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Film Compensation of the Optically Compensated Splay Liquid Crystal Device

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Optically compensated splay (OCS) mode, where the LCs are almost homeotropically aligned with a rubbed parallel at both surfaces, and where a mid-director orients itself parallel to the substrate, is known to show a wide-viewing-angle, due to self-compensation effect. Since a cell retardation value exists in the presence of an electric field, film compensation is necessary to realize a wide-viewing-angle and high contrast ratio. In this paper, we show various electro-optic characteristics, depending on cell configurations with optical compensation films.

Keywords: fast response time; splay; vertical alignment; wide viewing angle

INTRODUCTION

Recently, the liquid crystal display (LCD) was applied to the cellular phone, personal digital assistant (PDA), note-book computer, monitor, and TV. Recently, the LCD has been tested to replace cathode ray tube (CRT). However, in order to replace the CRT, LCDs must achieve the

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following: high image quality, wide viewing angle, high brightness and fast response time. In order to realize these requirements, multi-domain vertical alignment (MVA) [1], in-plane switching (IPS) [2], fringe-field switching (FFS) [3,4], and optically compensated bend (OCB) [4–6] must be introduced. Among these components, the OCB mode exhibits the fastest response time, less than 10 ms, due to the flow acceleration effect; thus this device is one of the strongest candidates for LC television application. However, in order to realize an effective dark state, this device needs some compensation films. We showed that a vertically aligned LC rubbed in parallel directions on both top and bottom substrates can be deformed to produce a configuration in the optically compensated splay (OCS) [7–10] when a high pulse voltage is applied to the cell. This structure exhibits mirror symmetry around the middirector such that an optical self-compensation effect exists, and thus the cell is able to exhibit a wide viewing angle intrinsically. However, in the OCS cell, a certain amount of cell retardation values always appears, irrespective of the applied voltage. Consequently, insertion of compensation film is an absolute requisite in the obtainment of a decent darts state. In this study, we investigate a cell, in which the cell retardation value which is cell gap (d) times birefringence (Δn) changes from $\lambda/2$ to λ according to the voltages, where the device shows a white state at an initial state, and with applied voltage, it shows a dark state.

COMPENSATION PRINCIPLES AND CONFIGURATION OF THE OCS CELL

Figure 1 shows the cell structure of the OCS mode with local director orientation in the off and on states. The rubbing was conducted on the top and bottom substrates in a parallel direction. As indicated by Figure 1, with increasing voltage, the LC with negative dielectric anisotropy tries to orient itself perpendicular to a vertical field direction, that is, the LC tries to orient itself parallel to the substrates. In addition, molecular deformation occurs only in two dimensions (x-z plane). Due to this deformation, the $d\Delta n$ value at the normal direction increases as applied voltage increases.

In order to obtain a complete dark state for a cell with uniaxial medium under crossed polarizers, the optic axis of the LC should coincide with the polarizer axis, or when the LC makes an angle of 45° with respect to the crossed polarizer axis, the phase difference caused by the cell should be 0 or λ. In the OCS cell, the LC behaves as a virtual uniaxial medium in the on state, since most of the LCs are parallel to the substrate. Therefore to can the phase difference

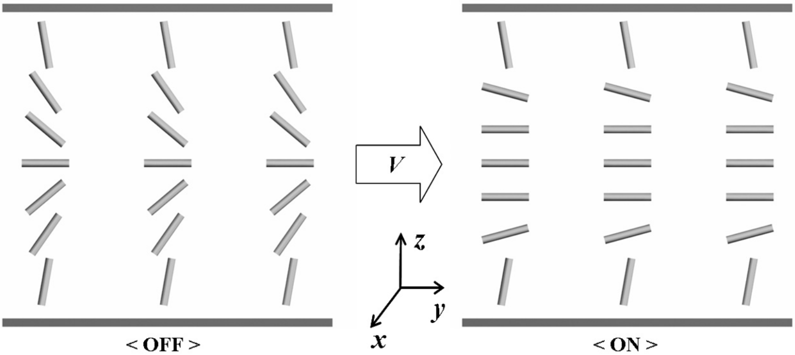


FIGURE 1 Orientation of the LC in the OCS cell depending on the applied voltage.

