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Study on the light leakage mechanism of a blue phase liquid crystal cell with oblique interfaces

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Abstract
The mechanism of light leakage in the dark state of a blue phase liquid crystal display cell which has protruded electrodes was investigated. We have performed a hybrid numerical simulation by combining the geometrical optics with the extended Jones matrix method. The light leakage in the cell was caused by changes in the polarization state which has been explained by the asymmetric amplitude change of transverse electric and transverse magnetic fields at the oblique interface and the change in an effective angle between crossed polarizers by the light path refraction. Based on our analysis, light leakage can be suppressed by the matching of the refractive indices of adjacent materials to the interface of the protruded electrodes whose surfaces are not parallel to the substrate.

(Some figures may appear in colour only in the online journal)

1. Introduction

For the sake of driving a liquid crystal display (LCD) with high refresh rate for future applications, the improvement of response time of liquid crystal itself is crucial [1, 2]. A polymer-stabilized blue phase liquid crystal (PS-BPLC) is a deserving candidate for fulfilling this requirement, as it has been reported to have sub-millisecond order superior response time [3, 4]. It has the additional merits of achieving optically isotropic dark state, thickness-independent wide viewing angle and no need of an alignment layer. One of the important problems remaining for PS-BPLC is high operating voltage. It is required to develop a new composite of BPLC with a higher Kerr constant so that it enables lower operating voltages [5, 6]. However, it has a trade-off relation between higher Kerr constant and other stability parameters (residual birefringence, hysteresis and long-term stability) [7, 8]. Design approaches have been investigated to achieve lower operating voltages with a given stabilized BPLC [9–11]. Normally, PS-BPLCD is applicable with in-plane switching (IPS)-type configuration.

As one of the best solutions for lowering the operating voltage, the IPS concept with protruded electrodes in which indium tin oxide (ITO) on the formerly formed protrusion is patterned as electrodes was proposed [11]. The implemented cell showed better V–T characteristics but it showed higher light leakage than conventional normal IPS type. In this paper, for the better understanding of the light leakage mechanism in the implemented cell, we have performed a numerical simulation combining the ray optics and the extended Jones matrix method [12] with supplementary optical measurements about light leakage. Based on the analysis, light leakage can be suppressed by the matching of the refractive indices of adjacent materials to the interface of the protruded electrodes whose surfaces are not parallel to the substrate.

2. Cell structure and experimental

Figure 1 shows the implemented cell structure. As shown in figure 1, we have formed the protruded electrodes by patterning ITO (patterned width: 4 μm, interval between patterned ITO: 4 μm) on the protrusion with a height of 2 μm. In order

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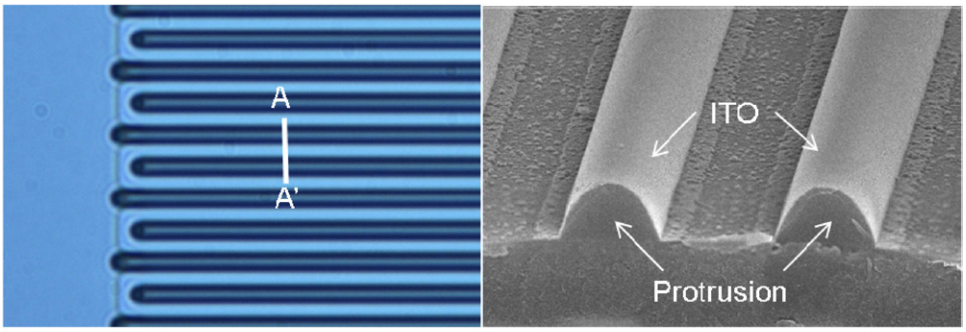

(a) (b)

Figure 1. Cell structure with protruded electrodes: (*a*) top view of microscopic image and (*b*) cross-sectional view taken by a scanning electron microscope (SEM) in the A–A′ direction.

