P-141: A Wide-view Multi-domain Vertical-alignment Liquid Crystal Display with High Transmittance and High Contrast

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Abstract

A wide viewing angle multi-domain vertical-alignment liquid crystal display (VA-LCD) is proposed. According to this design, by integrating a kind of wide-view circular polarizer, a contrast ratio higher than 800:1 is predicted over the entire ±85° viewing cone with the transmittance higher than 33% for an eight-domain VA-LCD. Potential application for LCD television is emphasized.

1. Objective and Background

The traditional definition of viewing angle is at contrast ratio greater than 10:1. This is far from adequate for LCD TVs. Multi-domain LCDs have been developed to improve the uniformity of the image quality over all the azimuthal angles. However, to satisfy the continuity the LC directors twist continuously from domain to domain so that the boundary areas are formed between domains [1-8]. These domain boundaries appear dark under crossed *linear* polarizers so that the transmittance of the whole pixel is reduced. However, under crossed *circular* polarizers the transmittance is independent of the twist angles of LC directors so that these dark areas are removed and the transmittance is improved [4-8]. A wide-view circular polarizer using the combinations of optimized uniaxial A-plates and C-plates is applied to a multi-domain vertical alignment (MVA) LCD. Both high transmittance and high contrast ratio are maintained over a wide viewing zone [9]. However, its sophisticated device configuration results in complicated manufacture and high cost. There is an urgent need to develop a simple and low cost wide-view LCD with high transmittance.

Comparing to a uniaxial retardation film, the biaxial film provides an extra degree of freedom so that the device configuration of the wide-view circular polarizer can be simplified [6]. In this paper, we start with the design of a wide-view circular polarizer consisting of a linear polarizer and two biaxial films, and then we apply the designed wide-view circular polarizer to a MVA-LCD. The contrast ratio of the proposed MVA-LCD is predicted to be higher than 800:1 over the ±85° viewing cone at $\lambda = 550$ nm and the calculated bright state transmittance is higher than 33.3% (out of 37.8%) at normal view.

2. Wide-View Circular Polarizer Consisting of A Linear Polarizer and Two Biaxial Films

To design the wide-view circular polarizer, we laminate two biaxial retardation films to the linear polarizer as shown in Fig. 1. Since all of the three Stokes parameters are modified inside a biaxial film, the azimuthal angles and the $d\cdot(n_x - n_y)$ as well as the NZ factors of both biaxial films are the key design parameters [10, 11]. Here the azimuthal angle of biaxial film is the angle between the n_x axis of the biaxial film and the absorption direction of the polarizer as Fig. 1(a) shows. Using genetic algorithm [12], by minimizing the following cost function

$$\cos t = \max\left\{\sqrt{2(S_{3\_(2B)}+1)} \mid \left(\theta_{in} = 0^0 \sim 85^0, \phi_{in} = 0^0 \sim 360^0\right)\right\}, \quad (1)$$

where $S_{3\_(2B)}$ is the S_3 of the produced state of polarization $\mathbf{P}_{(2B)}$, we obtain the parameters of the biaxial films [8]. For the two biaxial films, the azimuthal angles are: $\phi_1 = 0.49^o$ and $\phi_2 = 49.02^o$; the $d\cdot(n_x - n_y)$ values are: $d\cdot(n_x - n_y)_1 = 265.43$ nm and $d\cdot(n_x - n_y)_2 = 129.57$ nm; and the NZ factors are: $NZ_1 = 0.75$ and $NZ_2 = 0.53$.

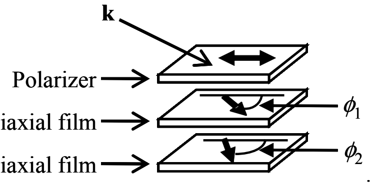

Figure 1. Device configuration of a wide-view circular polarizer with a linear polarizer and two biaxial films.

