Zigzag Electrodes for Suppressing the Color Shift of Kerr Effect-Based Liquid Crystal Displays

Linghui Rao, Zhibing Ge, and Shin-Tson Wu, *Fellow, IEEE*

***Abstract*—The electro-optic properties of Kerr effect based liquid crystal display (LCD) with zigzag electrode structure are studied using a three-dimensional simulator. The optimal bending angle of the zigzag in-plane switching (IPS) electrodes is found to be 90°, which is different from the conventional strip electrodes. Although the zigzag structure exhibits a slightly lower transmittance than the strip IPS electrodes, it significantly suppresses the color shift while providing a relatively wide viewing angle.**

***Index Terms*—Blue phase (BP), color shift, fast response time, in-plane switching, Kerr effect.**

I. INTRODUCTION

LIQUID CRYSTAL displays (LCDs) are widely used nowadays for mobile devices, notebook computers, desktop monitors, and large screen TVs. For large screen LCD TVs, it is important to have fast response time, high contrast ratio, wide viewing angle as well as weak color shift. Recently, blue phase liquid crystal displays (BP LCDs) based on Kerr effect are emerging due to their attractive features, such as: 1) submillisecond response time which not only reduces motion picture image blurs but also enables color sequential operation; 2) isotropic dark state which leads to a wide and symmetric viewing angle, and 3) no need for alignment layers which greatly simplifies the fabrication processes [1]–[4]. However, till now almost all the ongoing research on BP LCDs focuses on in-plane switching (IPS) with strip electrodes [5], [6], and the color shift issue has not been addressed.

In this paper, we investigated zigzag electrode structures for BP LCDs using a three-dimensional (3D) simulator developed in our group. These discussions apply equally well to the general Kerr effect-based LCDs, which include isotropic-to-anisotropic switching. The electro-optic properties of the zigzag structure under different bending angles, electrode width-to-spacing ratios were characterized by the voltage-dependent transmittance (VT) curve. We also found that IPS BP-LCD with zigzag electrode structure significantly suppresses the color shift while preserving a relatively wide viewing angle. The responsible physical mechanisms are discussed through the comparisons with conventional strip electrode IPS structure.

II. DEVICE PHYSICS AND MODELING

Blue phases exist in a narrow temperature range between the isotropic and helical cholesteric phase near the LC clearing temperature with cubic symmetry structure [7], [8]. These high speed electro-optical operations are mainly based on a local director reorientation within the unit lattice of the cubic blue phase structure [1]. Macroscopically, it appears as Kerr effect which is a second-order electro-optic effect occurred in optically isotropic substances. When there is no voltage applied, the BPLC medium appears optically isotropic, and it becomes anisotropic when a strong electric field is applied. The induced birefringence can be expressed by [6], [9]:

$$\Delta n = \lambda K E^2 = (\Delta n)_o (E/E_s)^2 \tag{1}$$

where $\Delta \mathrm{n}$ is the induced birefringence, λ is the wavelength, K is the Kerr constant, $(\Delta \mathrm{n})_\mathrm{o}$ is the maximum induced birefringence, and the induced $\Delta \mathrm{n}$ saturates at $(\Delta \mathrm{n})_\mathrm{o}$ when the electric field E reaches a saturation field $\mathrm{E_s}$ since $\Delta \mathrm{n}$ cannot increase unlimitedly with the increasing electric field.

Recently, our group has developed a device model for calculating the electro-optic properties of the blue phase LCDs [10]. It consists of three steps: 1) calculate the potential distribution Φ from solving the Poisson equation $\nabla(\nabla \cdot \varepsilon\Phi) = 0$ and then the distribution of electric field $\mathbf{E}$ in the LC media; 2) calculate the induced birefringence by (1), limit it to be below the intrinsic $(\Delta \mathrm{n})_\mathrm{o}$ of the LC/polymer composite and assign the local optic axis direction of each unit to be along the $\mathbf{E}$ vector; and 3) calculate the voltage-dependent transmittance and other electro-optic properties with extended Jones matrix.