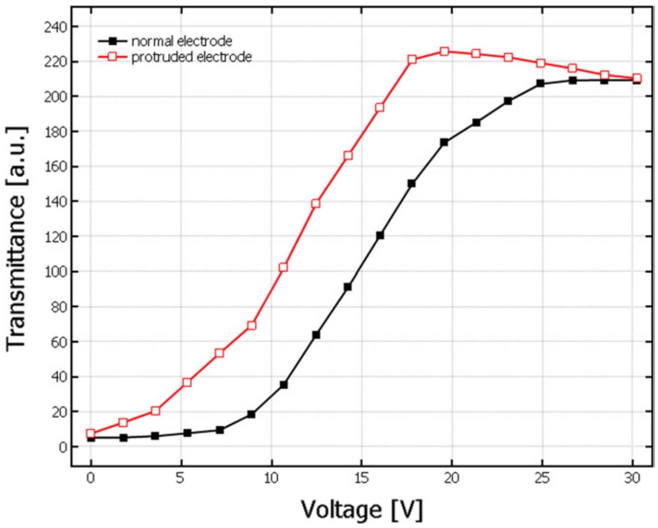

Figure 2. Voltage-dependent transmittance characteristics for the IPS cells with protruded and normal electrodes.

to confirm the difference in light leakage in a dark state and voltage-dependent transmittance (V–T) characteristic between two IPS cells with normal and protruded electrodes, V–T curves were measured, as shown in figure 2. Here, the commercially available BPLC mixture (LCMS-BP-081009-1 from LC Matter Corp., USA) was tested and the cell gap of all cells was 10 μm. Each cell was placed between the crossed polarizer in which the electrode patterned direction was at 45° with respect to the optical axes of the crossed polarizer. As indicated in figure 2, the protruded electrode cell shows lower operation voltage and higher transmittance than the normal cell. However, at the dark state, the protrusion cell seems to have a higher light leakage.

To understand the intrinsic characteristics of light leakage in a dark state of the IPS cell with a protruded electrode, the light leakage was measured by an optical microscope, first without the BPLC. Figure 3 shows the light intensity distribution of the IPS cell with protruded and normal electrodes when the electrode pattern direction is at 45° with respect to the crossed polarizer. Referring to figure 3(*a*), most of the light leakage of the protruded electrode cell appears at the side of the wall which has a sloped interface. Furthermore, the light leakage has dependence on the slope angle of the interface because the light leakage decreases on top of the protruded electrode whose slope is parallel to the other interface. Therefore, the light leakage seems to have a relationship with the sloped interface of protrusion. The polarization of light passing through the sloped interface electrode seems to have changed according to the angle between polarization of light and the slope angle of the sloped interface. In good accordance with our assumption, the normal electrode cell has no light leakage, as shown in figure 3(*b*).

In order to clarify the light leakage in more detail, we have measured light leakage by rotating the cell between the crossed polarizer for three difference cases: normal, protruded electrode without BPLC and protruded electrode with BPLC. Figure 4 shows the light leakage characteristics according to the rotation of the cells. Referring to figure 4, the light leakage of the normal electrode cell (marked with solid circles) was not affected by the rotation of the cell as we expected. On the other hand, the light leakage of the protruded electrode cells (marked with solid squares and triangles) showed a big difference through the rotation of the cell. The maximum light leakage appeared when the patterning direction of the protruded electrode made 45° with respect to the optical axes of the crossed polarizer. Therefore, light leakage can be considered as a function of the angle between polarization direction of light after passing through the polarizer and the normal direction of the protrusion surface. Furthermore, it was observed that the maximum of light leakage decreases with the insertion of BPLC. Therefore, the decrease in light leakage can be explained by the change in the refraction angle according to the boundary condition of media which have a different refractive index, not any depolarization by scattering through BPLC insertion or irregular reflection. Therefore, through BPLC insertion, greater mismatching reduction in refractive index between the BPLC and the organic resin for protrusion than that of air and organic resin seems to reduce the light leakage by minimizing the change of light path.

3. Light leakage mechanism

The light leakage of the protruded electrode cell can be explained by the irregular refraction by objects whose surfaces

