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Intensifying the density of a horizontal electric field to improve light efficiency in a fringe-field switching liquid crystal display

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Abstract

The transmittance in fringe-field switching liquid crystal (LC) displays, which show a wide viewing angle, is dependent on the position along the electrode position. The reason for this is that the dielectric torque (and hence the twist angle) varies with position. This effect depends on the type of LC: a display using an LC with positive dielectric anisotropy has less transmittance than one with negative dielectric anisotropy. Furthermore, the transmittance decreases with decreasing cell gap. The difference between the LC types can be reduced and the transmittance can be improved greatly even for a low cell gap by optimizing the electrode structure to enhance the region of in-plane twist.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

At present, the image quality of liquid crystal displays (LCDs) has been greatly improved, due to the development of new liquid crystal (LC) modes such as in-plane switching (IPS) [1], fringe-field switching (FFS) [2–5], and multi-domain vertical alignment (MVA) [6, 7]. In particular, in both IPS and FFS modes, the LCs are aligned homogeneously in the initial state and in-plane and fringe electric field rotate the LC, respectively. In the IPS mode, the transmittance of the cell is not dependent on the dielectric anisotropy ($\Delta\varepsilon$) of the LC since the in-plane field drives the LC to rotate [8]. However, in the FFS mode, it depends on the dielectric anisotropy of the LC since the LC can be tilted upwards for a LC with positive $\Delta\varepsilon$ (+LC) along the vertical component of a fringe-electric field while the tilt angle is not much generated for the LC with negative $\Delta\varepsilon$ (−LC) [5, 9, 10]. In the FFS mode, display products using both +LC and −LC have been commercialized, but the recent main products such as tablet PC, monitors and LC-televisions use +LC, because of the low operating voltage and fast response time.

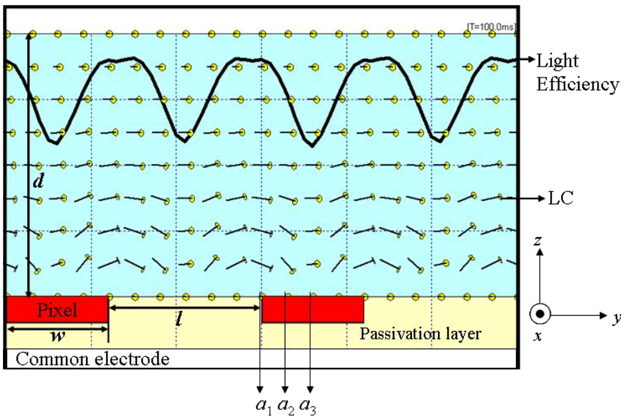

Figure 1. Light efficiency and LC orientation dependent on the electrode position in the white state when $w = 3\,\mu$m, $l = 4.5\,\mu$m.

However, when the +LC is used, the light efficiency of the LC cell is slightly decreased compared with the LC cell with −LC because the transmittance above the centre of the electrode, in which the LC is rotated by elastic torque between neighbouring

