Characteristics of a 12-Domain MVA-LCD

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***Abstract*—A multi-domain (12-domain) vertical alignment liquid crystal display (MVA-LCD) device is proposed and its electro-optic characteristics evaluated through a 3-D simulator. The MVA-LCD exhibits advantages in wide viewing angle, high transmittance, fast response time, and small color shift when a pair of wide view crossed circular polarizers is employed. Potential applications of this MVA-LCD for high quality LCD TVs and computer monitors are emphasized.**

***Index Terms*—Color shift, compensation film, high transmittance, liquid crystal display (LCD), multi-domain vertical alignment (MVA), three-dimensional (3-D) simulation, wide viewing angle.**

I. Introduction

FOR large-screen liquid crystal displays (LCDs), high transmittance, fast response time, high contrast ratio, wide viewing angle, and small color shift, all have to be satisfied simultaneously [1]. The normally black vertical alignment (VA) LCDs exhibit an excellent contrast ratio at normal incident angle. To achieve a wide viewing angle, multiple domains are required. Therefore, how to control the formation of multi-domain vertical alignment (MVA), especially when the voltage is applied, is an important task. In the meantime, the symmetric formation of the multiple domains can greatly reduce the color shift observed at oblique angles. In addition, in a MVA-LCD, although a thin polyimide alignment layer is used, no rubbing process is required. This non-rubbing process is beneficial for the high yield mass production.

Currently, four-domain and eight-domain VA LC configurations are commonly practiced. Takeda *et al.* proposed a MVA LCD using the protrusion method, where the chevron-patterned protrusions are created on the top and bottom substrates to form a four-domain LCD cell in multiple independent directions [2], [3]. Since the horizontal gap between the upper and the lower protrusions must be less than 30 μm in order to obtain good performance, a high precision pixel alignment is required. Thus, the design specification and preparation process are not easy and the aperture ratio is limited. Lien proposed a ridge and fringe-field multi-domain homeotropic (RFF-MH) mode, where one substrate is with protrusions but the other with slits to form multiple domains [4], [5]. However, the device needs a high driving voltage and the response time is not fast. Lien and John previously proposed a slit fringe field method for generating multiple domains with the slits on one side of the electrode substrates [6], and Samsung proposed a patterned vertical alignment (PVA) with the slits on both sides of the electrode substrates to produce multi-domain structures under electric fields [7], [8]. A general concern of MVA LCDs is the reduced light efficiency if two crossed linear polarizers are used. By using two crossed circular polarizers, the optical efficiency of MVA is improved significantly [9]–[11].

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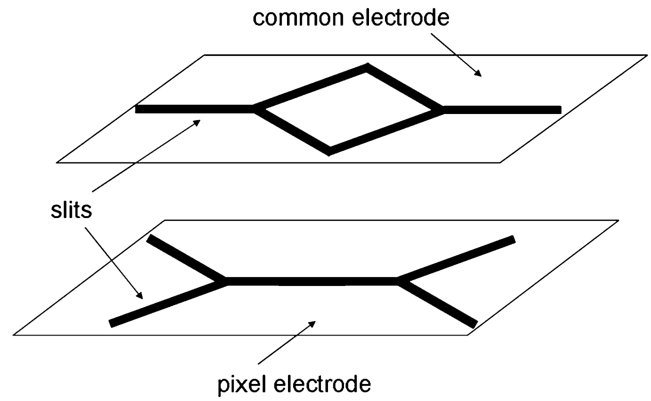


Fig. 1. Proposed 12-domain MVA electrode structure.

In this paper, we proposed a 12-domain MVA using two sets of double Y-shaped slits on the respective pixel and common electrodes. We simulate the LCD performances using a reliable 3-D simulator which combines the finite-element method (FEM) and finite-difference method (FDM). The electro-optic properties of the MVA mode under varied slit widths and different types of polarizers were characterized by the time-dependent transmittance curve, the color shift diagram, and the viewing angle contour bar. We demonstrate a MVA-LCD with wide viewing angle, high transmittance, fast response time, and small color shift by using our wide view circular polarizers that consist of a series of uniaxial compensation films.