Figure 2 depicts the polarization states inside this circular polarizer on Poincaré sphere. As Fig. 2 illustrates, the first biaxial film serves as a wide-view half-wave plate so that the light entering the second biaxial film is almost linearly polarized and vibrating at ~45° with respect to the n_x axis of the second biaxial film. Meanwhile, the second biaxial film performs as a wide-view quarter-wave plate. Therefore, although the polarizations across each biaxial film vary with the incident angle, they compensate each other so that the final polarization remains circular over a wide viewing cone

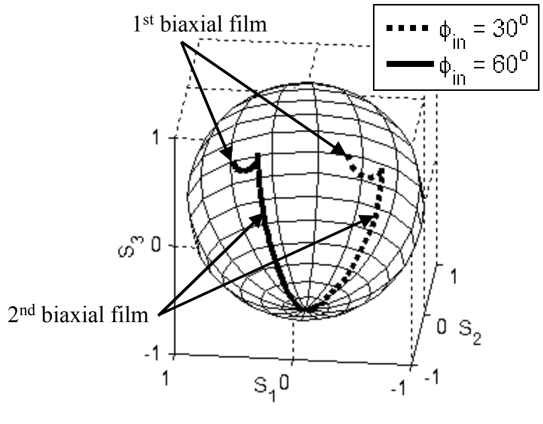

Figure 2. States of polarization inside the wide-view circular polarizer at oblique incidence $\theta_{in} = 85^o$. Dotted lines and solid line show the polarization states when the azimuths of incident plane ϕ_{in} are at 30° and 60°, respectively.

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As demonstrated in Fig. 3, for the proposed right-handed circular polarizer S_3 only increases to –0.997 when the viewing angle increases to 85°. This is equivalent to having the polarization difference $\Delta\mathbf{P}_{(2B)-(RCP)}$ less than 0.078 over the ±85° viewing cone. The produced S_3 remains at −1 at normal angle as in the conventional right-handed circular polarizer.

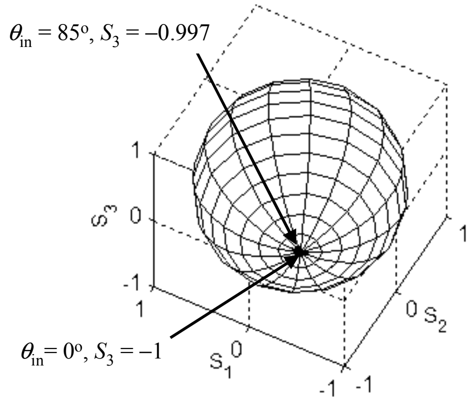


Figure 3. States of polarization produced by the wide-view circular polarizer when $\theta_{in} = 0^o \sim 85^o$ at each fixed ϕ_{in}, where $\phi_{in} = 0^o \sim 360^o$ with 10° interval.

3. Multi-Domain VA-LCD Using Wide-View Circular Polarizers

Vertical alignment (VA) has been used in many LCDs because of its excellent contrast ratio. In a VA-LCD, in order to have uniform image quality over all the azimuthal angles, four domains are formed along the bisectors of the crossed linear polarizers [13, 14]. However, due to the continuity the LC directors twist continuously from domain to domain so that the boundary areas are formed between domains. These boundary areas become dark areas under crossed linear polarizers so that the transmittance of the whole pixel is reduced [5-8, 13]. Nevertheless, under crossed circular polarizers, the transmittance of LCD only depends on the phase retardation (δ) of the LC layer:

$$T = \sin^2(\delta/2). \tag{2}$$

Hence, the azimuthal angles of the LC directors are not necessary to be at the bisectors. As a result, the use of circular polarizers greatly enhances the bright state transmittance [5-8].