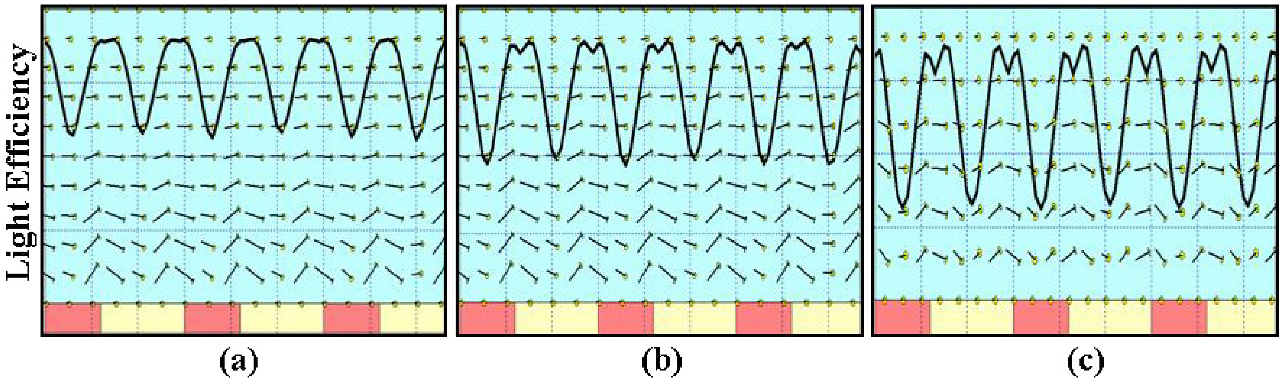

Figure 2. Light efficiency profile dependent on the electrode position in the white state with different cell gaps: (*a*) $d = 4\,\mu$m, (*b*) $d = 3\,\mu$m and (*c*) $d = 2\,\mu$m.

molecules, is lower for the cell with +LC than that of the cell with −LC. Furthermore, light efficiency of the LC cell decreases when the cell gap decreases, since more LCs are affected by strong surface anchoring so that the LC above the centre of electrodes becomes harder to rotate as the cell gap decreases [9, 10]. All the previous works assume that the electrode width is larger than 3 μm, reflecting the present process capability. Nowadays, LCDs with very high resolution are strongly required, particularly for small size displays. Therefore, a fine pitch process is being developed with the minimum line width less than 3 μm.

In this paper, we investigate the electrode structure of the FFS cell to maximize the light efficiency, particularly with +LC by optimizing electrode design. Our study demonstrates that as the pixel electrode width decreases from 3 to 1 μm with an optimized distance between them, the region with horizontal field intensity increases so that the LCs rotate fully above the entire electrode surface, giving rise to transmittance along the electrodes as high as the LC cell with −LC, and also the high transmittance can be achieved even in the cell with a low cell gap such as 2 μm.

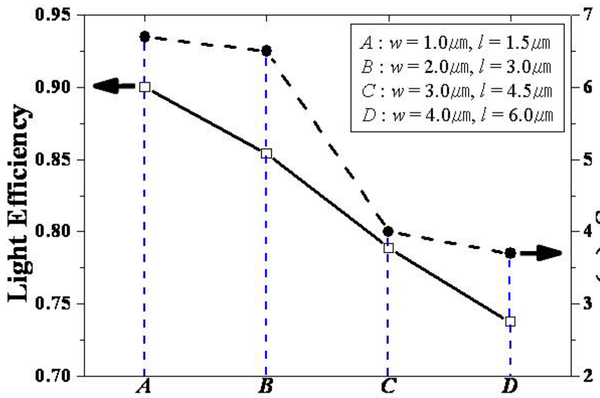

Figure 3. Light efficiency at operating voltages for different electrode conditions.

2. Cell structure and switching principle of the FFS mode

In the FFS mode, the signal and counter electrode exist only on one substrate. The pixel electrode exists in a slit form with the electrode width (w) and distance (l) between them, and the counter electrode exists as a plane with a passivation layer between the pixel and counter electrodes, as shown in figure 1. The nematic LCs are homogeneously aligned with the optic axis coincident with one of the crossed polarizer axes so that the normalized transmittance (light efficiency) is given as follows:

$$T/T_o = \sin^2 2\psi(V)\sin^2(\pi d \Delta n_{\mathrm{eff}}(V)/\lambda),$$

where ψ is the angle between one of the transmission axes of the crossed polarizers and the LC director, d is the cell gap, Δn_{eff} is the voltage-dependent effective birefringence of the LC medium and λ is the wavelength of the incident light. From the equation, one can understand that ψ is a voltage-dependent value, that is, with no bias voltage (off state), ψ is zero and the cell exhibits a dark state. With bias voltage (on state), ψ starts to deviate from the polarizer axis, giving rise to light transmittance. In addition, in this device, effective $d\Delta n$ is also dependent on the applied voltage, affecting the transmittance.