II. Simulation Methods

Fig. 1 shows the proposed MVA electrode structure, where the double Y-shaped slits are arranged alternatively on the pixel and common electrodes. The double Y-shaped slits can be regarded as consisting of two Y-shaped ones with head-to-head or tail-to-tail arrangement. The slit legs are preferred to be equally separated at 120° in a single Y slit. During simulations, we chose the MVA device with an average slit leg length of 25 μm and the slit width was varied at 3, 5, and 7 μm, respectively. The cell gap is 4 μm and a negative LC material Merck MLC-6608 (birefringence $\Delta n = 0.083$ at $\lambda = 550$ nm wavelength, dielectric anisotropy $\Delta\varepsilon = -4.2$ and rotational viscosity $\gamma_1 = 0.186$ Pa $\cdot$ s at room temperature) is used for simulations. The linear polarizer pair has a maximum light transmittance of 35%.

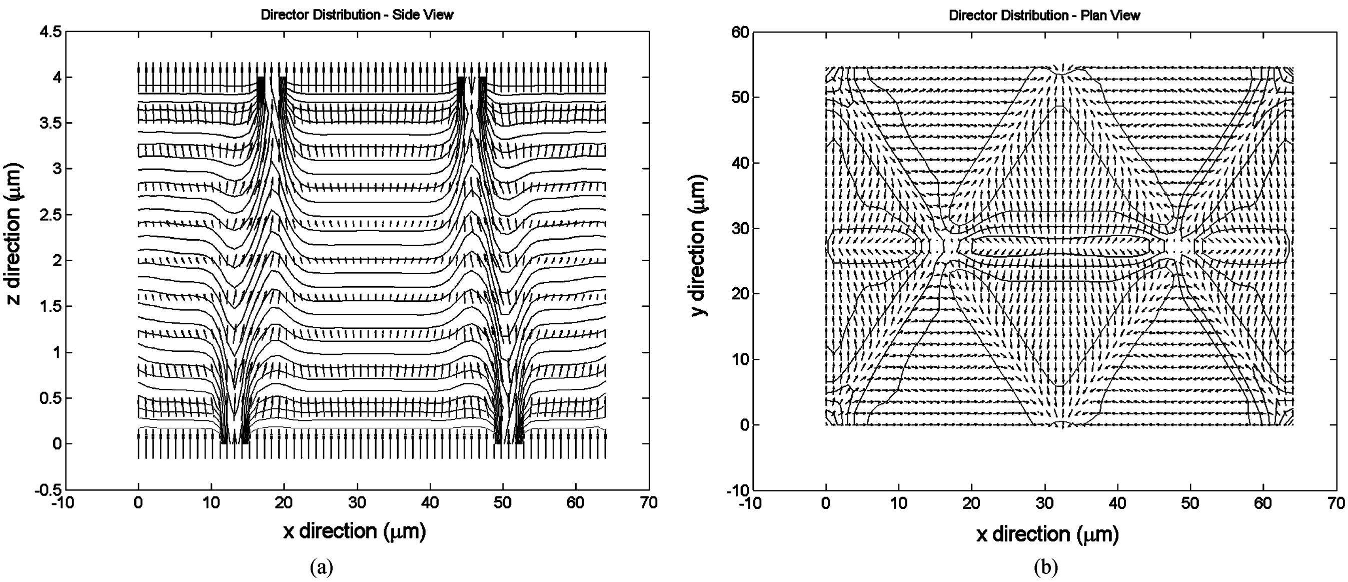


Fig. 2. Typical LC director distributions where the applied voltage is 5 $\mathrm{V_{rms}}$ and the slit width is 3 μm. (a) Side view. (b) Plane view.

The simulation sequence is to obtain the dynamic 3-D LC director distributions first and then calculate the detailed electro-optics of the LCD. We have developed our own 3-D simulator for calculating the LC director distributions, which combines the FEM and FDM approaches to improve the calculation speed [12]. Once the LC director distribution profiles were obtained, we calculated the electro-optic properties of the LCD using the extended Jones matrix method [13]. The LC layer was modeled as a stack of uniaxial homogeneous layers. Here, we assume the reflections between interfaces are negligible. Therefore, the transmitted electric field is related to the incident electric field by

$$\begin{bmatrix} E_x \\ E_y \end{bmatrix}_{N+1} = \boldsymbol{J} \begin{bmatrix} E_x \\ E_y \end{bmatrix}_1 = \boldsymbol{J}_{\mathrm{Ext}} \boldsymbol{J}_N \boldsymbol{J}_{N-1} \cdots \boldsymbol{J}_2 \boldsymbol{J}_1 \boldsymbol{J}_{\mathrm{Ent}} \begin{bmatrix} E_x \\ E_y \end{bmatrix}_1 \tag{1}$$