Now we apply the above wide-view circular polarizer to the design of a VA-LCD as shown in Figure 4. The top linear polarizer and the first two biaxial films compose a wide-view right-handed circular polarizer. The bottom analyzer and the last two biaxial films form a second circular polarizer crossed to the first one. The absorption axis of the analyzer and the azimuthal angles of the last two biaxial films are perpendicular to their counter parts in the first circular polarizer. To compensate the phase changes introduced by the vertical alignment LC cell at oblique viewing angles, two negative uniaxial C-plates with equal phase retardations are laminated to the both sides of LC cell. The $d\cdot(n_x - n_y)$ values of both C-plates are −161.67 nm when the $d\cdot(n_x - n_y)$ of the VA LC layer is 341.88 nm. The LC director distributions are simplified into eight domains at every 45° from 22.5° to 337.5° in the bright state.

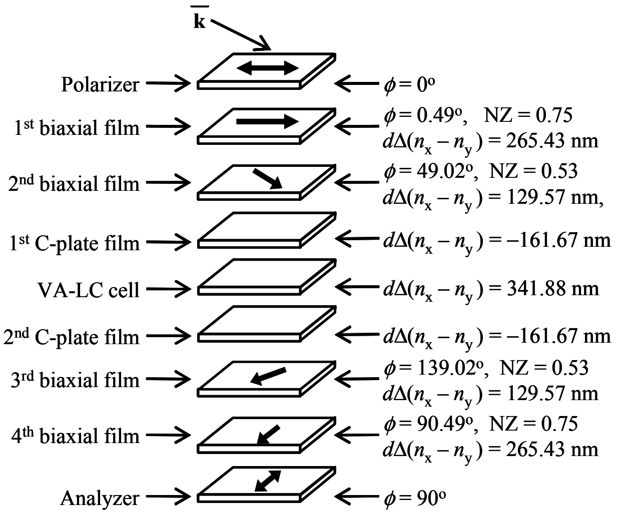
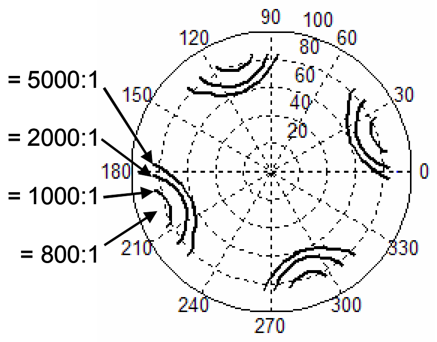


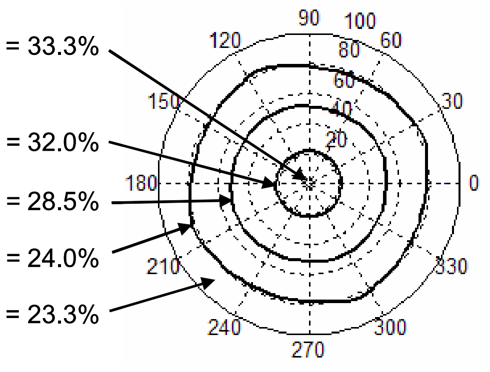
Figure 4. Configuration of a wide-view multi-domain VA-LCD with crossed wide-view circular polarizer.

In the dark state, since the phase changes due to the VA-LC layer are compensated by the negative C-plates. the circular polarization emerging from the first circular polarizer reaches the second circular polarizer and is converted into linear polarization after it passes though the two biaxial films attached to the analyzer. Due to the symmetric configuration of the crossed circular polarizers, this linearly polarized light vibrates along the analyzer's absorption direction. Therefore, the dark state light leakage is significantly reduced so that the calculated contrast ratio is higher than 800:1 between ±85° viewing angles as shown in Fig. 5(a). Since the bright state transmittance is only determined by the phase retardation of the LC layer as Eq. (2) shows, the simulated bright state transmittance is higher than 33.3% (of 37.8%) at the normal view as Fig. 5(b) depicts. Furthermore, if the air-interface surface reflection is assumed to be reduced by an ideal anti-reflection film in Figure 6, the variation in the bright state transmittance is less than 15% over the entire ±85° viewing cone as demonstrated in Fig. 5(b).