In the conventional LC mode such as twisted nematic (TN), a uniform vertical electric field causes the LC to be deformed, giving rise to transmittance independent of electrode position. However, in the FFS device, a fringe-electric field dependent on the horizontal and vertical positions is generated such that the dielectric torque on the LC is electrode-position dependent, and thus the LC orientation periodically changes along the electrodes, resulting in oscillating transmittance, as shown in figure 1. As clearly indicated, the transmittance is highest at the edge of the pixel electrode (a_1) and lowest at the centre of the electrode (a_3), which results from high and low twisted angles at each electrode position, as described in previous work [9]. The major reason for the low twist angle at the centre of the electrode is the high tilt angle between the centre and edge of the electrode (a_2) since the +LC orients parallel to the electric field associated with the vertical and horizontal component. Another interesting feature of the FFS device is that light modulation occurs using polarization rotation and phase retardation effects at a_1 and a_3, respectively.

3. Simulation conditions for the FFS mode

To investigate the transmittance with the pixel electrode width of the device, we performed a simulation using

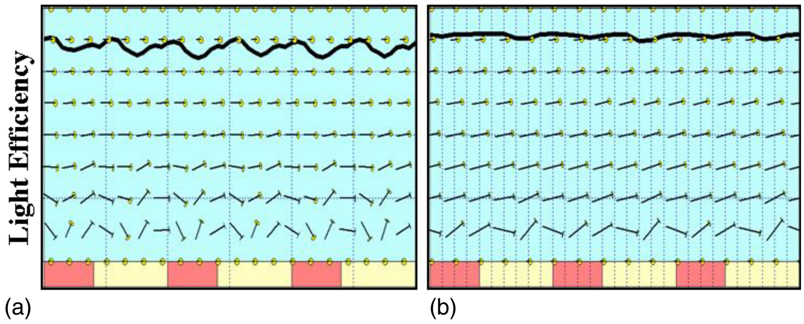

Figure 4. Light efficiency and the LC director orientation dependent on the electrode position in the white state when (*a*) $w = 2.0\,\mu$m, $l = 3.0\,\mu$m and (*b*) $w = 1.0\,\mu$m, $l = 1.5\,\mu$m for $d = 4\,\mu$m.