generated by the LC, a uniaxial compensation film with birefringence in the x-y plane should be added and the slow axis of the film should be oriented at on orthogonal to the LC axis such that their phase retardations are subtracted as follows:

$$\delta = 2\pi\,(d_1\Delta n_1 - d_2\Delta n_2)/\lambda$$

where $d_{1,2}$ and $n_{1,2}$ represent the thickness and birefringence of the LC layer and compensation film, respectively. Here, the $d_2\Delta n_2$ value has an important effect on the dark state voltage, such that the higher $d_2\Delta n_2$, the phase cancellation (i.e. the dark state) would take place at a lower voltage. Therefore, as $d_2\Delta n_2$ decreases, the dark state gradually shifts toward a higher voltage.

One noticeable characteristic is that the effective cell retardation value ($d\Delta n_{\mathrm{eff}}$) is about half that of the real cell $d\Delta n$ at a normal direction since the LC has a hybrid orientation around the mid-director.

SIMULATION RESULTS AND DISCUSSION

We simulated the electro-optic characteristics of the OCS cell for several possible conditions, using the commercially available software LCD Master (Shintech, Japan). Under these observations, the LC has physical properties, such as $\Delta\varepsilon = -4.0$, $\Delta n = 0.11$, $K_{11} = 13.5\,\mathrm{pN}$, $K_{22} = 6.5\,\mathrm{pN}$, $K_{33} = 15.1\,\mathrm{pN}$, and the surface pretilt angle is 88°. Optical transmittance was calculated based on the 2×2 extended Johns matrix method. Transmittance of the two parallel polarizers was assumed to be 0.35. Here, the LC slow axis makes a 45° to the crossed polarizer axes.

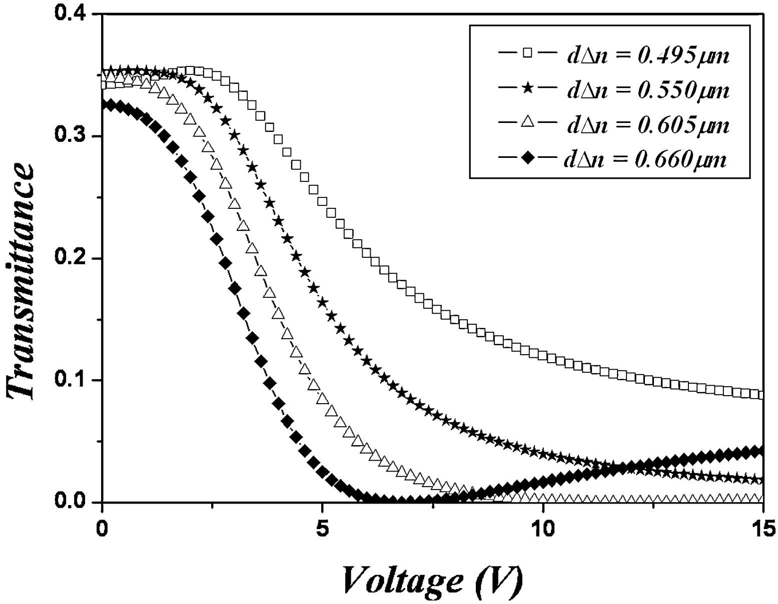


FIGURE 2 Voltage-dependent transmittance curves in the NW OCS cell as a function of the retardation value.

