Maximizing electro-optic performances in the fringe-field switching liquid crystal mode with negative dielectric anisotropic liquid crystal

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Abstract — The fringe-field switching (FFS) mode that uses liquid crystals (LCs) with negative dielectric anisotropy is used in high-resolution FFS liquid crystal display owing to its higher transmittance over positive LC, although its response time becomes slow and operating voltage (V_{op}) becomes high. In the device, reduction of the cell gap is required to achieve fast response time, which results in increase in V_{op} in general. In this paper, we propose the FFS mode with electrode width 1 μm and distance between the electrodes 1.5 μm. In such an electrode structure, V_{op} decreases with decreasing cell gap to 2 μm so that a proper V_{op}, high LC's light efficiency of 90%, a high color temperature, and a fast response time less than 10 ms, can be achieved, which maximizes electro-optic performance of the FFS mode.

Keywords — *fringe-field switching, fine pattern, transmittance, response time.*

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1 Introduction

Nowadays, the fringe-field switching (FFS) mode[1–13] is being widely used in liquid crystal displays (LCDs) for high performance, owing to its unique characteristics such as wide viewing angle, high transmittance, low operating voltage, and suitability to touch screen display. In the FFS mode, a LC with positive dielectric anisotropy (+LC) has been mainly used for a long time since 2000. Recently, the resolution of LCDs becomes higher and higher reaching over 400 ppi in mobiles, and then, a LC with negative dielectric anisotropy (−LC) showing higher light efficiency than that of +LC becomes attractive for low power consumption LCDs and then commercialized.[14–17]

A −LC has a polar head perpendicular to the long axis of an LC molecule to induce a large perpendicular component of a dielectric constant. As a result, it has a limitation in increasing magnitude of dielectric anisotropy ($\Delta\varepsilon$), and at the same time, the hindrance of rotation in −LC molecule results in a higher rotational viscosity (γ) generally larger than 100 mPa s while γ of +LC is less than that, in general. In addition, LC molecules rotate mainly in plane in the FFS device with −LC, and thus, threshold voltage (V_{th}) is inversely proportional to a cell gap (d) and so does an operating voltage (V_{op}).[8,18] Consequently, the use of −LC in the FFS mode results in relatively higher V_{op} because $V_{op}\sim 1/d\,(K_{22}/\Delta\varepsilon)^{1/2}$ where K_{22} is twist elastic constant of LC and also slower response time than those of the FFS mode with +LC because it is mainly proportional to $\gamma d^2/K_{22}$. Therefore, lowering a d less than 3 μm is required to obtain a faster response time; however, such an approach results in a decrease in a transmittance (LC's light efficiency) as well as an increase in V_{op}.[14]

In this paper, we propose a solution that maximizes transmittance and makes the response time fast in the FFS mode with −LC, while keeping a proper V_{op}. We find that when an electrode is finely patterned such that electrode width is 1 μm and distance between the electrodes is about 1.5 μm, the V_{op} decreases with decreasing d, contradicting a conventional concept of $V_{op}\sim 1/d$, so that electro-optics of the FFS mode with −LC is improved while keeping a proper V_{op}.

2 Switching principle of FFS mode and simulation conditions

In the FFS mode using −LC, the LCs are homogeneously aligned with an optic axis coincident with one of the crossed polarizers so that the cell appears to be black in an absence of an electric field. With bias voltage above Frederick's transition, the normalized transmittance starts to appear, approximately following an equation given in the succeeding text:[7]

$$T/T_0 = A\sin^2\left(2\psi_{eff}\right)\sin^2\left(\pi d\Delta n_{eff}/\lambda\right) + B\left(1-\frac{\sin^2\left(\pi/2\sqrt{1+\left(2d\Delta n_{eff}/\lambda\right)^2}\right)}{1+\left(2d\Delta n_{eff}/\lambda\right)^2}\right) \qquad (1)$$

where ψ_{eff} is an effective voltage-dependent angle between one of the transmittance axes of the crossed polarizers and the LC director, Δn_{eff} is the voltage-dependent effective birefringence of the LC medium, and λ is the wavelength of an incident

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light. The first and the second terms in Eqn. (1) are associated with light modulation of phase retardation and polarization rotation, respectively, and A and B are constants associated with weighting factor of transmittance ratio.