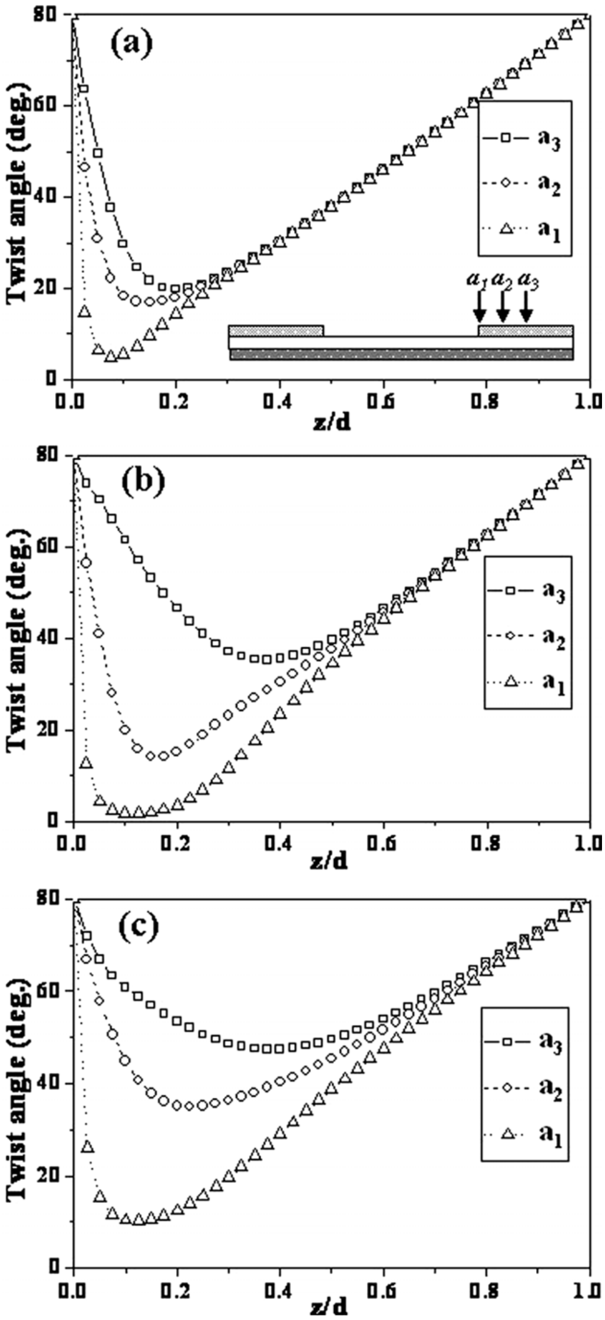

Figure 5. Director profile of twist angle along a cell gap at three different electrode positions: (*a*) $w = 1.0\,\mu$m, $l = 1.5\,\mu$m, (*b*) $w = 2.0\,\mu$m, $l = 3.0\,\mu$m and (*c*) $w = 3.0\,\mu$m, $l = 4.5\,\mu$m.

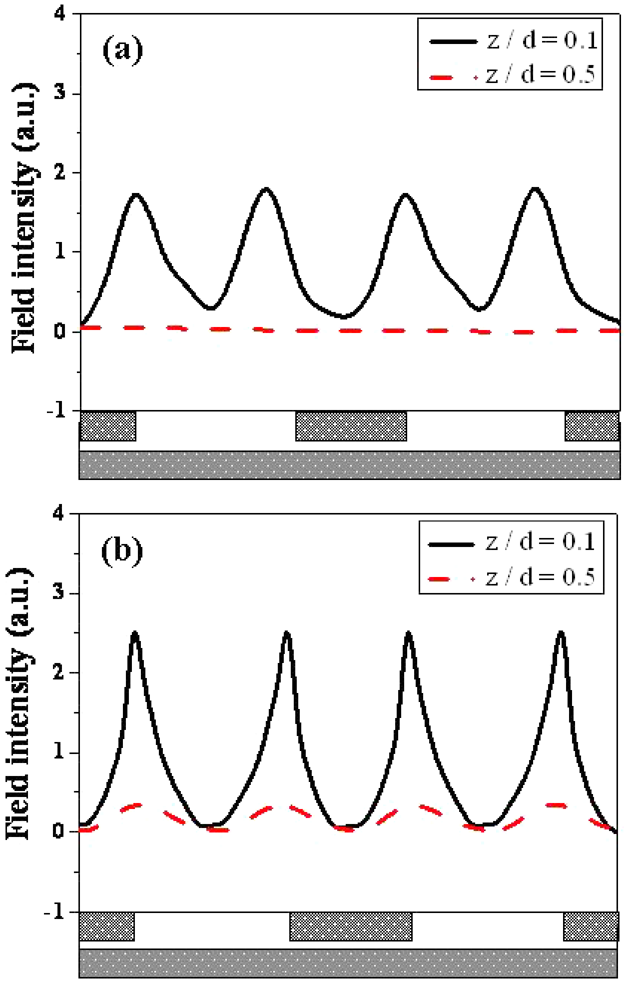

Figure 6. Field distribution of the horizontal field intensity along the horizontal axis at $z/d = 0.1$ and 0.5; (*a*) $w = 1\,\mu$m, $l = 1.5\,\mu$m and (*b*) $w = 3.0\,\mu$m, $l = 4.5\,\mu$m.

the commercially available software 'LCD Master' (Shintech, Japan) where the motion of the LC director is calculated based on the Eriksen–Leslie theory and the 2×2 extended Jones matrix is applied for optical transmittance calculation [11]. Here, the LC with physical properties (dielectric anisotropy $\Delta\varepsilon = +8.2$, $K_1 = 9.7$ pN, $K_2 = 5.2$ pN, $K_3 = 13.3$ pN) is used and birefringence of the LC is tuned to yield a cell retardation value of $0.4\,\mu$m under each condition. Strong anchoring at both

