposite sides of the non-conductive gap in the electrodes; these wall defects are normally less light-scattering as compared to the umbilics. The DVA and PDVA modes imply additional manufacturing processes (surface treatment and material doping) as compared to the PVA but this deficiency can be justified when the requirement is to achieve better electro-optic characteristics.

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