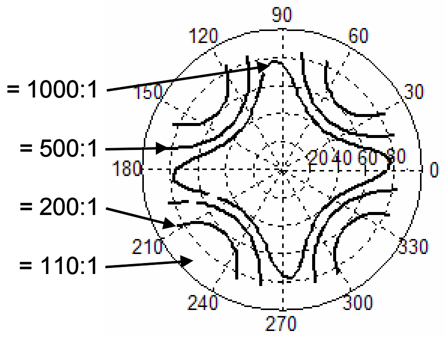
For direct-view LCDs, broad bandwidth is as important as wide viewing angle [1-8]. Although the above wide-view circular polarizer is designed at a single wavelength λ=550 nm, however, at normal incidence the retardation of the first biaxial film is almost equal to one half of the designed wavelength, i.e., $d\cdot(n_x - n_y)_1$ = 265.43 nm ≈ 550 nm/2 = λ/2, and the retardation of the second biaxial film is close to a quarter of the designed wavelength, $d\cdot(n_x - n_y)_2$ = 129.57 nm ≈ 550 nm/4 = λ/4. At the same time, the azimuthal angles of the two biaxial films satisfy the relationship $2\phi_1 - 4\phi_2 \approx 90^0$, which describes the relationship between the azimuthal angles of the half-wave plate and the quarter-wave plate inside a broadband circular polarizer [15]. Therefore, over ±85° viewing cone, the contrast ratio of the proposed wide-view LCD remains higher than 110:1 for both blue and red light as Figs. 5(c) and (e) illustrate. At the same time, as depicted in Figs. 5(d) and (f), the bright state transmittance maintains higher than 34.0% and 28.9% for the blue and red light, respectively.



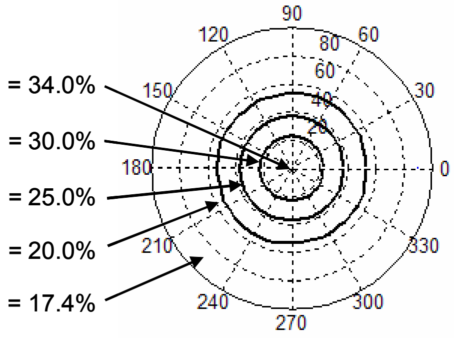
(a)



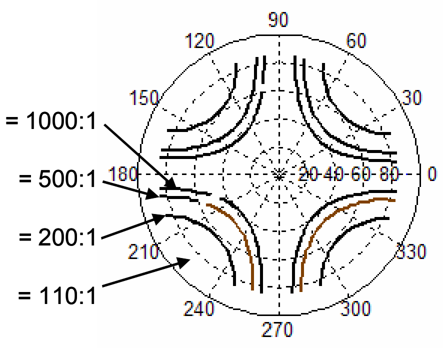
(b)



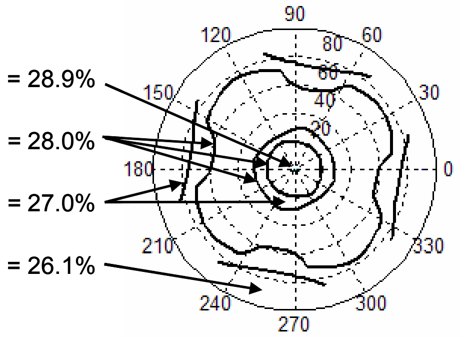
(c)



(d)

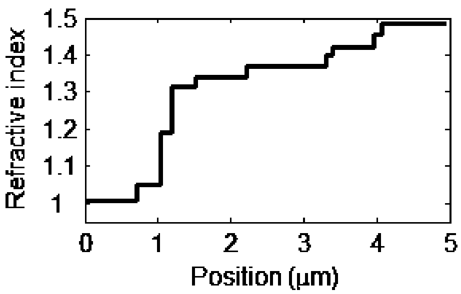


(e)