where $\boldsymbol{J}_{\mathrm{Ext}}$ and $\boldsymbol{J}_{\mathrm{Ent}}$ are the correction matrices considering the transmission losses in the air-LCD interface, which are given by

$$\boldsymbol{J}_{\mathrm{Ent}} = \begin{bmatrix} \frac{2\cos\theta_p}{\cos\theta_p + n_p \cos\theta_k} & 0 \\ 0 & \frac{2\cos\theta_k}{\cos\theta_k + n_p\cos\theta_p} \end{bmatrix}$$
$$\boldsymbol{J}_{\mathrm{Ext}} = \begin{bmatrix} \frac{2n_p\cos\theta_k}{\cos\theta_p + n_p \cos\theta_k} & 0 \\ 0 & \frac{2n_p\cos\theta_p}{\cos\theta_k + n_p\cos\theta_p} \end{bmatrix}. \tag{2}$$

Correspondingly, the overall optical transmittance is represented as

$$t_{op} = \frac{|E_{x,N+1}|^2 + \cos^2(\theta_p)|E_{y,N+1}|^2}{|E_{x,1}|^2 + \cos^2(\theta_p)|E_{y,1}|} \tag{3}$$

where n_p is the refractive index of the polarizer, and θ_p is given by

$$\theta_p = \sin^{-1}\left(\frac{\sin(\theta_k)}{\mathrm{Re}\left(\frac{(n_{e,p}+n_{o,p})}{2}\right)}\right) \tag{4}$$

in which $n_{e,p}$ and $n_{o,p}$ are the two refractive indices of the polarizer and θ_k is the azimuthal angle of the incident wavevector, $\boldsymbol{k}$.

III. Results and Discussion

A. LC Directors Distribution

Fig. 2 plots the typical simulated LC director distributions of the VA cell when the applied voltage is 5 $\mathrm{V_{rms}}$ and the slit width is 3 μm. The distribution is cut from the middle layer of the LC cell gap and nearby the center of the pixel unit. From the side view in Fig. 2(a), the LC directors are reoriented perpendicular to the electric field direction due to the fringing field effect. The LC directors above the slit areas are only partially switched which form various domain walls. This is an important prerequisite for developing multiple domains in a LCD cell. From the plane view in Fig. 2(b), the LC directors are divided into twelve evident domains. It indicates that a multi-domain LCD device is indeed formed from the double Y-shaped slits under the application of electric field.

B. Time-Dependent Transmittance Under Crossed Linear Polarizers

Fig. 3 plots the time-dependent transmittance (T-t) curves of the 12-domain MVA LCD with various slit widths at $V = 5\ \mathrm{V_{rms}}$ and $\lambda = 550$ nm under crossed linear polarizers. As the slit width increases, the LC directors are liable to respond to the electric field in the initial time stage but slow to get saturated. And the transmittance is lowered due to the reduction of

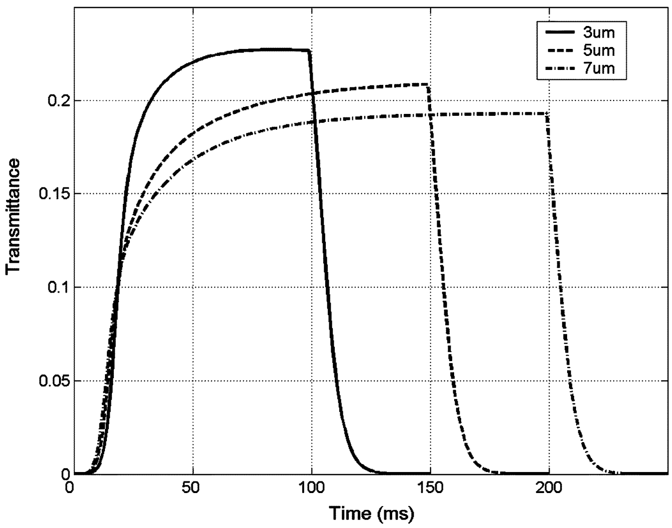


Fig. 3. Time-dependent transmittance curves with varied slit widths at $V = 5\ \mathrm{V_{rms}}$ and $\lambda = 550$ nm. The two linear polarizers are crossed.