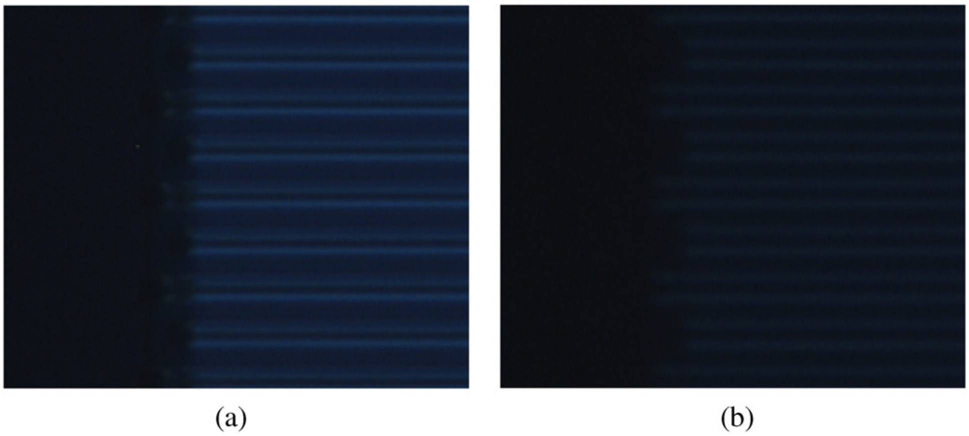

Figure 3. Light intensity distribution of the IPS cell when the electrode pattern direction is at 45° with respect to the crossed polarizer: (*a*) protruded electrode cell, (*b*) normal electrode cell.

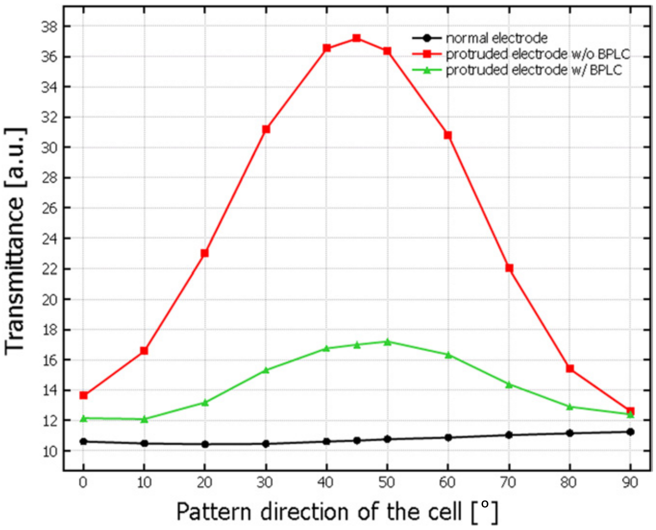

Figure 4. Light leakage according to the pattern direction of the cell with crossed polarizer for three different cells: normal, protruded electrode without BPLC (w/o BPLC) and protruded electrode with BPLC (w/ BPLC).

are not parallel to the substrate and polarization rotation caused by the asymmetrical amplitude changes of transverse electric (TE) and transverse magnetic (TM) fields passing through the media interface obliquely. Figure 5 shows the vector representation of refraction and reflection at an interface between two media and the schematic cross-sectional view of the normal and protruded electrode cells with a full path of light observed in the normal direction. Referring to figure 5(*a*), the refractive indices of two media are n_1 and n_2, where propagation directions are denoted by vectors $s(i)$, $s(t)$, $s(r)$ for the incident, refracted and reflected rays, respectively, and N is the normal direction of the interface.

The amplitude changes of TE and TM fields at the interface can be described by the Fresnel equations [13], given in equations (1) and (2), where A, T and R are the amplitude of electric vector of the incident, transmitted (or refracted) and reflected field with subscripts 's' and 'p' meaning TE and TM fields, respectively:

$$T_s = \frac{2n_1\cos\theta_i}{n_1\cos\theta_i + n_2\cos\theta_t}A_s$$
$$T_p = \frac{2n_1\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}A_p \quad (1)$$

$$R_s = \frac{n_1\cos\theta_i - n_2\cos\theta_t}{n_1\cos\theta_i + n_2\cos\theta_t}A_s$$
$$R_p = \frac{n_1\cos\theta_t - n_2\cos\theta_i}{n_1\cos\theta_t + n_2\cos\theta_i}A_p \quad (2)$$

According to equation (1), the amplitude changes of TE and TM fields in the normal electrode cell is symmetric because all propagation directions at the interfaces are parallel to the normal direction N, as shown in figure 5(*a*). Therefore, there is no polarization rotation resulting in light leakage at the normal electrode cell. In the protruded electrode cell, as shown in figure 5(*c*), there are oblique interfaces to the observation direction, so asymmetrical amplitude changes naturally happen. Furthermore, the mismatching of refractive indices between BPLC and protrusion results in an oblique incidence angle θ_P which is another reason for light leakage in the protruded electrode cell.