Initially, we use only the LC to obtain effective voltage-dependent transmittance (V-T) curves, as shown in Figure 2. Here, the cell gap was varied to change its retardation value. As indicated, when the $d\Delta n$ value is 0.55 µm at 550 nm, a decent dark state cannot be achieved, even at 15 V, since the cell could not generate a phase difference of λ due to some vertically aligned LCs near both surfaces. In other words, the cell phase must have a change from $\sim\lambda/2$ to λ to obtain the white and dark state such that it should be larger than 0.55 µm to obtain a dark state. Therefore, to realize a good dark state at a relatively low driving voltage, the $d\Delta n$ of a LC cell should be larger than 0.55 µm at least to generate a phase change of 2π. As indicated in Figure 2, when the $d\Delta n$ is 0.66 µm, a decent dark state is observed at 6.8 V. In this case, the device exhibits an excellent luminance uniformity in the white state, however problems such as wavelength dispersion, and light leakage in the dark state in oblique directions exist, which cause a poor dark state. Therefore, in order to improve this, the use of compensation films such as uniaxial or discotic is inevitable with slight loss of light transmittance.

Figure 3 shows simulation conditions in the OCS mode where the transmittance occurs at the initial state, called normally white (NW)

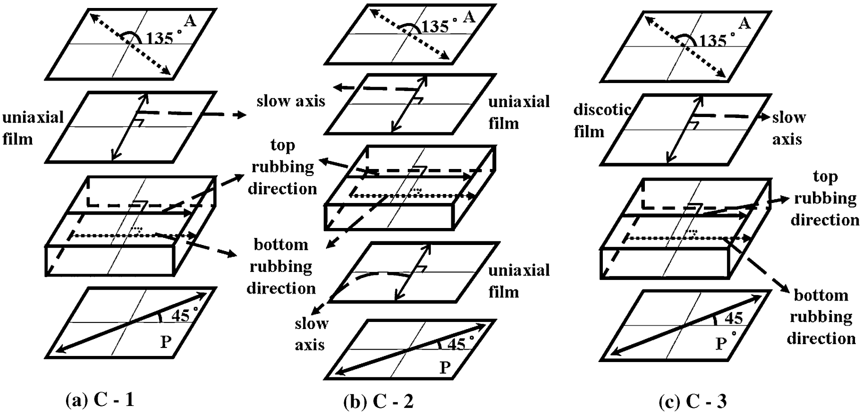


FIGURE 3 Cell configuration of the NW OCS: (a) using a positive uniaxial film, (b) using two positive uniaxial films, and (c) using a negative uniaxial discotic film.

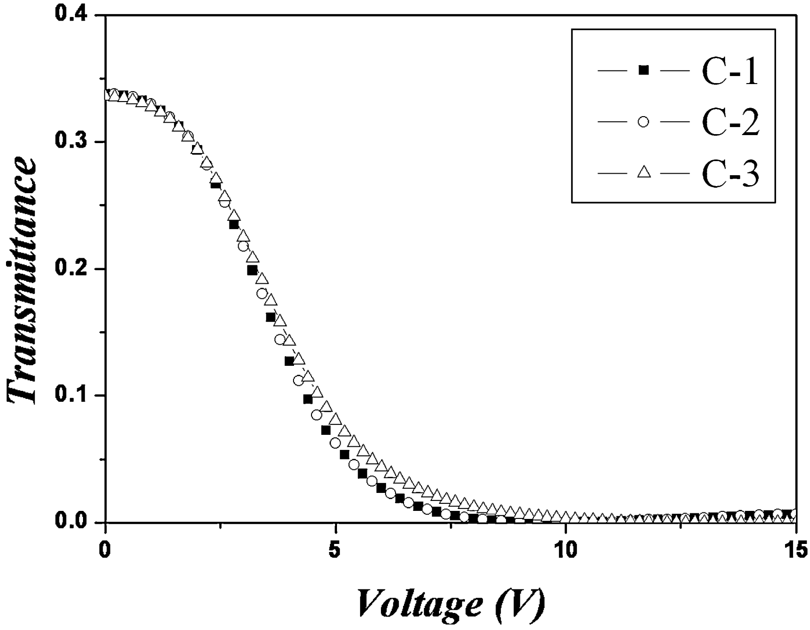


FIGURE 4 Calculated voltage dependent transmittance curves for film compensated NW OCS cells.