Considering the conventional electrode structure, a common electrode in a plane sheet is located below the slit-shaped pixel electrodes and a passivation layer exists in between the pixel and common electrodes, as shown in Fig. 1. Here, each pixel electrode has a width (w), and it is separated by distance (l). With a bias voltage, a fringe-electric field with both horizontal (E_y) and vertical (E_z) components is generated. In the FFS mode, the intensity of E_y is oscillating periodically such that it is the highest between edges of pixel and common electrode and zero at the center of pixel electrode and the center of inter-pixel electrodes, resulting in different levels of rotating angle of LC director at different electrode positions because of different dielectric torques ($\sim\Delta\varepsilon E_y^2$). The LCs in the region where E_y is zero and only E_z exists above the center of pixel electrodes and in the middle between patterned slit-shaped electrodes are rotated by elastic torques between neighboring molecules such that the smaller the patterned electrode width, the region becomes smaller, resulting in a higher transmittance.

In order to test what we expect, three sets of (w, l) in μm (3, 4.5), (2, 3), and (1, 1.5) have been evaluated, and passivation layer thickness is chosen to be 0.29 μm. The −LC with physical properties ($\Delta\varepsilon = -4.1$, $K_{11} = 14.5$ pN, $K_{22} = 7.25$ pN, $K_{33} = 15.1$ pN, $\gamma = 100$ mPa s) has been used, and the strong anchoring of the LC to the surface has been set as a boundary condition for the simulation. The surface pretilt angle at both surfaces is 1°, and the initial LC director is aligned to 10° with respect to E_y. The birefringence of the LC is tuned to yield a cell retardation value of 0.36 at 550 nm because it gives rise to maximal light efficiency while the d is varied from 4 to 2 μm. To investigate the electro-optic characteristics of the device, we performed a simulation using a "LCD Master" (Shintech, Japan) where the motion of the LC director is calculated based on the Eriksen–Leslie theory[19] and 2 × 2 Jones matrix is applied for an optical transmittance calculation.[20]

3 Results and discussion

Figure 2 shows transmittance profile along electrode positions. In this case, the ratio l/w is kept to be 1.5. As indicated, when $w = 3$ μm, the transmittance above the center of pixel and counter electrodes and also at both edges of pixel electrodes decreases rapidly as the d is reduced from 4 to 2 μm, resulting

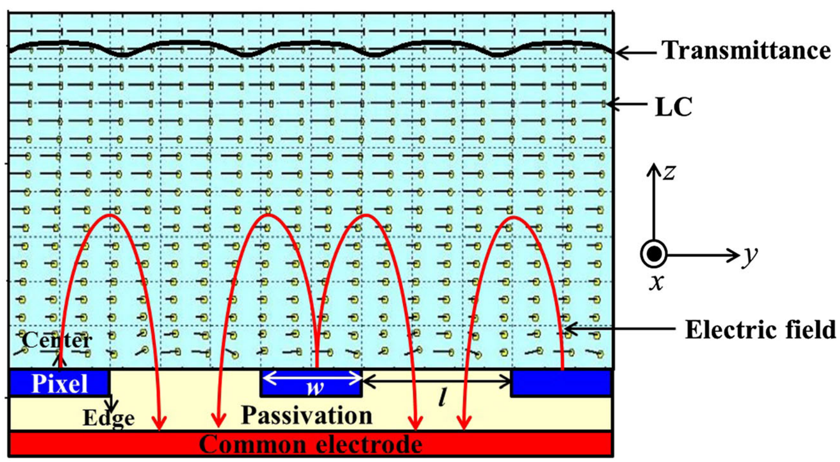

FIGURE 1 — Cross-sectional view of the FFS cell with electrode structures, field direction, transmittance, and LC director profile in the voltage-on state at $w = 1$ μm and $l = 1.5$ μm.