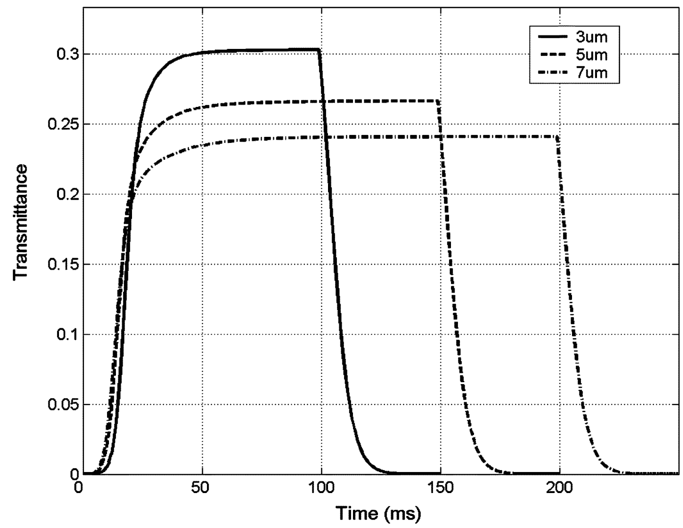


Fig. 4. Time-dependent transmittance curves with varied slit widths at $V = 5\ \mathrm{V_{rms}}$ and $\lambda = 550$ nm. The two circular polarizers are crossed.

the effective aperture ratio. The saturated transmittance reaches 22.7% for the 3-μm slit width but drops to 19% for the 7-μm slit width. Therefore, it is important to choose an appropriate slit width while forming the MVA configuration in order not to sacrifice the light efficiency too much.

C. Time-Dependent Transmittance Under Crossed Circular Polarizers

The T-t curves with different slit widths under crossed circular polarizers are shown in Fig. 4, where the applied voltage is 5 $\mathrm{V_{rms}}$ and the wavelength $\lambda = 550$ nm. Compared to the results shown in Fig. 3, the transmittance of a MVA under circular polarizers is $\sim$ 30% higher than that of using linear polarizers. For instance, the light transmittance of the MVA with 3 μm slit width exhibits a 30.2% transmittance (out of 35% maximum) under crossed circular polarizers. Moreover, the response time, especially in the rising period, is shortened with the use of circular polarizers. The rise time of a MVA at the slit width of 3 μm under the linear polarizers is $\sim$ 21.5 ms (transmittance changes from 10% to 90%) while it is only 14 ms when the circular polarizers are used. This improvement is particularly important for TV and computer monitor applications where fast response time is needed.

D. 3-D Light Transmittance Distributions Under Different Polarizers

Fig. 5 shows the typical 3-D light transmittance distributions of a 12-domain MVA LCD under different types of crossed polarizers. Here, the slit width is kept at 3 μm, the applied voltage is at 5 $\mathrm{V_{rms}}$ at the saturation time point of 90 ms. There are evident dead zone areas with low light transmittance above or nearby the slit regions no matter what kind of polarizers are used. The dead zones divide the transmittance areas into different parts due to the multi-domain formation. In Fig. 5(a), the separated transmittance areas are not equal and the profiles are uneven under crossed linear polarizers. When the crossed circular polarizers are used, the transmittance profiles become flat and even with a same averaged transmittance value to the different separation areas as Fig. 5(b) shows. The light transmittance has also improved nearby the slit regions as compared to that of under crossed linear polarizers.

As we know, the normalized light transmission through the LC medium under crossed linear polarizers can be described as [14]

$$\frac{T}{To} = \sin^2(2\varphi)\sin^2\left[\frac{\pi \cdot d \cdot \Delta n}{\lambda}\right] = \sin^2(2\varphi)\sin^2\left(\frac{\delta}{2}\right) \quad (5)$$

where φ is the azimuthal angle of the LC director, Δn is the effective LC birefringence, d is the cell gap and λ is the incident wavelength. $\delta = 2\pi \cdot d \cdot \Delta n/\lambda$ is defined as the phase retardation of the LC medium. From (5), the light transmission depends on the LC phase retardation and the azimuthal angle φ. Only when $\varphi = 45^\circ$, a maximum light transmission can be possibly obtained under crossed linear polarizers. In a typical MVA device, the LC directors distribute in different directions in the voltage-on state. Obviously, the 45° azimuthal angle cannot be easily met by all the LC domains, do not even mention the phase retardation effect. As a result, the transmission of a MVA mode is not optimized under crossed linear polarizers.