The light leakage caused by the oblique incidence angle in the protruded electrode cell can be explained by a light leakage mechanism at the crossed polarizer [14]. Figure 6 shows the change of the angle difference between absorption axes of the analyser and the transmittance axes of the polarizer. As shown in figure 6(*a*), in the case of oblique incidence with azimuthal angle = 0° to the crossed polarizer (azimuth = −45°, and +45°, relatively), the angle between absorption axes of two polarizers increases according to the increase in the polar angle of incidence [5]. For the same reason, the oblique incidence by irregular refraction at the sloped interface of the protrusion makes the change of the transmittance axes position of the polarizer, as shown in figure 6(*b*). Therefore, the mechanism of light leakage of the cell with protruded electrodes can be understood as a change in light propagation by the mismatching of refractive indices of the protrusion and BPLC which have a sloped interface not parallel to the observation direction and asymmetrical amplitude changes of TE and TM fields.

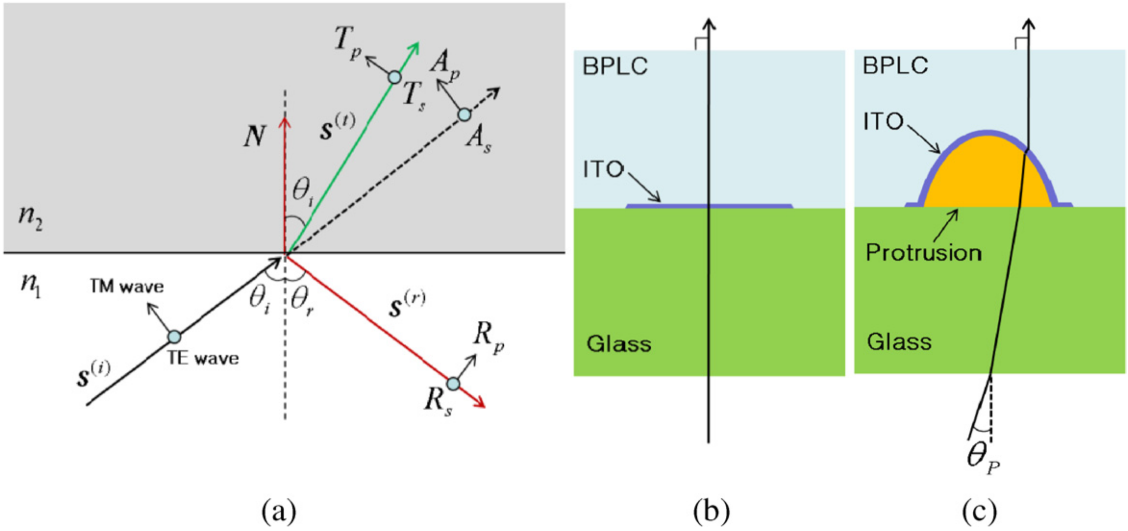

Figure 5. Vector expression of (*a*) a relatively refracted angle to the incidence direction and full path of light in (*b*) the conventional normal cell and (*c*) the protruded electrode cell.

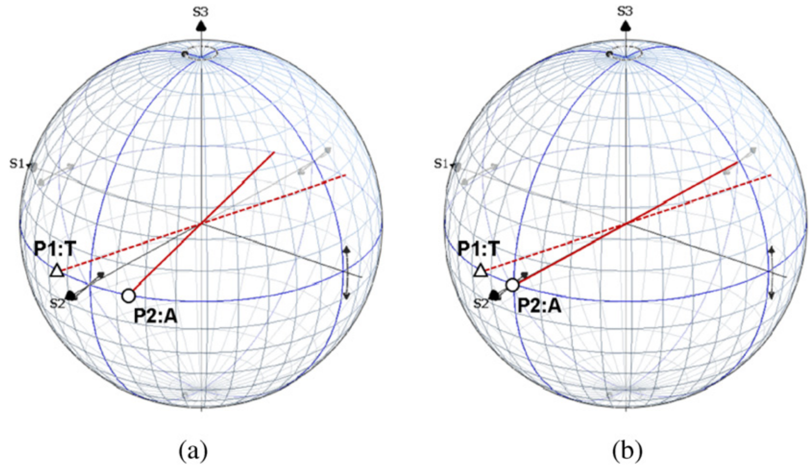

Figure 6. Change in the effective angle between two polarizers (P1:T—transmittance axes of the polarizer and P2:A—absorption axes of the analyser) in the case of (*a*) oblique incidence to the crossed polarizer and (*b*) the sloped interface.