III. ZIGZAG ELECTRODE STRUCTURE

Current research of BPLC for display applications is conducted under the traditional strip electrode structure using IPS cells, as depicted in Fig. 1(a). The cell is placed between two crossed linear polarizers. The horizontal electric fields generated from IPS electrodes induce phase retardation for the incident light. Here, w represents the electrode width and l is the spacing between the electrodes. Fig. 1(b) shows the zigzag electrode structure for blue phase LCDs, where α stands for the bending angle of the electrodes. Our purpose is to compare the transmittance, viewing angle, and color shift between these two electrode configurations.

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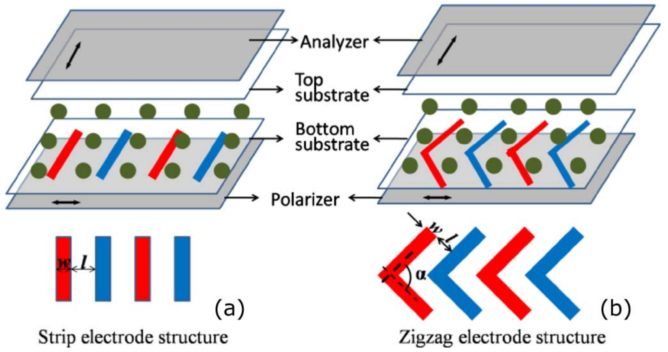

Fig. 1. (a) Strip electrode structure and (b) zigzag electrode structure for blue phase IPS cells.

A. Bending Angle Effect

As shown in Fig. 1(b), the zigzag electrode is bent at an angle α, which is set as the angle between the two arms of the electrode. A serial of the zigzag electrodes are alternatively arranged to form the inter-digital electrodes on the same substrate as the common electrode and the pixel electrode, respectively, which are connected to the thin-film transistors (TFTs) in the practical LCD devices. During simulations, we calculated a blue phase LC cell with an electrode width $w = 5\ \mu$m, spacing between electrodes $l = 10\ \mu$m, Kerr constant $K \sim 12.7^2$ nm/V^2 [10] and wavelength $\lambda = 550$ nm. Unlike conventional LCDs which are affected by the cell gaps, the transmittance does not change too much with cell gap variance in BPLCs [11]. Therefore, all the simulations used throughout this paper have a cell gap $d = 10\ \mu$m.

Voltage dependent transmittance curves for three different bending angles $\alpha = 110°$, 90° and 70° are shown in Fig. 2, respectively. The transmittance has been normalized to the maximum transmittance of two parallel polarizers. It has been reported by Lu, *et al.* [12] that for conventional nematic liquid crystal in an IPS cell with zigzag electrode structures, the larger the bending angle, the lower the operating voltage and the higher the transmittance. As the bending angle of the zigzag electrode decreases, higher on-state voltage is needed for the required effective projected electric field to switch the LC directors. However, among the three zigzag structures of blue phase LC in the IPS cell described here, the 90° bending angle has the highest transmittance. Their on-state voltage is roughly the same. The reason comes from the unique symmetric molecular structure of the blue phase LCs. The 90° bending angle can always be an optimal, because it provides a more symmetric electric field for BPLCs so that a larger maximum electric-induced birefringence can be obtained. The following discussions are all based on a 90° bending angle for the zigzag electrode structure.

B. Electrode Structure Effect

Electrode dimension plays an important role in the electro-optic properties of the IPS BPLC cell. To better understand the zigzag electrode structure, we compared it with the strip structure in the following ways with different electrode dimensions as shown in Fig. 3. The transmittance is normalized to the maximum value from two parallel polarizers (34.83%).