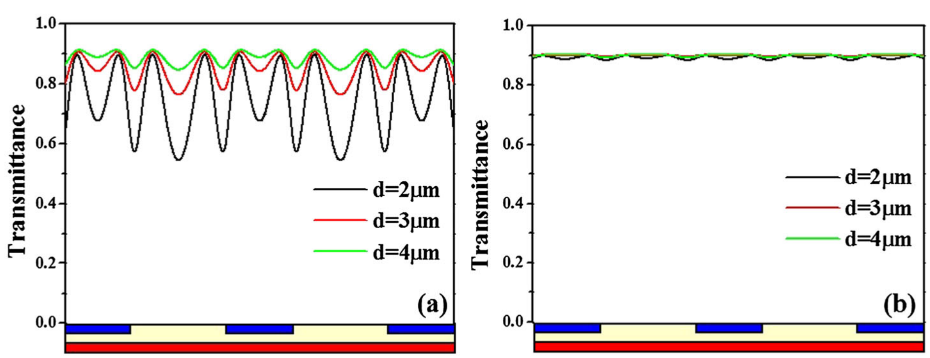

FIGURE 2 — Cell gap-dependent transmittance along electrode positions in the FFS cells: (a) $w = 3$ μm and $l = 4.5$ μm and (b) $w = 1$ μm and $l = 1.5$ μm.

in overall light efficiency of LC of about 0.74 at $d = 2\,\mu m$ (more than 16% drop of transmittance compared with the cell of $d = 4\,\mu m$). Consequently, advantage of high transmittance of the FFS mode with −LC disappears, as shown in Fig. 3. In addition, the V_{op} increases from 4.8 to 5.5 V. However, when the w reduces to 1 μm, the light efficiency of −LC keeps high value of 0.90 (which is almost equal to the value of maximal light efficiency that any LC device can perform) although the d is reduced from 4 to 2 μm. Interestingly, the V_{op} also decreases from 7.0 to 6.5 V when the d decreases from 4 to 2 μm, indicating an abnormal relationship of V_{op}~d, contradicting a conventional concept of V_{op}~$1/d$ (Fig. 2). Nevertheless, V_{th} increases from 1.9 to 2.1 V when the d decreases from 4 to 2 μm (not shown in Fig. 2), following a conventional concept of V_{th}~$1/d$. In general, the reduction of the cell gap requires higher electrical energy to rotate the LC director because more LC is influenced by surface anchoring than LC–LC interaction, resulting in the increase in V_{th}.

The origin of the decrease in the V_{op} when decreasing the d in FFS mode with $w = 1\,\mu m$ and −LC is investigated. In order to understand this, the E_y is calculated along the electrodes at two vertical positions $z/d = 0.1$ and 0.5 when 6.5 V is applied to all cases. We expect that, when $w = 1\,\mu m$, the field intensity is more localized near bottom electrode surface than that with $w = 3\,\mu m$. As indicated in Fig. 4, when d is 4 μm, a strong E_y exists near the bottom substrate ($z/d = 0.1$), but it decreases rapidly to almost zero at $z/d = 0.5$. However, when $d = 2\,\mu m$, the E_y still exists even at $z/d = 0.5$ with intensity of 0.67 V/μm, and also, the intensity 5.6 V/μm of E_y at $z/d = 0.1$ is much stronger than that 2.8 V/μm with $d = 4\,\mu m$. Therefore, the increase of E_y at $z/d = 0.1$ compensates increases in elastic energy of the LC cell with reduction of d, and the existence of E_y at $z/d = 0.5$ in $d = 2\,\mu m$ contributes to rotate the LC director in the middle layer, resulting in lower V_{op} in $d = 2\,\mu m$ than that in $d = 4\,\mu m$.

