Electro-optic characteristics of 4-domain vertical alignment nematic liquid crystal display with interdigital electrode

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We have fabricated a vertically aligned 4-domain nematic liquid crystal display cell with thin film transistor. Unlike the conventional method constructing 4-domain, i.e., protrusion and surrounding electrode which needs additional processes, in this study the pixel design forming 4-domain with interdigital electrodes is suggested. In the device, one pixel is divided into two parts. One part has a horizontal electric field in the vertical direction and the other part has a horizontal one in the horizontal direction. Such fields in the horizontal and vertical direction drive the liquid crystal director to tilt down in four directions. In this article, the electro-optic characteristics of cells with 2 and 4 domain have been studied. The device with 4 domain shows faster response time than normal twisted-nematic and in-plane switching cells, wide viewing angle with optical compensation film, and more stable color characteristics than 2-domain vertical alignment cell with similar structure. © *2000 American Institute of Physics.* [S0021-8979(00)01412-2]

I. INTRODUCTION

Nowadays liquid-crystal displays (LCDs) are mainly used in various fields such as notebook, monitor, handphone, etc. The twisted nematic (TN) mode is still dominant in LCDs owing to its strong stability in structure and wide process margin. However, it has an intrinsic problem in viewing angle and the response time. Many different display modes are suggested to improve the image quality of displays over TN mode. Among them are TN with optical-film compensation,[1] optically compensated bend (OCB),[2] vertical alignment (VA) with protrusion,[3] patterned indium tin oxide (ITO),[4,5] in-plane field,[6–12] in-plane switching (IPS),[13] and fringe-field switching (FFS).[14] The IPS and FFS modes show a wide viewing angle but response time is rather slow, about 50 ms. The multidomain VA modes with optical film compensation also show a wide viewing angle and are known to exhibit a relatively faster response time than those of TN and IPS modes. Owing to two characteristics, the VA modes are of importance to display a high quality image and moving picture. Among VA modes, the approach with protrusion and patterned ITO needs an additional process compared with that of the TN cell. However, VA mode driven by in-plane field does not require an additional process and even an electrode of ITO on bottom and top substrates is unnecessary. In addition, the device utilizes LC with positive dielectric anisotropy unlike conventional VA modes using LC with negative dielectric anisotropy. Previously we have suggested dual domainlike VA mode driven by in-plane field and studied electro-optic characteristics of it.[6,7,9,10] The dual domain VA mode does not show a symmetric viewing angle, especially in gray scale in horizontal and vertical directions. Another study suggested in-plane driven 4-domain VA (FDVA) applying a wedge shape of electrodes.[9] However, this did not mention in detail the configuration of LC director in a real thin film transistor (TFT)–LCD.

In this article, we will show how to form a 4 domain with interdigital electrodes in TFT–LCD and its electro-optic characteristics are studied and compared between 2- and 4-domain VA modes.

II. SWITCHING PRINCIPLE OF A VA MODE DRIVEN BY IN-PLANE FIELD

As studied in the previous work,[7] the normalized transmission of light of the cell filled with birefringence medium under crossed polarizers is

$$T/T_0 = \sin^2(2\Psi)\sin^2[\pi d\Delta n(\theta,\Phi,\lambda)/\lambda],$$

where Ψ is an angle between the crossed polarizers and the liquid crystal director, Δn is the birefringence of liquid crystal medium, and λ is the wavelength of the incident light. The transmittance depends on the phase retardation of the LC cell, i.e., viewing angle, and wavelength of incident light. Therefore, the viewing angle dependency in the LCD is the intrinsic problem. In order to minimize the viewing angle dependency, the symmetric director configuration in the bright state is required with complete dark state. Figure 1 shows the cell structure in the off and on states. In the VA mode, the LC molecules are vertically aligned so that the polarization state of linearly polarized light passed through a polarizer does not change while propagating through the cell, and thus the light is blocked by an analyzer. Therefore, in the voltage-off state, the Ψ is zero at normal direction and the cell appears to be black. However, the light leakage at off-normal direction occurs due to imperfect light control of polarizers and this can be suppressed by insertion of a negative-birefringent film between the cell and the polarizer. With bias voltage larger than Freedericksz transition threshold,