On the other hand, the normalized light transmission through the LC medium under crossed circular polarizers can be described as [9]

$$\frac{T}{To} = \sin^2\left[\frac{\pi \cdot d \cdot \Delta n}{\lambda}\right] = \sin^2\left(\frac{\delta}{2}\right). \quad (6)$$

Equation (6) indicates that the transmittance of the MVA LCD is only determined by the phase retardation of the LC medium but is independent of the azimuthal angle of the LC directors. Therefore, the MVA LCD under crossed circular polarizers would have a much higher maximum transmittance than that of under crossed linear polarizers. The 3-D light transmittance distributions plotted in Fig. 5 validate the above theories.

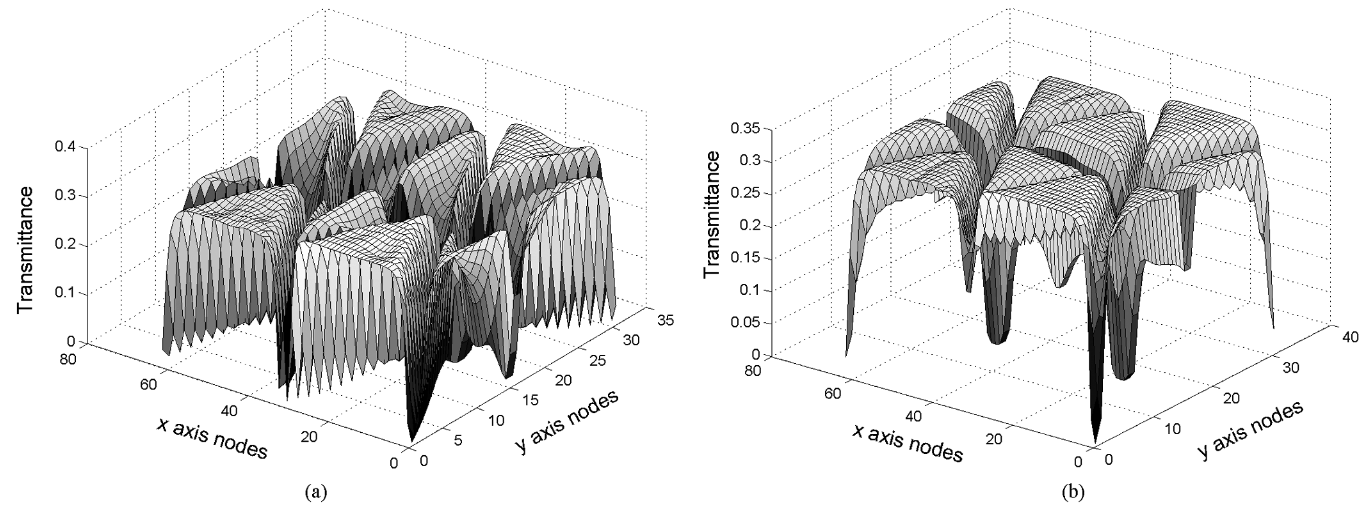


Fig. 5. 3-D light transmittance distributions of the 12-domain MVA LCD under different types of crossed polarizers, where the slit width is 3 μm and $V = 5\ \mathrm{V_{rms}}$ at the saturation time point of 90 ms.