In the FFS mode,[10] it was reported that the light modulation is mainly dependent on polarization rotation in fine-patterned FFS electrodes with $w = 1\,\mu m$ when using a +LC with $d = 4\,\mu m$. However, when the cell gap becomes very thin like 2 μm, the light modulation may not be associated with polarization rotation only because most of LCs are strongly anchored by both surfaces with homogenous alignment. In order to understand the light modulation in a fine-patterned

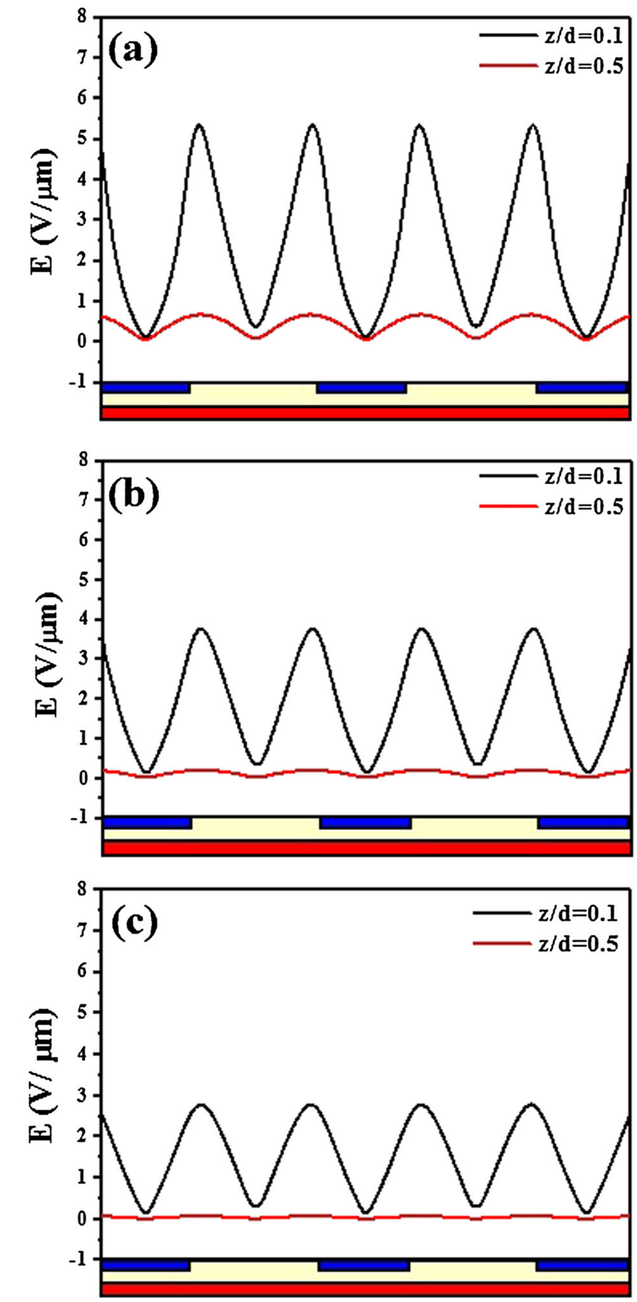

FIGURE 4 — Field distribution of the horizontal field intensity along the horizontal axis at $z/d = 0.1$ and 0.5 when $w = 1.0\,\mu m$ and $l = 1.5\,\mu m$ at different cell gaps: (a) $d = 2\,\mu m$, (b) $d = 3\,\mu m$, and (c) $d = 4\,\mu m$.