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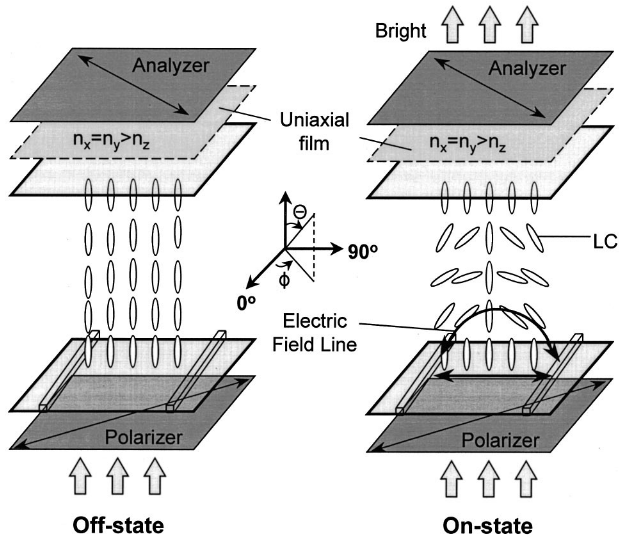

FIG. 1. The cell structures of the off and on states driven by in-plane field.

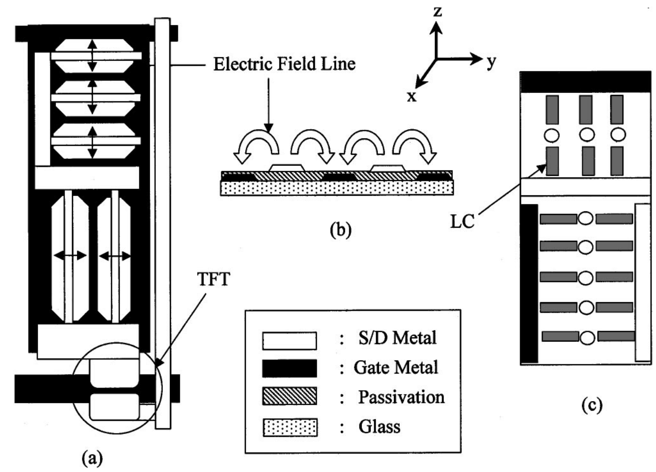

FIG. 2. (a) The array structure of the 4-domain VA cell with electric field lines, (b) cross-section view of one pixel, and (c) top view of molecular director configuration of the midplane in the on state.

*V*th, the paraboliclike field lines are formed by interdigital electrodes existing on bottom substrates. Consequently, the LC molecules tilt down to the left and right along the field direction when a liquid crystal with positive dielectric anisotropy is present in the cell, giving rise to transmission of the incident light. When the tilting direction of the LC director is 45° with respect to the optic axes of polarizers given the birefringence, the transmission is maximal. The LC molecules existing at the center area do not tilt down due to symmetric force from left and right so that the dark line exists between electrodes.

III. FORMATION OF 4-DOMAIN VA AND ITS ELECTRO-OPTIC CHARACTERISTICS

With only in-plane field in horizontal direction, two domains are formed in one pixel so that the asymmetric viewing angle characteristics between vertical and horizontal directions occur. Therefore, the formation of 4 domain is necessary in order for the VA modes to exhibit symmetric brightness in gray ones as well as white level. Here we propose one pixel design with TFT where the vertically aligned LCs can be tilted down in four directions stably. Figure 2(a) shows schematic drawing of one pixel design of new structure with electric field directions. The MoW metal with thickness of 3000 Å for gate and common line and Mo/Al/Mo metal with thickness of 2800 Å for data, and source and drain lines were patterned with TFT which was used in order to switch liquid crystal in active manner. In the one pixel, the patterned electrodes consisted of two parts. The top part had the electrodes of horizontal direction, so the resulting field direction was in *x-z* plane, whereas the bottom part had the electrodes of vertical direction, resulting in field in *y-z* plane. Figure 2(b) shows the cross-section view of one pixel with fringe field lines. The passivation layer exists between different metals to block short between them. As the result, the fringe field drives the top part of liquid crystal to tilt down to upper and lower directions, whereas the bottom part of liquid crystal to tilt down to left and right directions. Figure 2(c) indicates molecular director configuration of the LCs in the midplane describing that the LC molecules tilt down vertically and horizontally except for the center between electrodes.

In a view point of manufacturing process of in-plane driven FDVA cell, it is greatly advantageous over the conventional TN, IPS, and VA cells because it does not require transparent electrodes like ITO and rubbing process on top and bottom substrates.

For a cell fabrication, the width of electrode was 9 μm and the distance between electrodes was 8 μm. The liquid crystal obtained from Merck Korea had a birefringence $\Delta n = 0.0784$ at 550 nm (20 °C) and dielectric anisotropy $\Delta\epsilon = 12.3$(1 kHz,20 °C). The four kinds of cells were made as cell gap is varied, that is, 5, 6.3, 8.3, and 11 μm. The resultant phase retardation ($d\Delta n$) of four cells are 0.39, 0.49, 0.65, and 0.94 μm, respectively. The polarizer and analyzer crossed each other with transmission axes diagonally.