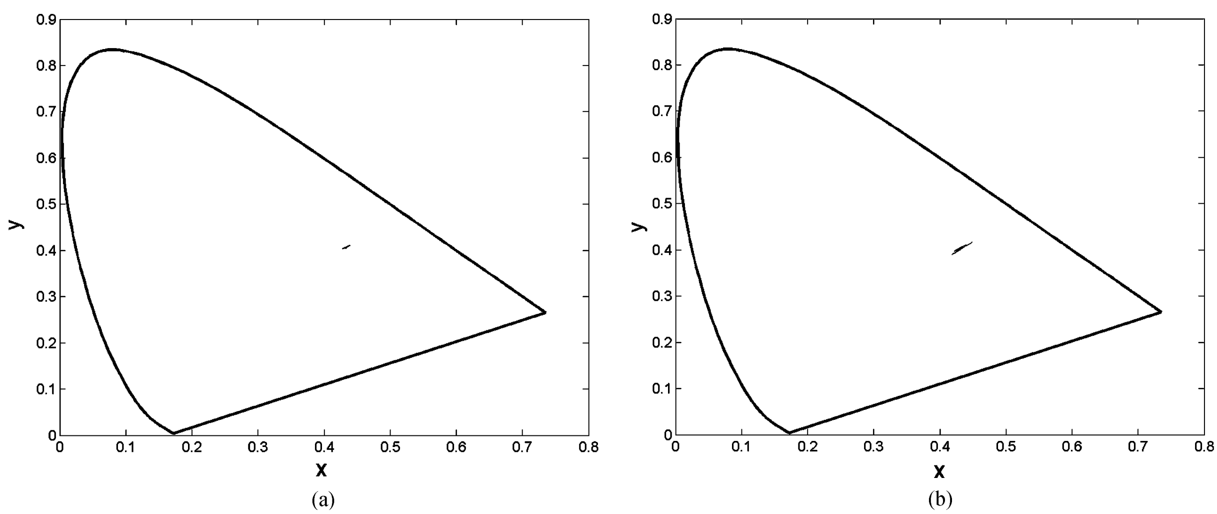


Fig. 6. Comparison of color shift between (a) 12-domain and (b) 6-domain MVA-LCDs under the CIE 1931 chromaticity diagram.

E. Color Shift

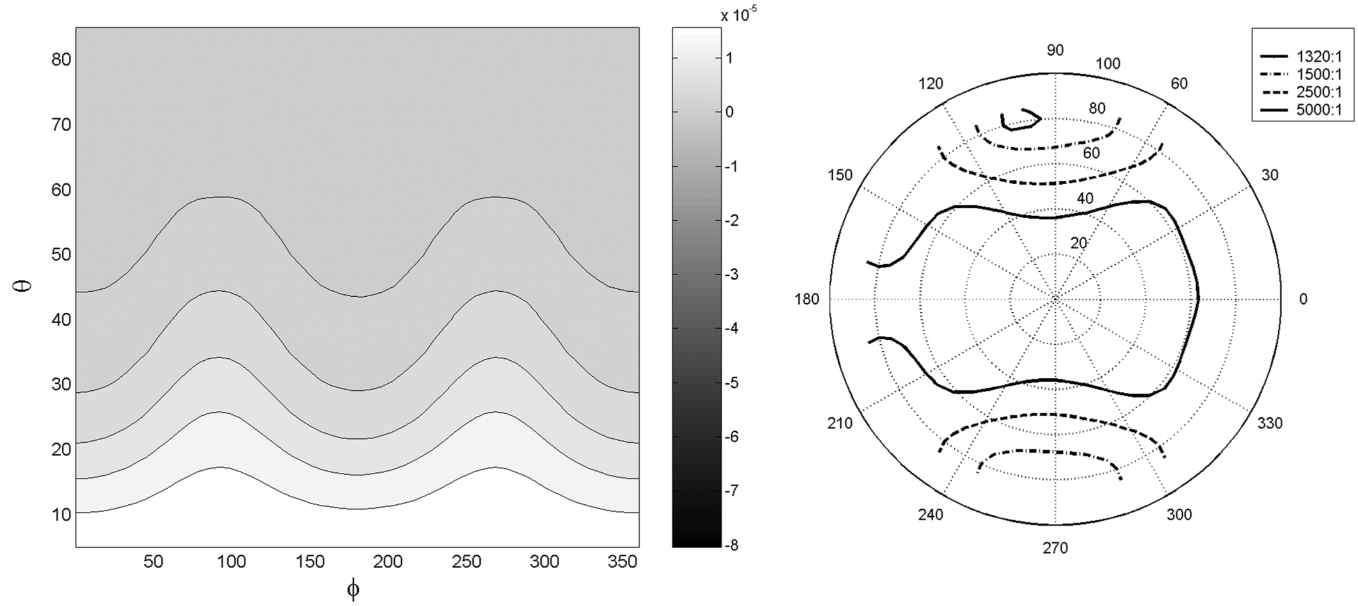
Color shift at oblique viewing direction is a serious concern for all LCD TVs. Fig. 6 compares the color shift of the 12-domain MVA-LCD with that of a 6-domain MVA-LCD where the double Y-shaped slits are on the pixel electrode only and the common electrode is a flat ITO. The white light of the standard illuminant D65 is incident from 50° and scanned across the whole azimuthal range under the CIE 1931 chromaticity diagram. From Fig. 6(a), a small color shift in the 12-domain MVA-LCD still exists, especially in the short and long wavelength regions. However, this color shift is much less than that of the 6-domain MVA-LCD shown in Fig. 6(b) since the formed 12 domains can effectively self-compensate each other topologically as shown in Fig. 2. An optimized device design should further reduce the color shift.