4. Simulation results and discussion

In order to minimize the light leakage in the protruded electrode cell, we have performed the numerical simulation. The conventional matrix methods, such as the extended Jones and Berreman method, cannot deal with irregular refraction by an oblique interface from protrusion. Therefore, we have employed the hybrid method combining a geometrical optics routine for ray tracing and an extended Jones matrix routine for optical polarization calculation [12].

Figure 7 shows the simulated light leakage characteristics according to a tangential angle of the protrusion interface and refractive indices combinations of BPLC, ITO and protrusion. The simulated light leakage characteristics are plotted in terms of the intensity ratio, defined as the transmittance ratio of the BPLC cell under the two parallel polarizers to that under two crossed polarizers at 550 nm when the pattern direction of electrodes is 45° to the optical axes of the crossed polarizers. Therefore, the higher the intensity ratio, the lower is the light leakage in a dark state of the BPLC cell. Figure 7(*a*) shows the intensity ratio and incidence angle (θ_P) as a function of the tangential angle of protrusion interface (θ_S) when the refractive indices of the BPLC, protrusion and ITO are 1.53, 1.6 and 1.9, respectively. As the tangential angle increases over 40°, the intensity ratio decreases dramatically. Among two major mechanisms for light leakage one is asymmetric amplitude changes between TE and TM waves by the tangential angle and the other is oblique incidence caused by the mismatching of the refractive index. We have simulated the intensity ratio with the variation of refractive index of BPLC to find out which one plays the dominant role. Figure 7(*b*) shows the intensity ratio and the incidence angle variation with respect to the refractive index of BPLC when the tangential angle is 70° and refractive indices of ITO and protrusion are 1.9 and 1.6, respectively. According to the result, when the refractive index of BPLC is 1.6, the incidence angle caused by mismatching of refractive index between BPLC and protrusion is zero and thus the intensity ratio increases because there is no light leakage caused by oblique incidence. However, since polarization rotation by asymmetrical amplitude changes of