For measurements of the electro-optic characteristics of the cell, the used light source was the halogen lamp, and the wave form of the applied voltage was the square wave. Then the signal was detected to the photomultiplier tube.

Figure 3 shows a photo of the 4-domain device with $d\Delta n = 0.49$ μm in the gray and bright states. Between pixel and common electrodes, the electric field was produced with the symmetric distribution, so the LC molecules tilt down in four directions, giving rise to transmittance. However, the disclination lines that result from the vertical alignment of the LC though the voltage is applied was generated in the center of them and kept stably though high voltage of 20 V is applied. This is an intrinsic problem of the device, which lowers the transmittance slightly. One can also observe splitted disclination lines near the edge of electrodes, which results from complex field, i.e., $E = E(x,y,z)$ unlike center parts.

Figure 4 shows the voltage-dependent transmittance curves as the $d\Delta n$ is varied. As the $d\Delta n$ is increasing much larger than λ/2, the driving voltage at which the transmittance of the cell becomes maximum is decreasing whereas

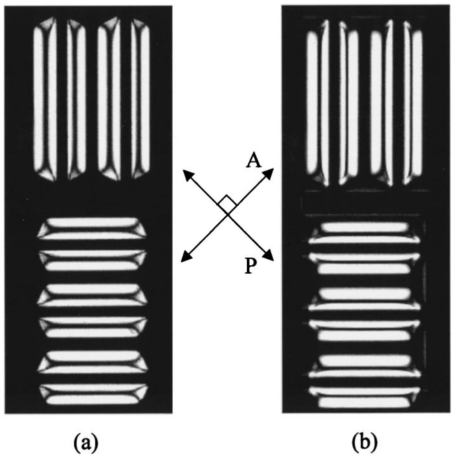

FIG. 3. A photo of one pixel with (a) low and (b) high-applied voltages in the 4-domain VA cell. P and A represent polarizer and analyzer, respectively.

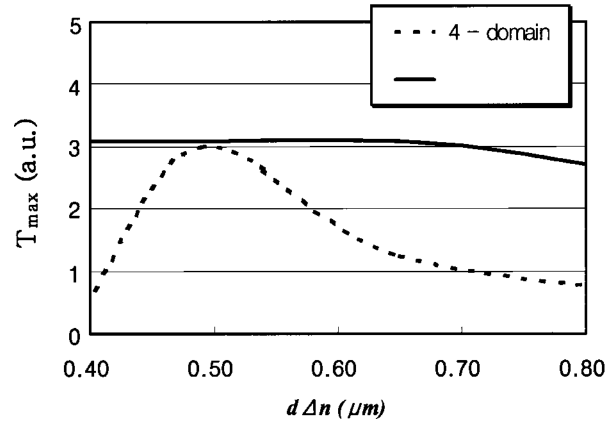

FIG. 5. Comparison of $d\Delta n$-dependent transmission between vertical-field driven single domain and in-plane driven VA cells.

the total transmittance is decreasing. The cell with phase retardation of 0.49 μm has maximum transmittance. In order to compare the dependence of phase retardation of the cell on transmittance between singe domain and in-plane driven VA cells, the simulation is performed by varying Δn for given cell gap, as shown in Fig. 5. In the conventional vertical-field driven single domain of VA cell, the transmittance becomes maximum when the phase retardation is a little above $\lambda/2$ as indicated in the equation of transmission and then saturates with further increasing of phase retardation. However, in in-plane driven VA cell, the high value of phase retardation is required to get maximum transmittance. This is due to existence of vertical alignment of the LC director at the center of electrodes which blocks tilt-down deformation of the LC director near them. This behavior is also well described by previous simulational result[12] and the results are similar to each other although the director deformation in actual TFT–LCD is little different from that of simulation due to complex field at the corner of pixel electrodes. We also have measured the response time of four cells. The rise and decay time was measured with a transmittance change of 80% as shown in Table I. The rising time mainly depends on the applied voltage. When the cell gap is smaller, the applied voltage to the cells becomes higher. As the result, it is below 12 ms till the cell gap is as high as 11 μm. However, the decay time is proportional to the square of cell gap. Therefore, it is increasing from 10 to 59 ms as the cell gap is increasing from 4 to 11 μm. The total response time of the cell with a cell gap of 6 μm is 25 ms which is much faster than those of the TN and IPS cells.