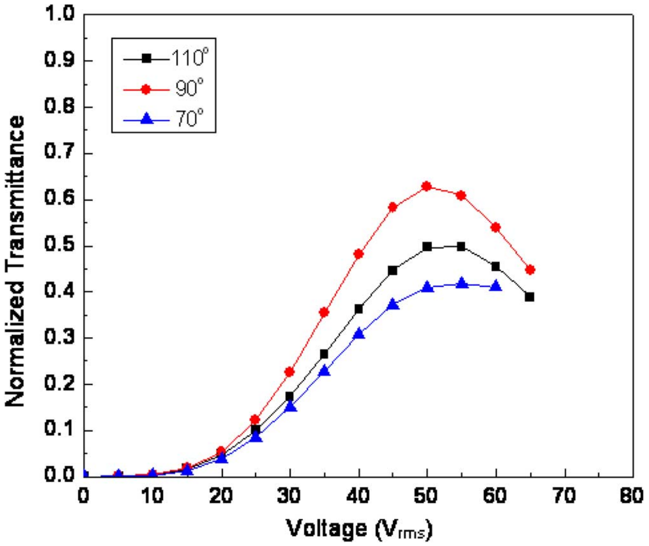

Fig. 2. VT curves of the IPS BP cell with zigzag electrode structure for different bending angles at $\lambda = 550$ nm.

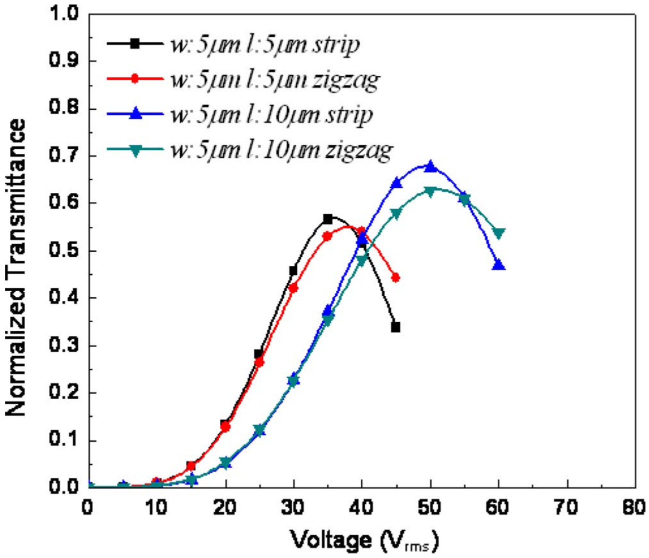

Fig. 3. VT curves of the IPS BP cell with different electrode dimensions and structures at 550 nm.

In the strip-electrode IPS cell, transmittance mainly originates from the induced birefringence by Kerr effect in the electrode spacing area [11]. Smaller spacing width l will result in a stronger electric field intensity which in turn leads to a lower driving voltage $\mathrm{V_{on}}$. The zigzag structure shows exactly the same trend. The VT curves of the zigzag structure with the electrode dimensions of [$w = 5\ \mu$m, $l = 5\ \mu$m] demonstrate lower driving voltages than those of [$w = 5\ \mu$m, $l = 10\ \mu$m]. Considering that only the regions between electrodes contribute to the transmittance, a larger l/w ratio is in favor. As shown in Fig. 3, both for strip electrode structure and zigzag electrode structure, the dimensions of [$w = 5\ \mu$m, $l = 10\ \mu$m] with $l/w = 2$ have a higher transmittance than the dimension [$w = 5\ \mu$m, $l = 5\ \mu$m] with $l/w = 1$. If we compare the strip structure with the zigzag