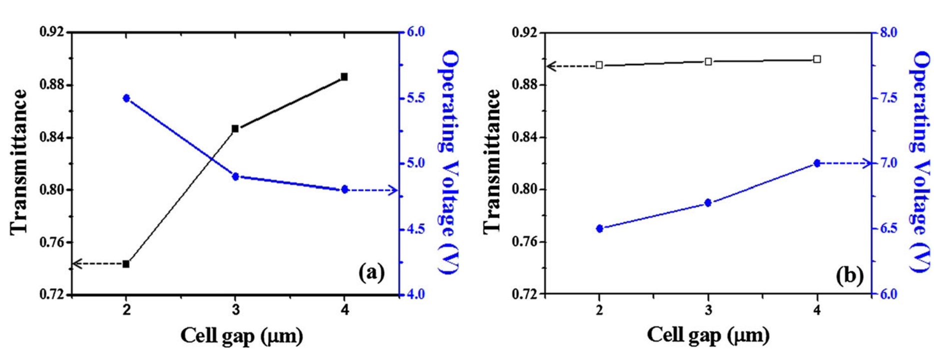

FIGURE 3 — Average transmittance (light efficiency) and operating voltage as a function of cell gaps in the FFS cells: (a) $w = 3.0\,\mu m$ and $l = 4.5\,\mu m$ and (b) $w = 1.0\,\mu m$ and $l = 1.5\,\mu m$.

FFS cell with −LC, twist angles of −LC in the white state are calculated at two electrode positions: center and edge of a pixel electrode, as shown in Fig. 5. When $d = 2\,\mu m$, the maximal twisted angle from the initial position is strongly dependent on electrode position such that it is about 63° at $z/d = 0.2$ for the edge of the electrode and about 51° at $z/d = 0.3$ for the center of the electrode. In addition, the twisted angle from maximum value in both positions is not decreasing linearly as it approaches top substrate. From these director profiles, we can assume that light modulation might be associated with polarization rotation effect at the edge electrode position and phase retardation effect at the center electrode position. When d is $4\,\mu m$, a maximal twisted angle of 67° occurs at $z/d = 0.1$ at the edge electrode position, and it is about 60° at $z/d = 0.2$ even at center electrode position. Unlike those with $d = 2\,\mu m$, the twisted angle reduces linearly from the maximal value to the initial 10° as it approaches top substrate. These larger twist angles and linear change in twisted angles at all electrode positions in the cell with $d = 4\,\mu m$ compared with the cell with $d = 2\,\mu m$ imply that the light modulation in both electrode positions is mainly associated with polarization rotation.

To confirm which effect plays a role in light modulation along d in the proposed device, the transmittance is calculated at 550 nm, and once a maximal transmittance (white state) is achieved, the FFS cell is rotated counterclockwise under the crossed polarizers and the transmittance change at two electrode positions (center and edge) is observed, as shown in Fig. 6. The transmittance changes at both positions of pixel electrodes show a repeating pattern of maximal and minimal transmittance at every 45°. When d is $2\,\mu m$, the minimal

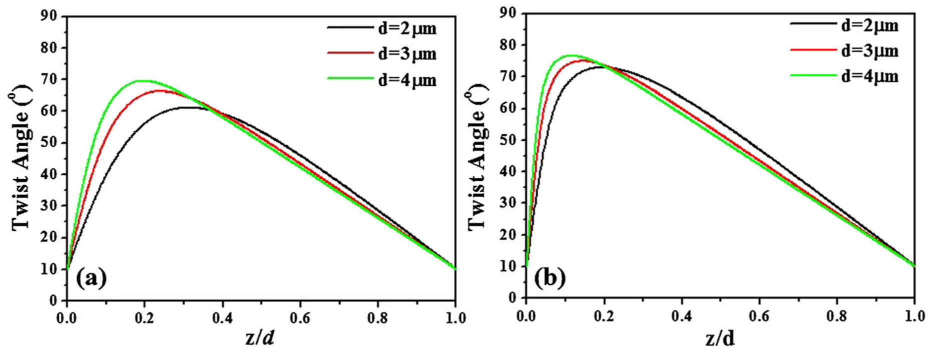

FIGURE 5 — Director profiles of twist angle in the FFS cells as a function of cell gaps at (a) center and (b) edge of electrode positions.