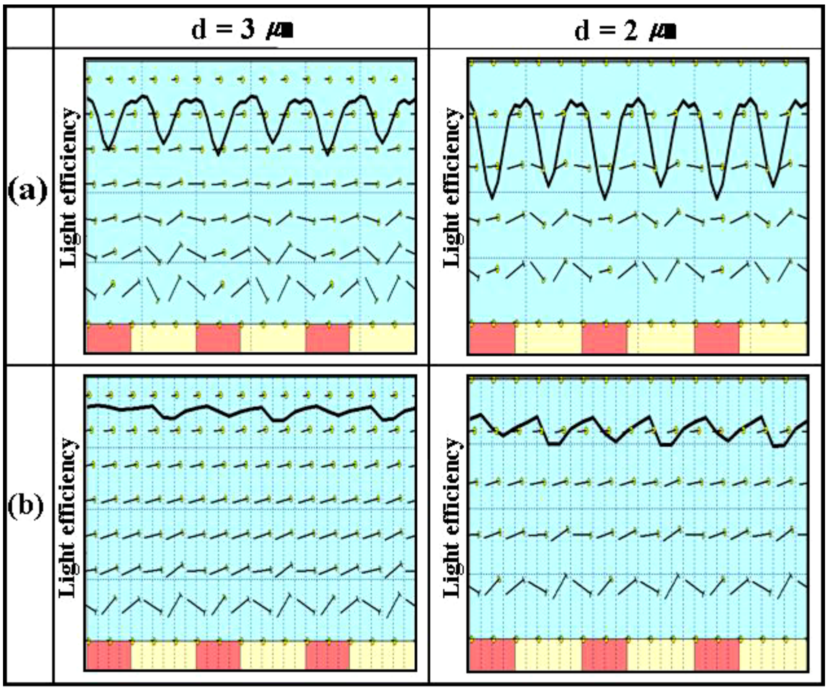

Figure 7. Light efficiency along the electrode position in the white state with different pixel electrode widths at two different cell gaps: (*a*) $w = 2.0\,\mu$m, $l = 3.0\,\mu$m and (*b*) $w = 1\,\mu$m, $l = 1.5\,\mu$m.

substrates with anchoring energy much larger than 10^{-3} J m^{-2} is assumed such that the LCs do not rotate at the interface. The surface pretilt angle for both substrates is 2°, and the initial rubbing direction is 80° with respect to the horizontal component (E_y) of the fringe electric field. The calculated LC orientation in this paper is achieved after a relaxation time of 100 ms.

4. Electro-optic characteristics of the FFS cell depending on cell structure

In the electrode structure with $w = 3\,\mu$m and $l = 4.5\,\mu$m, the transmittance was investigated when decreasing the cell gap from 4 to 2 μm. The light efficiency decreases with decreasing cell gap and, in particular, decreases more rapidly at the centre of electrodes, since more LCs are affected by strong surface anchoring that holds the LC at the initial state as the cell gap decreases, as shown in figure 2. In fact, only the vertical field E_z exists in this region so that no dielectric torque exists; instead, the LCs are rotated by elastic torque [9].

The only solution to the problem of a decrease in transmittance at the centre of the electrodes and the low cell-gap cell is to increase the region containing the horizontal field component so that the dielectric torque to rotate the LCs is enhanced. In other words, minimization of the region where the LC director is rotated only by the elastic torque is required. In this way, the LC will rotate fully above the entire electrode surface. To achieve this, we have reduced the pixel electrode width from 3 to 1 μm while maintaining the ratio of l/w at 1.5 and calculated the transmittance.

Figure 3 shows the light efficiency and operating voltage (V_{op}) for three different electrode conditions when the cell gap is 4 μm. Here, the light efficiency indicates the average value in the distance from the pixel to the counter electrode. When $w = 3\,\mu$m, $l = 4.5\,\mu$m, the light efficiency is 0.79 and the V_{op} is 4 V; however, as w and l decrease to 2 and 3 μm, the light efficiency increases to 0.85 and the V_{op} also increases to 6.5 V. Further, when $w = 1\,\mu$m and $l = 1.5\,\mu$m, the light efficiency reaches 0.9, which is about the same value as that using the −LC but V_{op} increases to 6.7 V. For comparison, we also calculated the light efficiency and V_{op} at $w = 4\,\mu$m and $l = 6\,\mu$m and the results show a decrease in light efficiency, confirming that it decreases with increasing electrode width. At the moment, the present process for mass production of thin-film transistors (TFT) cannot allow such a fine pattern to be less than 3 μm; however, we believe that an ultra-fine pattern process could be employed to achieve a high resolution display in the near future since a 1 μm pattern is already performed in high temperature poly-Si TFT. High V_{op} less than 7 V is not an issue at all, and, further, the dielectric anisotropy of the +LC can be easily controlled.