F. Viewing Angle Under Crossed Linear Polarizers

Fig. 7 plots the light leakage and iso-contrast contour of the 12-domain MVA-LCD under crossed linear polarizers, where the slit width is 3 μm, applied voltage is 5 $\mathrm{V_{rms}}$ and $\lambda =$ 550 nm. Two sets of uniaxial films (a positive A-plate with $d\Delta n = 93.2$ nm and a negative C-plate with $d\Delta n = -85.7$ nm) are placed after the polarizer and before the analyzer. The optimized compensation film design is to lower the oblique light leakage of the crossed linear polarizers [15]. The light leakage of an uncompensated MVA under crossed linear polarizers is typically at 10^{-3} level. At bisectors, the light leakage could reach 5×10^{-3}. With the proposed uniaxial films, the light leakage of the film-compensated MVA is reduced to 10^{-5} at different oblique angles, as Fig. 7(a) shows. Correspondingly, the 12-domain MVA-LCD exhibits a contrast ratio higher than 5000:1 at $\pm 40^\circ$ viewing cone. As the viewing cone increases, the contrast ratio decreases gradually. At $\pm 80^\circ$ viewing cone, the contrast ratio remains higher than 1300:1 as plotted in Fig. 7(b).

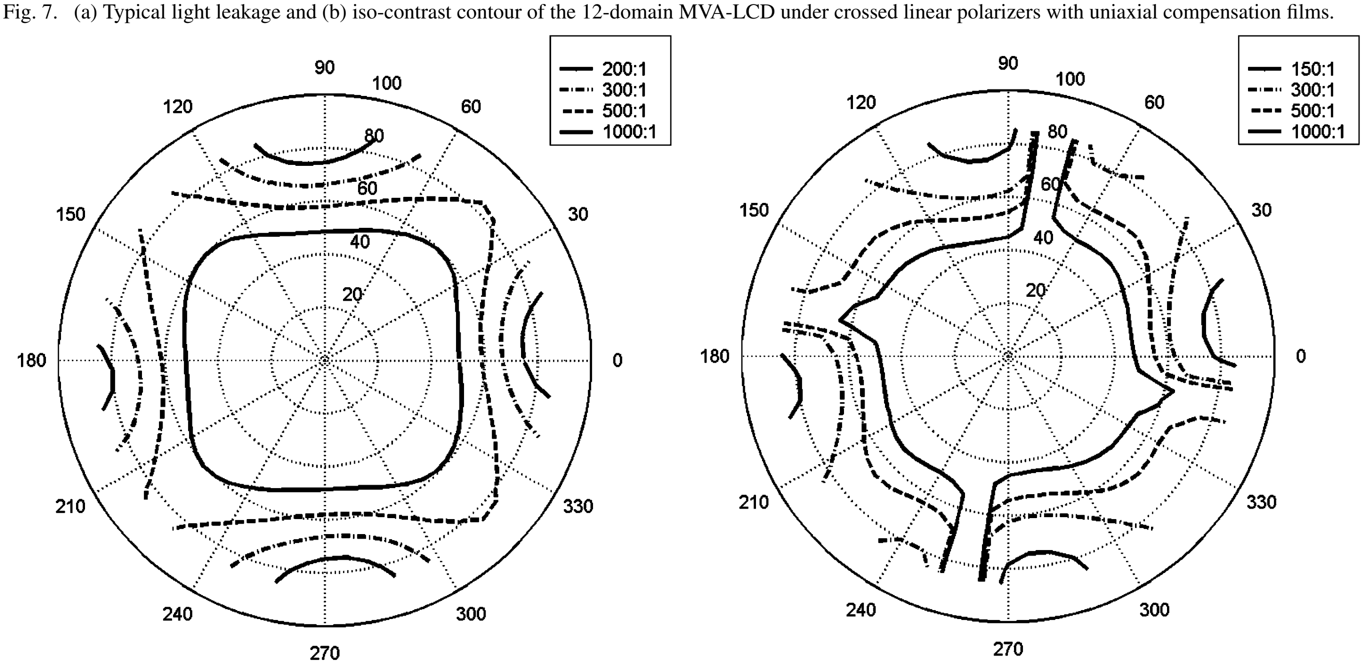
G. Viewing Angle Under Wide View Circular Polarizers