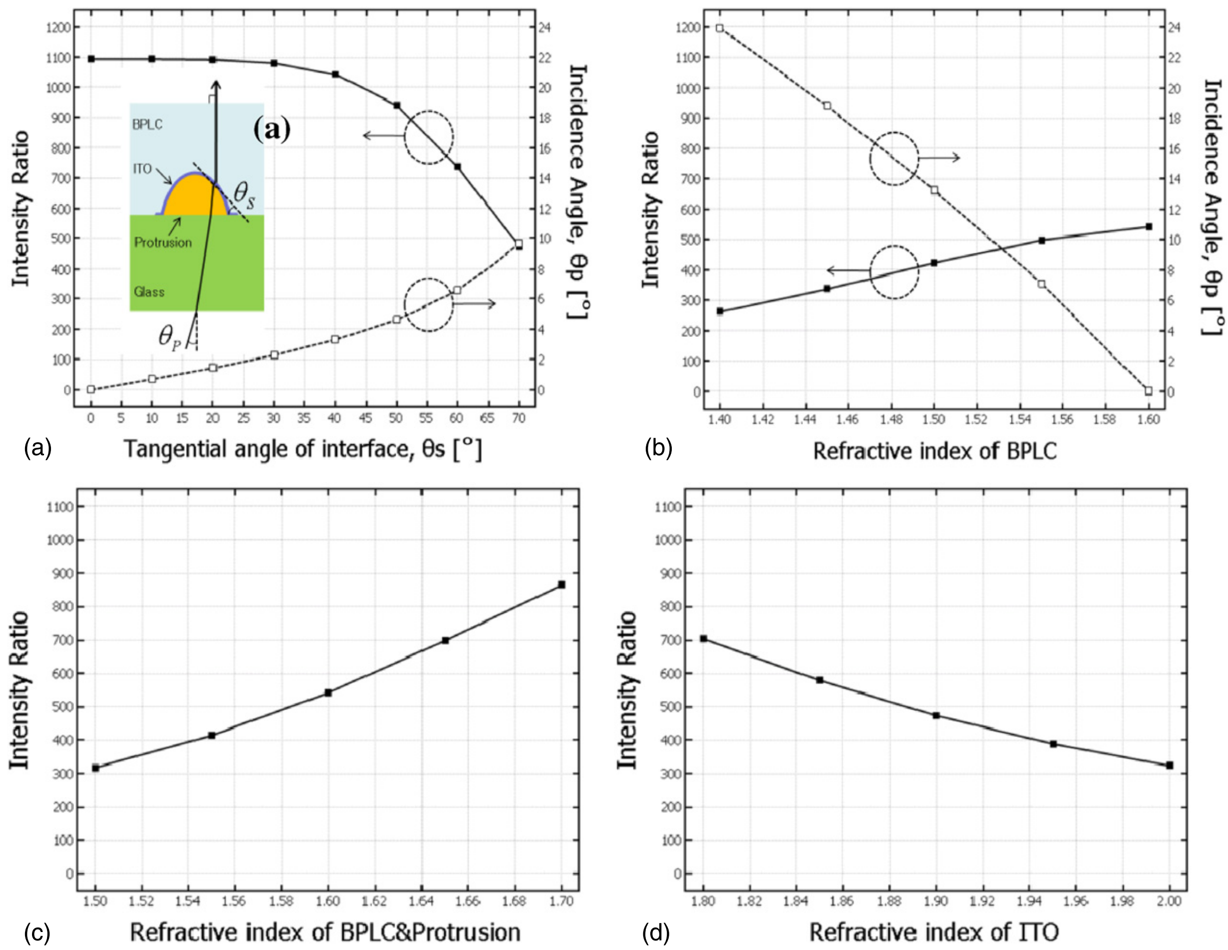

Figure 7. Intensity ratio curves according to (*a*) the tangential angle of protrusion interface, θ_S and variation of refractive index of (*b*) BPLC, (*c*) BPLC and protrusion (matched), and (*d*) ITO at 70° of tangential angle.

TM and TE fields remains, which is originally caused by the tangential angle of the protrusion interface, the improvement of intensity ratio is not significant. Furthermore, if we compare the improvement of light intensity ratio between matching to the protrusion in refractive index (from 1.5 to 1.6 of BPLC in figure 7(*b*)) and reduction in tangential angle of the protrusion interface (from 70° to 50° in figure 7(*a*)), the reduction in tangential angle of the protrusion interface gives more improvement. In other words, the tangential angle of the protrusion interface is more dominant for light leakage than the oblique incidence. Figure 7(*c*) shows the intensity ratio as a function of the matched refractive index of BPLC and protrusion at 70° of tangential angle when the refractive index of ITO is 1.9. As shown in figure 7(*c*), when the matched refractive index of BPLC and protrusion was close to that of ITO, the light leakage was reduced. This indicates that the direction of refraction in the interlayer is another main factor for light leakage. Therefore, the combination of refractive indices of the materials which have oblique interfaces is the most important factor for light leakage. Figure 7(*d*) shows the intensity ratio according to the refractive index of ITO under the mismatched refractive index condition (BPLC = 1.53 and protrusion = 1.6) with 70° of tangential angle. Similar to the result in figure 7(*c*), light leakage decreased when the refractive index of ITO became close to those of BPLC and protrusion. However, the reduction in light leakage seems to be maximized when the refractive indices of BPLC and protrusion were matched. The refractive index of the BPLC can be controlled by the host LC of the BPLC mixture. Furthermore, UV-stable wide nematic range fluoro mixtures of commonly used fluorinated compounds usually have $\Delta n < 0.25$, $n_o \sim 1.51$ depending on the molecular conjugation length [6]. Therefore, refractive index-matched BPLC can be used by controlling the host LC of BPLC.

5. Conclusion

We have investigated the mechanism of light leakage in a cell with protruded electrodes whose surface is not parallel to the substrate. We have performed a numerical simulation combining the geometrical optics and the extended Jones matrix method with supplementary optical measurements. As a result, we found that the light leakage was caused by the change in polarization state due to the asymmetrical amplitude difference between TE and TM fields at a tangential angle of the protruded electrode and refractive index mismatch at an interface between protrusion and BPLC. The light leakage decreases as the tangential angle of protrusion increases and it can also be effectively reduced by the proper combination of refractive indices of BPLC, ITO and protrusion. It is required to match the refractive indices of BPLC and the protrusion to avoid the light leakage by irregular refraction which gives the difference between angles of incidence and observation. Additionally, using the refractive index of ITO close to that of the matched BPLC and the protrusion also possibly reduces the light leakage significantly.

Acknowledgments

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