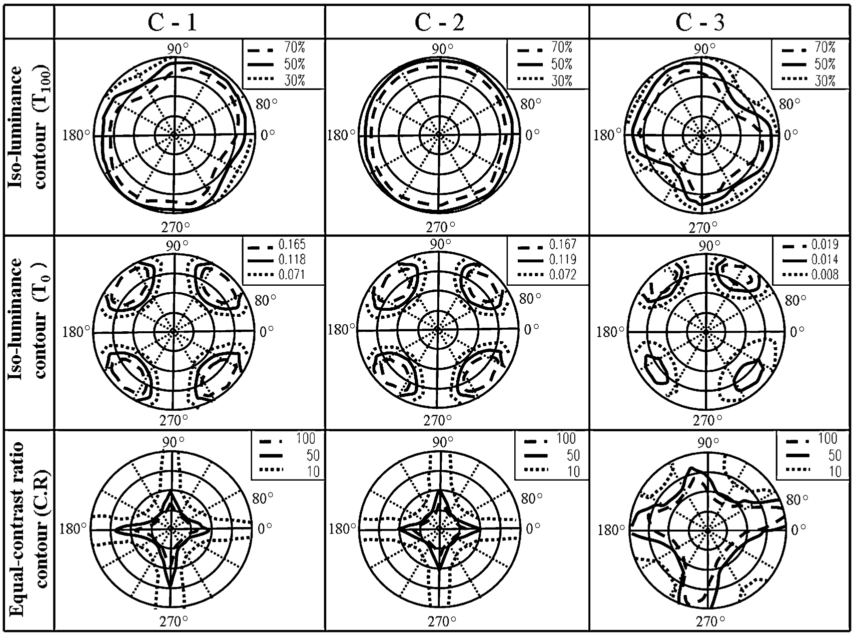
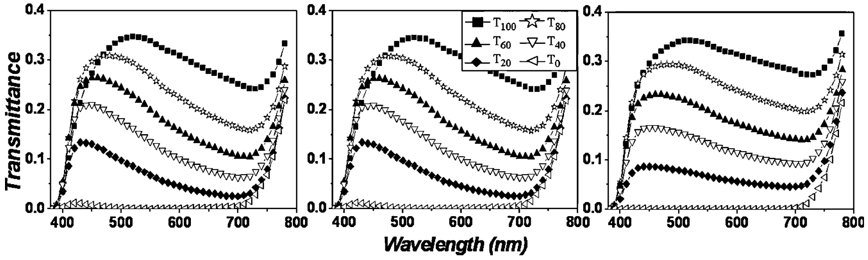


FIGURE 5 Iso-luminance contours and iso-contrast ratio contours.

cell. Here, all OCS cells were assumed to have $d\Delta n = 0.605\,\mu\text{m}$. To achieve optimal cell conditions, uniaxial and discotic films were used. In the first case, one uniaxial film was added to the top substrate (C-1) with a slow axis orthogonal to the LC axis. In the second case, two uniaxial films were used whose axes are parallel to each other (C-2). In the third case, a discotic film (C-3) was used, whose axis is 90° to the rubbing direction. First, we tried to evaluate the optimal retardation value for the uniaxial film, and acquired a value of 0.537 μm with a film thickness of 122 μm. For the discotic film, it was 0.506 μm.

Figure 4 shows the calculated voltage dependent transmittance curves for each of the three cases. In the case of C-1, the maximum transmittance was 0.338, which shows high light efficiency. In case of C-2, the optimal retardation value of each film was 0.269 μm, and the maximum transmittance was 0.337. In the case of C-3, it was 0.336. All three cases show high light efficiency but the driving voltage is relatively high, which is larger than 8 V. To lower the driving voltage, the film retardation value should be higher than the described values and in such a case, the transmittance will decrease somewhat.