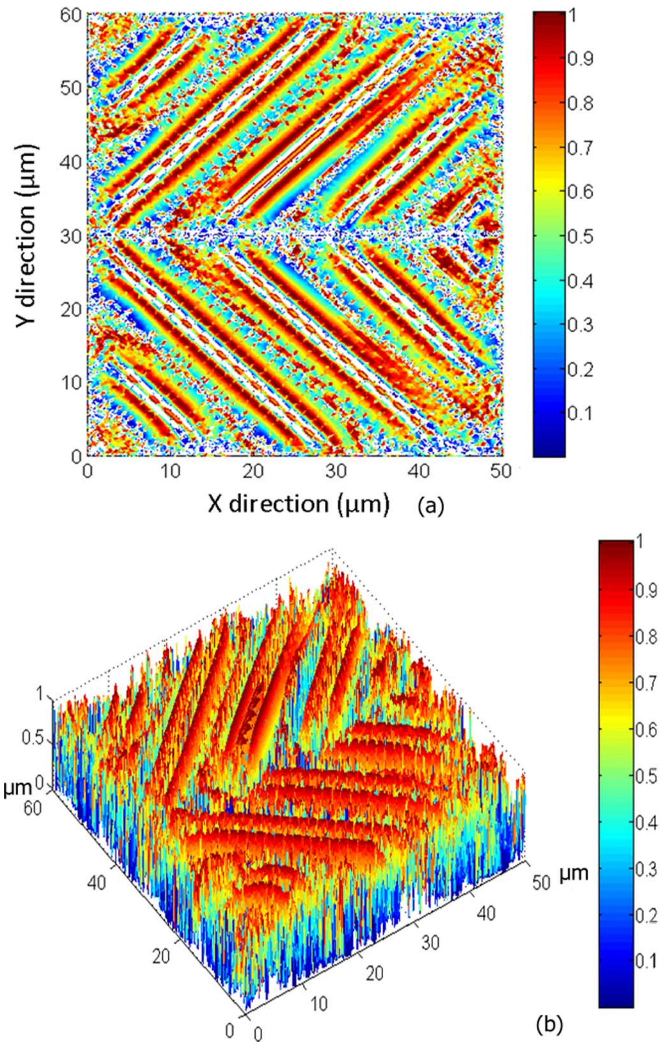

Fig. 4. (a) 2D and (b) 3D views of the transmittance profile for the zigzag structure with $w = 5\ \mu\text{m}$, $l = 5\ \mu\text{m}$, $\alpha = 90^\circ$, legend bar shows the normalized transmittance.

structure individually, we may find out that for the same electrode width and spacing width, zigzag structure exhibits a little lower transmittance. This is attributed to the dead zones at the turning corners of the zigzag electrodes shown in Fig. 4. The dead zone forms a horizontal disclination line locating at the position of $\sim 30\ \mu\text{m}$ in y direction in Fig. 4(a). The electric fields in the dead zones do not effectively induce birefringence for the LCs so that they make no contribution to the transmittance.

C. Viewing Angle

When no voltage is applied, the LC index ellipsoid is like an ideal sphere. The BPLC is optically isotropic with a perfect dark state. The only light leakage would rise from the oblique incidence that the two crossed polarizers appear to be no longer perpendicular to each other. In the voltage-on state, although electric field induces birefringence and the LC index ellipsoid is elongated, the overall cubic symmetry of the BPLC does not change. This again leads to a symmetric view of the LCD. Due to these features which are different from conventional nematic liquid crystals, the viewing angle plots shown in Fig. 5 are very