Now, we demonstrate how the reduction of the pixel electrode width improves the transmittance of the FFS mode when using the +LC. Figure 4 shows the transmittance and LC director orientation in the white state when the electrode width is 2 and 1 μm. One clear difference compared with the cell with $w = 3\,\mu$m and $l = 4.5\,\mu$m is that the transmittance difference between the edge (a_1) and the centre (a_3) of the electrodes reduces and becomes negligible when $w = 1\,\mu$m and $l = 1.5\,\mu$m.

To determine the origin of such a behaviour, we calculated the twisted angle at three electrode positions, as indicated in figure 5. When $w = 3\,\mu$m, the maximal twisted angle from the initial position is strongly dependent on the electrode position such that it is about 70° near the bottom substrate at the edge of the electrode and about 30° around the middle of the cell at the centre of the electrode. However, as w is

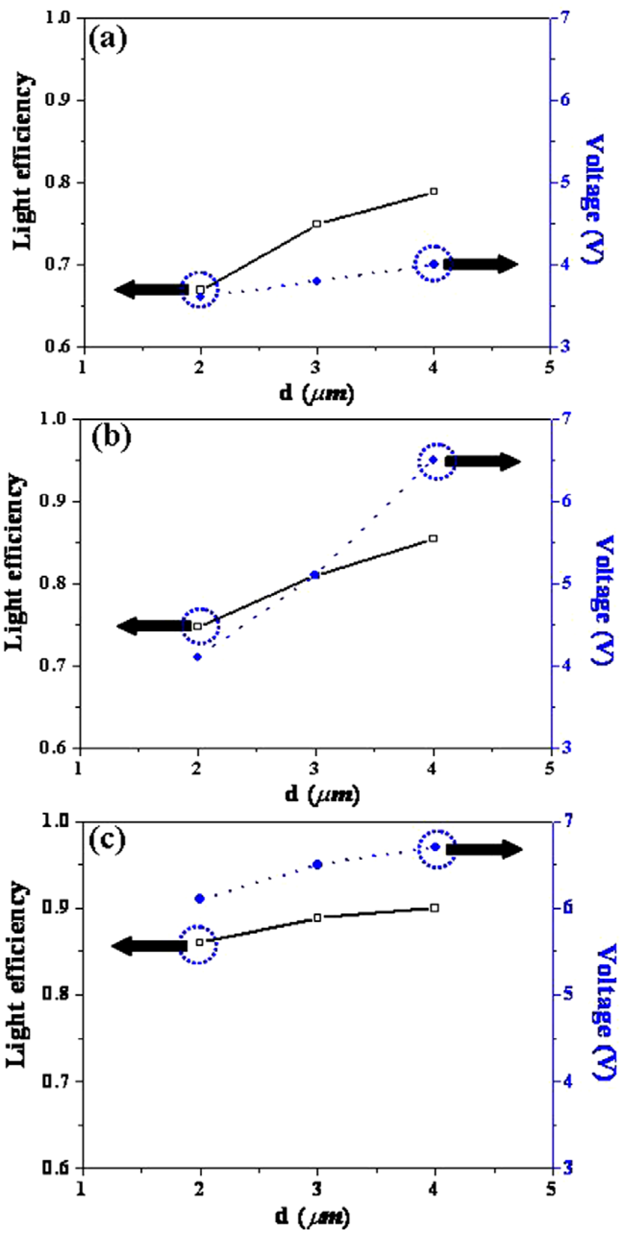

Figure 8. Light efficiency and V_{op} as a function of cell gap for three different electrode conditions: (*a*) $w = 3.0\,\mu$m, $l = 4.5\,\mu$m, (*b*) $w = 2\,\mu$m, $l = 3.0\,\mu$m and (*c*) $w = 1\,\mu$m, $l = 1.5\,\mu$m.