Figure 5 shows the iso-luminance and equal contrast ratio (CR) curves for each of the three cases, where the transmittance was



(a) C-1 (b) C-2 (c) C-3

FIGURE 6 Wavelength-dispersion in 6 gray levels for cells (a) C-1, (b) C-2, and (c) C-3.

calculated using all visible wavelengths. For the white state (T_{100}), the C-2 cell shows best performance, in which the region with the relative transmittance 30% covers up to 80° of polar angle in all directions. Nonetheless, the other two cells still show effective iso-luminance uniformity due to a self-compensation structure, although the device has a single domain. For the dark state (T_0), the C-3 cell shows the least light leakage at off-normal directions. For all cells, the leakage does not occur along the polarizer axis, but rather in four diagonal directions. A relatively strong light leakage occurs and in particular, the C-1 and C-2 cells show more light leakage than the C-3 cell. The light leakage at the darks state will decrease the CR value. Consequently, the calculated results show that the C-3 cell has the widest region with the CR of 10, such that it exists at 60° of polar angle in all directions.

Figure 6 shows the calculated wavelength dispersion of the film compensated NW OCS cells in 6-grey levels. For the C-1 and C-2 cells, the light leakage in the dark state occurs at low wavelength, and all the gray states exhibit a strong bluish color. However, for the C-3 cell, a good dark state is observed at all wavelengths, and the bluish color in all gray state is reduced.

CONCLUSION

In this study, we performed a film compensation of the normally white OCS cell to obtain the perfect dark and effective white state. When using positive uniaxial films, a strong light leakage occurs in four diagonal directions whereas it is greatly reduced when using a negative uniaxial discotic film. The OCS cell with the discotic film shows a beneficial wide viewing angle such that the region in which the CR is larger than 10 exists over 60° of polar angle in all directions. Furthermore, the cell exhibits beneficial wavelength dispersion in all gray levels.

REFERENCES

[1] Tanaka, Y., Taniguchi, Y., Sasaki, T., Takeda, A., Koike, Y., & Ohmura, K. (1999). *SID ’99 Digest*, *206*.

[2] Ohta, M., Oh-e, M., & Kondo, K. (1995). *Asia Display’95*, *707*.

[3] Lee, S. H., Lee, S. L., & Kim, H. Y. (1998). *Appl. Phys. Lett.*, *73*, 2881.

[4] Lee, S. H., Lee, S. M., Kim, H. Y., Kim, J. M., Hong, S. H., Jeong, Y. H., Park, C. H., Choi, Y. J., Lee, J. Y., Koh, J. W., & Park, H. S. (2001). *SID ’01 Digest*, *484*.

[5] Bos, P. J., Johnson, P. A., & Koehler/Beran, R. (1983). *SID ’83 Digest paper*, *30*.

[6] Lee, S. H., Hong, S. H., Noh, J. D., Kim, H. Y., & Seo, D.-S. (2001). *Jpn. J. Appl. Phys.*, *40*, L389.

[7] Kim, S. J., Jung, S. H., Hong, S. H., Shin, S. S., & Lee, S. H. (2002). Proc. of the 18th of korean society for imaging science and technology, 99.

[8] Kim, S. J., Shin, S. S., Kim, H. Y., Hong, S. H., Lim, Y. J., & Lee, S. H. (2003). Proc. of IMID ’03, 512.

[9] Kim, S. J., Kim, H. Y., Hong, S. H., Kim, S. Y., Lim, Y. J., & Lee, S. H. (2003). Proc. of IDW ’03, 173.

[10] Lee, S. H., Kim, S. J., & Kim, J. C. (2004). *Appl. Phys. Lett.*, *84*, 1465.