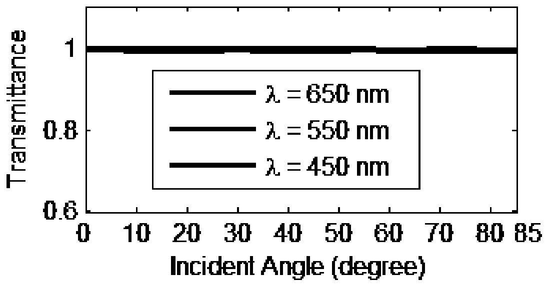


(f)

Figure 5. A VA-LCD using crossed wide-view circular polarizers when LC directors form eight domains in the bright state: (a) iso-contrast plot at λ= 550 nm; (b) iso-transmittance plot at λ= 550 nm; c) iso-contrast plot at λ= 450 nm; (d) iso-transmittance plot at λ= 450 nm; e) iso-contrast plot at λ= 650 nm; (f) iso-transmittance plot at λ= 650 nm.



(a)



(b)

Fig. 6. Ten-layer ideal anti-reflection film: (a) refractive indices profile, and (b) transmittance.

Design tolerance is an important concern from manufacturing viewpoint. For the proposed design of a wide-view VA-LCD, we calculate the minimum contrast ratio over the ±85° viewing cone if the film parameters of the biaxial films deviate from the optimal values by ±5%. The incident wavelength is 550 nm and the simulation results are plotted in Figure 7. First we evaluate the influence of film thickness. The solid line with plus sign markers in Figure 7 indicates that a −5% deviation in the first biaxial film thickness reduces the contrast to 400:1. By contrast, the light leakage is quite inert to the errors of the second biaxial film thickness (dashed line with plus sign markers). Next, we study how the NZ factor affects the contrast. As shown by the solid line with triangular markers in Fig. 7, the NZ factor of the first biaxial film plays a significant role. The contrast ratio decrease to 200:1 with a ±5% deviation. On the other hand, a −5% error in the NZ factor of the second biaxial film decreases the contrast ratio to 300:1 (dashed line with triangular markers). The solid and dashed lines with circle markers in Fig. 7 illustrate that the contrast ratio is almost invariant when the orientations of both biaxial films vary by ±5%. Thus, from this tolerance analysis we find that the accuracy of the first biaxial film parameters is more critical than that of the second biaxial film and the NZ factors of both biaxial films require a higher accuracy

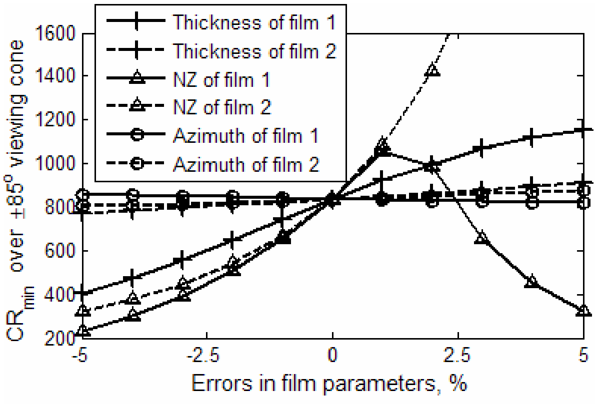


Figure 7. Design tolerance of the proposed wide-view VA-LCD. The viewing cone is ±85° and λ= 550 nm. Ten-layer anti-reflection film is assumed.

In conclusion, we demonstrate a wide view VA LCD with both high contrast ratio and high transmittance over the entire visual spectrums. We start from the design of a wide-view circular polarizer. By using phase compensation techniques the resultant polarization states are constrained to the desired circular polarization over a wide range of viewing angles. Then we apply the designed wide-view circular polarizer to a multi-domain VA-LCD. The maximum transmittance is predicted to be higher than 33% and the contrast ratio is higher than 800:1 for the green light. Over the entire visual spectrum the maximum transmittance is higher than 29% and the contrast ratio remains higher than 110:1. The uniformity of better than 70% in the bright state transmittance is predicted over the ±85° viewing cone if the air-interface surface reflection is suppressed.

4. Acknowledgements

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5. References

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