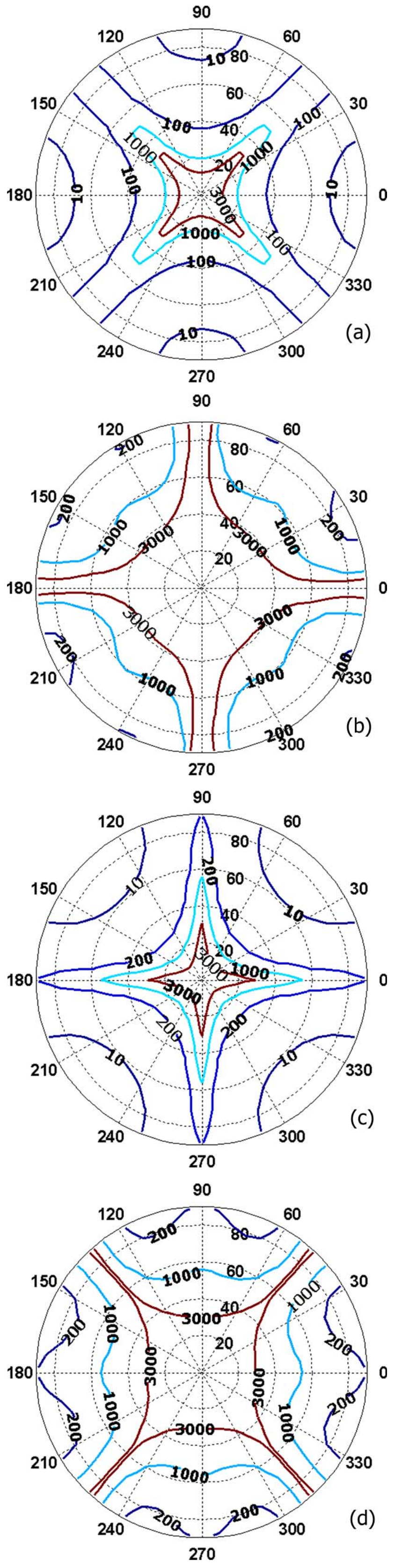

Fig. 5. Isocontrast plots of the IPS BPLC cell: (a), (b) strip electrodes without and with compensation films, and (c), (d) zigzag electrodes without and with compensation films. Biaxial film parameters: $N_z = 0.5, R_0 = (n_x - n_y) \cdot d = \lambda/2$. IPS cell parameters: $d = 10\ \mu\text{m}$, $w = 5\ \mu\text{m}$, and $l = 10\ \mu\text{m}$ and $\lambda = 550$ nm.

symmetric. Another advantage is that the LC alignment and rubbing which may cause light leakage for conventional LCDs do not exist here.

Fig. 5(a) and Fig. 5(b) are the isocontrast plots of the IPS BPLC cell with strip electrodes, while Fig. 5(c) and Fig. 5(d) are the plots with zigzag electrodes. The biaxial film compensated plots shown in Fig. 5(b) and Fig. 5(d) have the following parameters: $N_z = 0.5$ and $R_0 = (n_x - n_y) \cdot d = \lambda/2$ [13]. The cell dimensions used in simulation are: cell gap $d = 10\ \mu$m, electrode width $w = 5\ \mu$m, spacing width $l = 10\ \mu$m, and $\lambda = 550\ \mu$m. We find that the contrast ratio over 1000:1 can be expanded to $\sim 55°$–$66°$ with compensation films for both structures.

Shown in Fig. 6(a) and (b) are the luminance polar contour plots corresponding to IPS cells with strip electrodes and zigzag electrodes without compensation films. For BPLCs, the isotropic dark state is perfect and is affected only by the light leakage from the crossed polarizers at oblique incidence. The on-state transmittance of the zigzag electrode structure is a little lower than that of the strip electrode structure due to the presence of dead zones, so the contrast ratio is somewhat lower, too. This can be considered as one of the differences between BP-LCDs and conventional LCDs. But the more uniformly distributed brightness in Fig. 6(b) is related to the four domains formed by zigzag electrodes. The on-state brightness for the same electrode structure with and without compensation film is similar. Compensation film is used to compensate the light leakage induced by the crossed polarizers at oblique angle at dark state. Therefore, for both structures, the contrast ratio for the one with compensation film is larger than the one without.

Nevertheless, the viewing angle for both strip and zigzag electrode structures is reasonably wide and comparable to a conventional four-domain nematic IPS LCD with zigzag structure.

D. Color Shift

Color shift is a parameter determining the color uniformity of an LCD panel at different viewing directions. It is a very important issue for large screen display devices.

We calculated IPS BPLC cell with the configuration of electrode width $w = 5\ \mu$m, spacing $l = 10\ \mu$m and cell gap $d = 10\ \mu$m. Fig. 7(a) and Fig. 7(b) show the bright state color shift in CIE 1931 using a CCFL light source of the strip and zigzag electrode structures, while Fig. 7(c) and Fig. 7(d) are with the LED light source. The dots in the figures represent the color shift from the standard white point. We used the real data on light source, polarizer, compensation film, and color filters in the calculations. The wavelength dependent Kerr constant is also taken into consideration by the following single-band model [14], [15]:

$$\lambda K \approx G \frac{\lambda^2 \lambda^{*2}}{\lambda^2 - \lambda^{*2}} \tag{2}$$

where λ^* is the mean resonance wavelength and G is a proportionality constant. From the experiment of a LC cell based on Kerr effect in the FFS structure by Ge, *et al.* [5], we find $G \sim 8.78 \times 10^{-2}\ \mathrm{V}^{-2}$ and $\lambda^* \sim 250$ nm under the assumption that $K \sim 12.7\ ^{2}$ nm/V^2 at $\lambda = 550$ nm. Under this circumstance, we can obtain the Kerr constants in the visible range by (2) for the color shift.