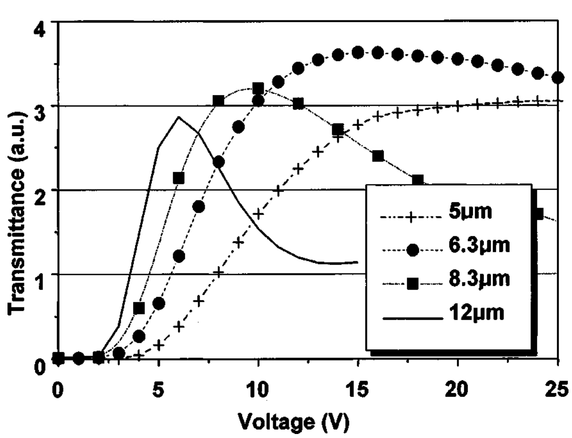

FIG. 4. The voltage dependent transmittance curves for several cells.

We have studied viewing angle characteristics of the FDVA cell with $d\Delta n = 0.49\,\mu$m, comparing with 2-domain VA (DDVA) one. Figure 6 shows uniformity in brightness of DDVA and FDVA cells in a fully bright state. In the DDVA cell, relative intensity (RI) to that at normal direction shows asymmetry in horizontal and vertical directions originating from anisotropy in phase retardation of vertical and horizontal ones. However, in the FDVA cell, RI almost does not depend on azimuthal (ϕ) directions owing to the same value of phase retardation in vertical and horizontal directions. The polar (θ) angle dependence of RI still exists, which is intrinsic problem in LCDs. Figure 7 shows the isocontrast curves of FDVA cell without and with optical compensation film. When there is no compensation film inserted, it shows four-fold symmetric viewing angle but the region in which the contrast ratio greater than 10 vertically and horizontally is about 30° due to incomplete dark state at off-normal directions. In general, the higher the phase retardation of the VA cell, the lower the viewing angle due to increasing light leakage in the dark state at off-normal direction not coincident with the polarization axis of crossed polarizers. In this point of view, the FDVA cell is disadvantageous to the conventional VA cell driven by vertical field. However, the light leakage at the dark state can be compressed with the help of negative birefringent film. We attached the optical compen-

TABLE I. Response time dependence of the FDVA cells on cell gap.

d (μm)	τ_{rise} (ms)	τ_{decay} (ms)
5	9	10
6.3	9	16
8.3	12	28
11	41	59

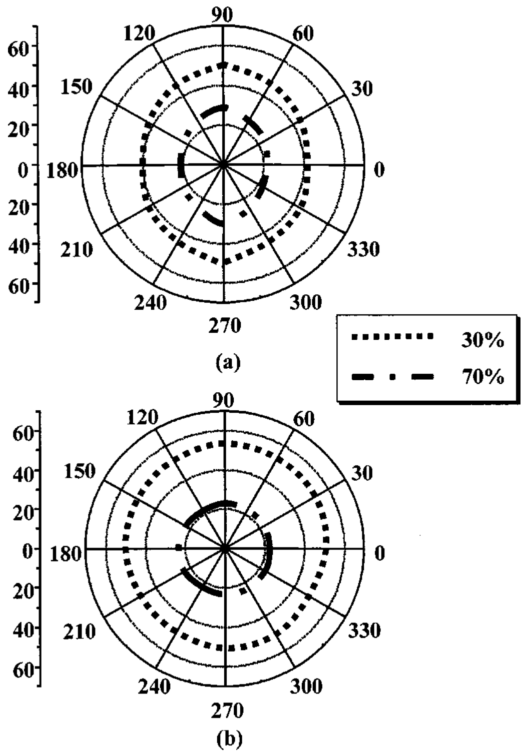

FIG. 6. The dependence of brightness of (a) 2- and (b) 4-domain VA cells in the white state on viewing angle.

sation films of $d(n_x - n_z) = 0.43\,\mu$m to the upper plate of cell, and $d(n_x - n_z) = 0.16\,\mu$m to the lower plate of one, respectively. As a result, the light leakage at the dark state is compressed so the region in which the contrast ratio greater than 10 extends to almost over 60° in all directions. This is much superior to that of the conventional TN cell.