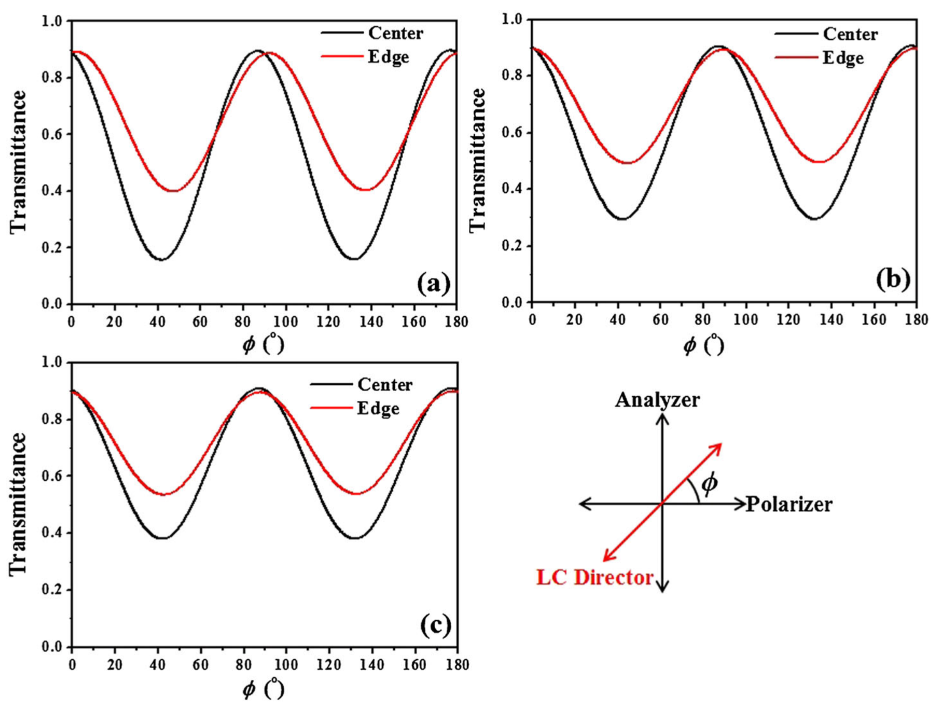

FIGURE 6 — Transmittance change at the center and edge of pixel electrode as a function of the rotation angles of the FFS cell in the white state under the crossed polarizers; (a) $d = 2\,\mu m$, (b) $d = 3\,\mu m$, and (c) $d = 4\,\mu m$. Here, the ratio of l/w is fixed to be 1.5.

transmittance at edge position is much higher than that at center position in which the transmittance is almost extinct. This means that the light modulation at the edge position is close to polarization rotation effect whereas it is closer to phase retardation effect at the center. When d is increased to 3 and 4 μm, the transmittance difference between minimum and maximum in both positions is reduced. Especially, when d is 4 μm, the minimal transmittance still shows about 0.4 such that the extinction condition does not exist. Therefore, we conclude that the light modulations in all positions are close to polarization rotation at high d. However, the average transmittances are almost unaffected by d when using fine-patterned electrode structure because the transmittance is already maximized to 0.90.

The color temperature of LCDs is also an important parameter because it determines color coordinates of a white state. In LC television, a color temperature over 10,000 K (bluish white) is required. Therefore, if LC mode itself shows a high color temperature, it is advantageous.[21] The color temperature of the proposed device with different electrode structures and cell gaps was calculated for 11 gray levels, as shown in Fig. 7. Here, D_{65} is used as a light source. As clearly indicated, the finer the electrode width, the color temperature is slightly higher for all grays. In LC device, a device which modulates a light with polarization rotation yields a less wavelength dispersion of the transmittance than that modulating with phase retardation. In the FFS mode, the optimal retardation which gives rise to maximal transmittance is about 0.36 μm for −LC, which is slightly higher than half-wavelength plate. Therefore, if the light modulation of the FFS cell is operated by phase retardation only, a yellowish white state will be generated, yielding a low color temperature below or close to 6500 K. The finer the patterned electrode width, the light modulation is associated with the polarization rotation, and the results clearly indicate that the FFS cell with finer electrode shows higher color temperature, and especially, the color temperature becomes much higher over 7000 K in all grays when the d increases from 2 to 4 μm, because the light