smaller than 3 μm, the difference in the twisted angles between the electrode positions is reduced significantly. For example, when $w = 1\,\mu$m, a maximal twisted angle larger than 60° occurs near the bottom substrate below $z/d = 0.2$ at all electrode positions and is larger than those in the cell with $w = 3\,\mu$m and besides the twist angles are about the same above $z/d = 0.2$, irrespective of the positions above the electrode. This indicates that the twisted angle is not electrode-position dependent for the cell with $w = 1\,\mu$m and $l = 1.5\,\mu$m, resulting in linear transmittance along the electrode position, as shown in figure 4. Here, the large twisted angle indicates that the LC rotates enough to maximize the light transmittance. Consequently, if we reduce w and l less than 2 μm, the transmittance corresponds to that using the −LC [9].

The origin of the increase in the V_{op} when decreasing the electrode width is investigated. The horizontal electric field is calculated along the electrodes at two vertical positions when 5 V is applied. As indicated in figure 6, when $w = 1\,\mu$m and $l = 1.5\,\mu$m, a strong horizontal electric field intensity exists near the bottom substrate ($z/d = 0.2$) but it decreases rapidly to almost zero at $z/d = 0.5$, which is different from the cell with $w = 3\,\mu$m and $l = 4.5\,\mu$m in that the E_y still exists even at $z/d = 0.5$. Therefore, for rotating the LC even at the middle of the cell, higher electrical energy is required to deform the LCs in the cell with $w = 1\,\mu$m than in the cell with $w = 3\,\mu$m.

Next, we observe that this electrode design is still effective even in the cells with low cell gaps such as 3 and 2 μm. When $w = 2\,\mu$m and $l = 3\,\mu$m, the difference in light efficiency between the electrode positions a_1 and a_3 still exists and becomes stronger with decreasing cell gap from 3 to 2 μm, as shown in figure 7. However, when $w = 1\,\mu$m and $l = 1.5\,\mu$m, the light efficiency is for the most part constant along the electrodes in the cell with $d = 3\,\mu$m, and even in the cell with $d = 2\,\mu$m, the difference between a_1 and a_3 is much reduced compared with the cell with $w = 2\,\mu$m and $l = 3\,\mu$m.

Figure 8 summarizes the relationship between the light efficiency and V_{op} as a function of cell gap for three different electrode conditions. When $w = 3\,\mu$m and $l = 4.5\,\mu$m, the light efficiency, 0.79 at $d = 4\,\mu$m, decreases to 0.67 at $d = 2\,\mu$m, while maintaining a V_{op} less than 4 V (see figure 8(*a*)). When $w = 2\,\mu$m and $l = 3\,\mu$m, the light efficiency is enhanced to 0.85 and 0.75 at $d = 4\,\mu$m and $d = 2\,\mu$m, respectively, whereas V_{op} is increased to 6.5 and 4.1 V at $d = 4\,\mu$m and $d = 2\,\mu$m, respectively (see figure 8(*b*)). When $w = 1\,\mu$m and $l = 1.5\,\mu$m, the light efficiency is maximized to 0.90 and 0.86 at $d = 4\,\mu$m and $d = 2\,\mu$m, respectively, although V_{op} is increased over 6 V (see figure 8(*c*)). Further, one can note that as the cell gap decreases from 4 to 2 μm, the light efficiency of the cell with $w = 3\,\mu$m decreases by about 15.2%, whereas that with $w = 1\,\mu$m decreases by only 4.4%, indicating that the narrower the electrode width, the more advantageous the light efficiency.

5. Summary

In this study, we determined the most efficient way to improve the light efficiency of the FFS cell with +LC by optimizing the electrode design. Our study shows that as the pixel electrode width decreases from $w = 3$ to $1\,\mu$m with an optimized distance between them, the light efficiency increases to the value of the cell with −LC for a high cell gap of which the light efficiency is almost independent of the electrode position. This is due to the increase in the region with horizontal field intensity. Interestingly, the LC orientation in a white state shows that the LC near the bottom electrode surface is most twisted irrespective of the electrode position, giving rise to linear and high light efficiency along the electrode. Also, in the case of optimized pixel electrode width and distance between them, the transmittance is reduced only slightly, even though the cell gap decreases from 4 to 2 μm.

Acknowledgments

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