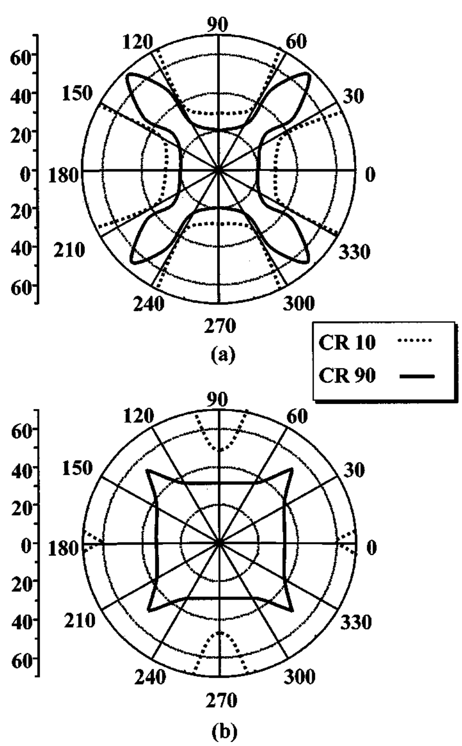

FIG. 7. The isocontrast curve (a) without and (b) with optical compensation film.

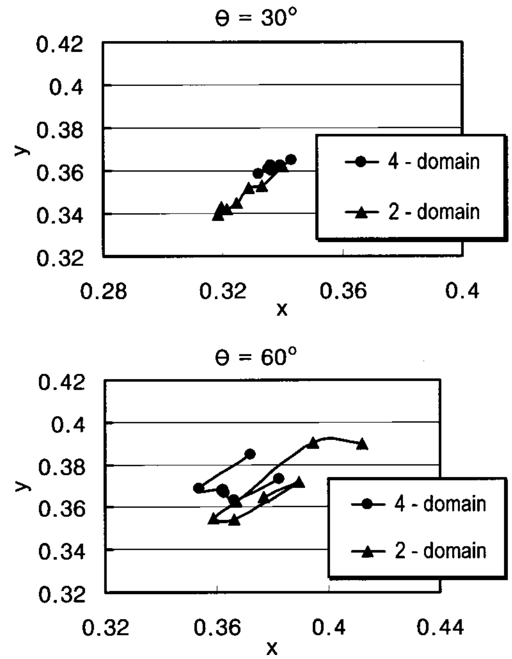

FIG. 8. The dependence of white color chromaticity at two fixed polar angles, 30° and 60° on viewing angle.

The color characteristics between the DDVA and FDVA cells have also been compared. Figure 8 shows a color shift of the fully bright state as the viewing direction changes in two polar directions, 30° and 60°. Owing to fully self-compensation effects in the FDVA cell, the dependency of white color chromaticity on azimuthal viewing directions is less for the FDVA cell than for the DDVA one. Since the LC director tilts down in four directions making 45° with respect to polarization axes of crossed polarizers in this device, the azimuthal angle dependency of phase retardation is minimized.

Comparing the DDVA cell to the FDVA one in image quality and light transmission, only if we measure a contrast ratio, that is, luminance (white)/luminance (black), the difference between 2 and 4 domains is not much different because the contrast ratio mainly depends on luminance of black state. However, in the FDVA cell, owing to less dependent phase retardation on viewing angle, the uniformity in brightness is slightly improved and the color shift is reduced compared to DDVA as shown in Figs. 6 and 8. Actually, making a 4-domain cell in VA mode is a final goal for high image quality comparable to cathode ray tube display. In light transmission, in TFT–LCD the transmission mainly depends on aperture ratio, that is, light transmitted area. Generally, in TN mode, it is about 60% in 12.1 in. with super video graphic array (SVGA) ($800\times3\times600$) resolution. However in a 2-domain device, it is decreased to 30% because the opaque common and data lines block light transmission and in addition the light does not transmit at the center between electrodes. In a 4-domain device, it is decreased to about 26% due to blocking lines at center of one pixel, which is major demerit of the device. This could be slightly increased if transparent metal is used.[12] Therefore, the FDVA cell with high image quality and low transmittance is applicable to monitor display.

IV. SUMMARY

We have developed the 4-domain VA cell with concept of in-plane field in vertical and horizontal directions. The liquid crystal director tilts down in four directions. As the result, owing to fully self-compensation effects, the device shows wide viewing angle over 60° and excellent color characteristics, which is superior to the DDVA and TN cells. The device also shows faster response time (<40 ms) than that of the TN and IPS cells. Another great advantage of the device is the simple manufacturing process, which does not need transparent metal on both top and bottom substrates and rubbing process. The demerit is low transmittance due to existence of disclination lines between electrodes, which is an intrinsic problem. Therefore, the device is greatly advantageous for monitor application in which the power consumption is relatively less critical.

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