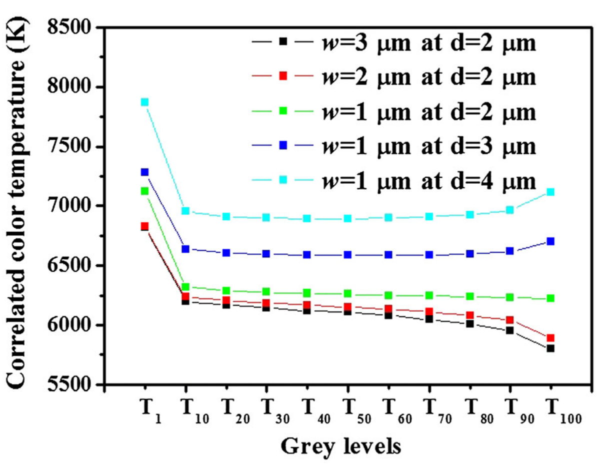

FIGURE 7 — Correlated color temperature in gray levels depending on electrode structures and cell gaps. Here, the ratio of l/w is fixed to be 1.5.

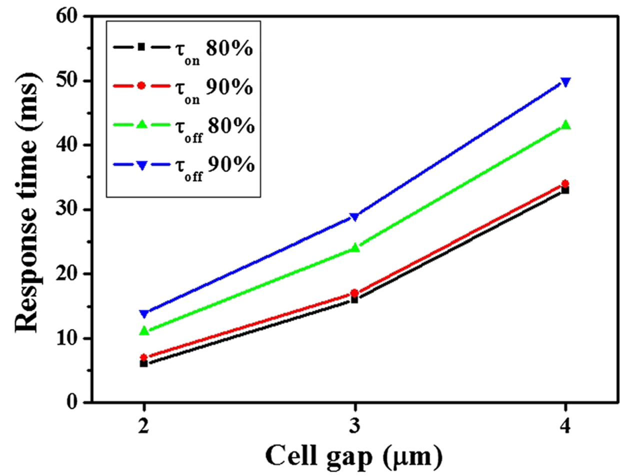

FIGURE 8 — Response times of the FFS cells with −LC as a function of cell gaps when w = 1 μm and l = 1.5 μm.

modulation of the FFS cell with w = 1 μm and d = 4 μm is mainly associated with the polarization rotation.

Figure 8 shows calculated response times as a function of d. Here, the response times for both 80 and 90% transmittance change are considered, and back flow effect associated with reorientation of LC director in tilt angles was not taken into account. In case of 80% variation of the transmittance, when the d is 4 μm, the rising and decaying times are 21 and 30 ms, respectively. However, with low d of 2 μm, the rising time is decreased by about 76%, that is, from 21 to 5 ms and the decaying time is also decreased by about 73%, that is, from 30 to 8 ms, which is associated with an increase in the electric field near the electrode surface for rise time and reduced cell gap effect for decay time when the d is reduced. (Here, back flow effect on operating times was ignored).

4 Summary

We investigated FFS mode using −LC with finer electrode pattern to achieve maximized transmittance. Our study can contribute to development of high-performance and high-resolution FFS LCD with negative LC, having maximized LC's light efficiency of 0.90, a high color temperature, and a very fast either rise or decay response time of less than 10 ms. The work will accelerate necessity of the fine patterning of electrodes in the FFS mode.

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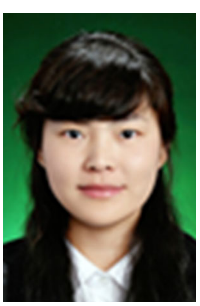

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