Fig. 8 plots the typical iso-contrast contours of a 12-domain MVA-LCD under the wide view circular polarizers, where the slit width is 3 μm and the applied voltage is 5 $\mathrm{V_{rms}}$. The wide view circular polarizers consist of a series of uniaxial



(a) (b)

Fig. 7. (a) Typical light leakage and (b) iso-contrast contour of the 12-domain MVA-LCD under crossed linear polarizers with uniaxial compensation films.



(a) (b)

Fig. 8. Typical iso-contrast contours of the 12-domain MVA-LCD under wide view circular polarizers. (a) Single wavelength $\lambda = 550$ nm. (b) White light.

compensation films (3 A-plates and 2 C-plates), where the first A-C-A film arrangement acts as a quarter-wave plate, and the additional A-plate and C-plate further reduce the viewing angle sensitivity of the film-laminated circular polarizer [16]. The films are placed in the mirror image style after the polarizer and before the analyzer, respectively. Under this compensation film arrangement, the azimuthal angles of the three A-plates corresponding to the neighboring polarizer's absorption axis are $\phi_{ne\_A\_1st} = 78.6^\circ$, $\phi_{ne\_A\_2nd} = -28.7^\circ$, and $\phi_{ne\_A\_3rd} = 42.5^\circ$, respectively. Correspondingly, the $d\Delta n$ value of the retardation films are $d\Delta n_{\_A\_1st} = 75.9$ nm, $d\Delta n_{\_A\_2nd} = 24.4$ nm, $d\Delta n_{\_A\_3rd} = 129.3$ nm, $d\Delta n_{\_C\_1st} = 161.0$ nm, and $d\Delta n_{\_C\_2nd} = -21.1$ nm. At a single wavelength $\lambda = 550$ nm, as shown in Fig. 8(a), it has a high contrast ratio of 1000:1 at $\pm 50^\circ$ viewing cone. On the whole viewing range, the contrast ratio is as high as about 200:1. To estimate the viewing angle properties for the white light, we calculated the results for the wavelengths at $R = 650$ nm, $G = 550$ nm and $B = 450$ nm and then multiplied these values by a weighting ratio of 30%, 60%, and 10%. As plotted in Fig. 8(b), the 12-domain MVA-LCD still keeps the contrast ratio of 1000:1 at $\pm 50^\circ$ viewing cone, and a high contrast ratio of 150:1 over the $\pm 80^\circ$ viewing cone.

Circular polarizers have been used extensively in small and medium-sized transflective LCDs [17], but it is still too costly for large LCD TV panels. The above design for the wide-view circular polarizer is too sophisticated to be practical. It is highly desirable to use as few compensation films as possible from the manufacturing and cost viewpoints. A simplified wide-view circular polarizer consisting of a linear polarizer with two biaxial films has been developed by our group [18]. This design is more realistic for practical applications.

IV. Conclusion

A new MVA mode with 12 domains is proposed and calculated with a 3-D simulator. It shows a small color shift under the CIE 1931 chromaticity diagram. The 12-domain MVA-LCD demonstrates a high contrast ratio of 1300:1 on the whole viewing cone with the optimized compensation films under crossed linear polarizers. With the circular polarizers, the light transmittance is improved by $\sim 30\%$ and the response time is shortened. Wide view circular polarizers consisting of a series of uniaxial films are optimized to obtain high contrast ratio and to enhance viewing angle. As a result, a 150:1 contrast ratio over the $\pm 80^\circ$ viewing cone of the 12-doamin MVA-LCD is simulated. The advantages demonstrated in the 12-domain MVA mode are beneficial for high quality LCD TV and computer monitor applications.

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