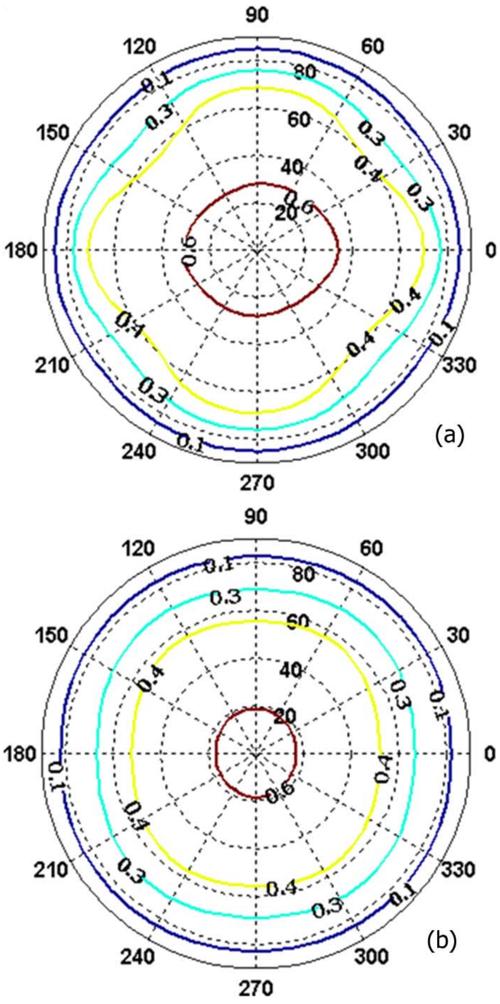

Fig. 6. Illuminance polar charts for the IPS BPLC cells: (a) strip electrodes, and (b) zigzag electrodes. Cell parameters: $d = 10\ \mu$m, $w = 5\ \mu$m, and $l = 10\ \mu$m and $\lambda = 550$ nm. (No compensation films are used).

Due to the unique symmetric feature of blue phase liquid crystals, even with only the strip electrode structure, a multi-domain-like distribution of induced Δn in the IPS structure could be produced to make the viewing angle symmetric. The color shift of the bright state is reasonably small; based on CIE 1976, we obtained the $\Delta u'v' = (0.0030, 0.0077, 0.0327)$ for CCFL light source and $\Delta u'v' = (0.0023, 0.0062, 0.0283)$ for LED light source at the RGB primaries, respectively. Nevertheless, in Fig. 7(b) and Fig. 7(d), if we use 90° zigzag electrodes instead of the strips, more sub-domains are created [16]. Liquid crystal molecules are rotating into the complementary directions, resulting in an even better and more uniformly compensated bright state. For the zigzag electrode structure, based on CIE 1976, the $\Delta u'v'$ values are reduced to (0.0019, 0.0028, 0.0161) for CCFL light source and (0.0013, 0.0024, 0.0127) for LED light source at the RGB primaries.

IV. CONCLUSION

We have studied the zigzag electrode structure for blue phase LCDs and compared its performances with the traditional strip

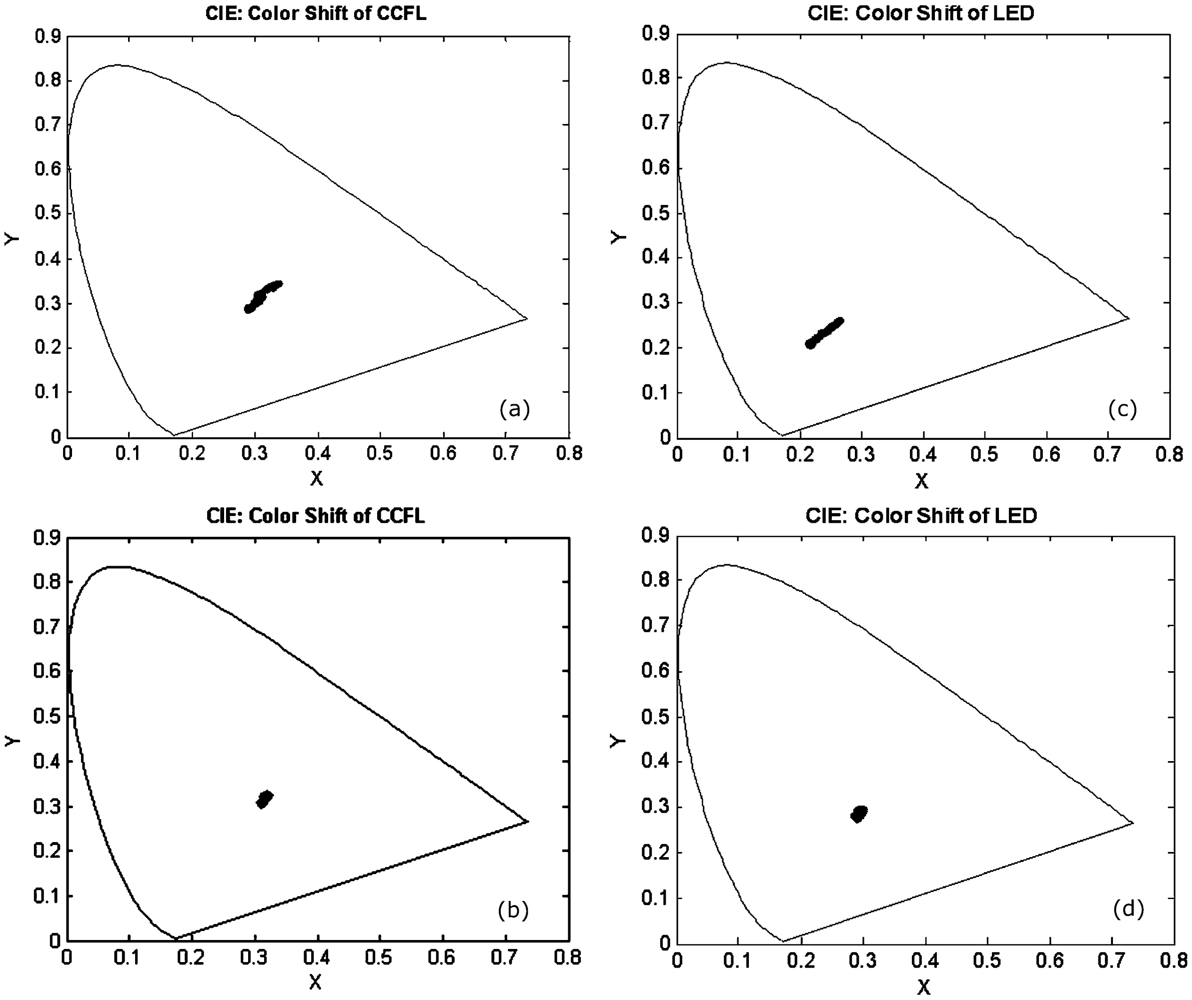

Fig. 7. Simulated bright state color-shift of the IPS BPLC cell without compensation film: (a) strips and (b) zigzag structure with CCFL light source, and (c) strips and (d) zigzag structure with LED light source. IPS cell parameters are: $d = 10\ \mu$m, $w = 5\ \mu$m and $l = 10\ \mu$m.

electrode structure. The 90° bending angle is found to be the best for zigzag structure in which the viewing angle is wide and symmetric, and the color shift is significantly suppressed. However, a tradeoff in slightly lower transmittance is found because of the presence of dead zones. This reduced transmittance also causes a slightly lower contrast ratio.

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