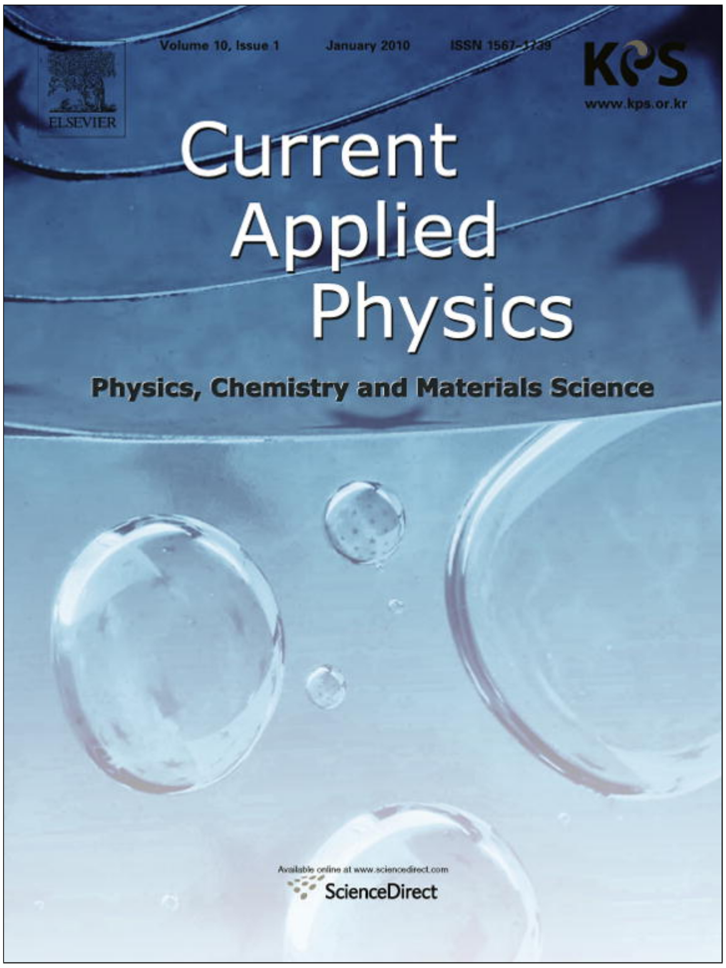
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Electro-optic characteristics as a function of pretilt angle in the optically compensated splay liquid crystal cell

Eun Jeong Jeon [a], Byoung Sun Jung [a], Byeong Gyun Kang [a], Myong-Hoon Lee [a], Jeoung-Yeon Hwang [b], Dae-Shik Seo [b], Seung Hee Lee [a,*]

[a] *Department of Polymer-Nano Science and Technology, Chonbuk National University, Chonju, Chonbuk 561-756, Republic of Korea*
[b] *Department of Electrical and Electronic Engineering, Yonsei University, Shinchon-dong, Seoul, Republic of Korea*

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Optically compensated splay (OCS) mode, where the liquid crystals (LCs) are almost homeotropically aligned with rubbed surfaces at parallel directions and a mid-director orients parallel to the substrate, was known to show a wide-viewing-angle due to self-compensation effect. The device requires a setting voltage and phase transition time in order for LC to have a transition from almost vertical alignment to the splay state. The setting voltage, transition time, and response time of the device as a function of surface pretilt angle were studied. The results indicate that with decreasing surface pretilt angle in the OCS cell, both phase transition time and setting voltage decrease and response time becomes faster.

1. Introduction

Nowadays, the liquid crystal displays (LCDs) are in charge of an important role in human to machine interfaces. The LCDs are greatly applied to various displays ranging from small size mobile phones to large size LC-television (TV). Especially, the LCDs should be satisfied with customer's high requirements such as wide-viewing-angle, fast response, high resolution, low power consumption and high brightness. In order to realize these requirements, several new nematic liquid crystal display modes have been introduced such as film-compensated TN using discotic liquid crystals [1], in-plane switching (IPS) mode [2], fringe field switching (FFS) mode [3–5], vertical aligned (VA) mode [6] and optically compensated bend (OCB) mode [7–8]. Especially, OCB mode has come into the spotlight because of requirements for fast response time and wide-viewing-angle characteristics among various LC modes. This mode shows fast response time less than 10 ms due to flow acceleration effects and relatively wide-viewing-angle characteristics due to help of self-compensation effect. However, in order to realize good dark state, this device needs some compensation films.

Recently, we proposed a new vertically aligned LC mode called optically compensated splay [9–16] where the surfaces are rubbed in parallel directions on both top and bottom substrate initially but transits to splay configuration with mid-director parallel to the substrate with critical voltage condition. This structure exhibits wide-viewing-angle characteristics because of self-compensation effects with mirror symmetry configuration along the mid-director and fast response time due to flow acceleration effects such as OCB mode as well as splay deformation. However, since the LC is almost vertically aligned at the initial state with mid-director perpendicular to the substrate, it requires a high electrical energy with transition time for the LC orientation to transit to the splay state where the mid-director is parallel to the substrate. In addition, the splay state cannot be kept at zero voltage since the elastic free energy of the LC cell in the vertically aligned state is lower than that in the splay aligned state. However, above some voltage (we call this setting voltage V_S), the elastic free energy of the cell in the splay state becomes lower than that of the cell in the vertically aligned state and then the OCS state is kept. In other words, V_S is the minimal voltage which keeps splay state just before transition to vertically aligned state.

In this letter, we describe how the voltage to generate the splay state from initial vertical alignment (called critical voltage V_C), transition time, and V_S can be reduced by changing surface pretilt angle (θ_P) of vertical alignment based on simulation and experiments in the OCS cell. In addition, we also measured response time of the cell as a function of pretilt angle.

* Corresponding author. Tel.: +82 63 70 2343; fax: +82 63 270 2341.
E-mail address: lsh1@chonbuk.ac.kr (S.H. Lee).

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2. Conditions of simulations and experiments

To perform the simulations, the LC with physical properties such as a negative dielectric anisotropy ($\Delta\varepsilon = -4$), elastic constants ($K_{11} = 13.5$ pN, $K_{22} = 6.5$ pN, $K_{33} = 15.1$ pN) and cell retardation ($d\Delta n = 0.55$) at incident light 550 nm, where d is thickness of the cell and Δn is birefringence of LC, were used. The rubbing direction of the cells was in parallel directions on both top and bottom substrate. And the θ_P in the OCS cells was changed into 88°, 60° and 45°. For calculations of electro-optic characteristics of the OCS cells for several possible conditions, we used commercially available software, "LCD Master" (Shintech, Japan), and the 2×2 extended Jones matrix method [17] is applied to perform the optical characteristics. The transmittances for the single and parallel polarizers were assumed to be 41%, and 35%, respectively.

To perform the experiments, the test cells was made having four different θ_P, 88°, 85°, 70° and 48° to prove effects of changing pretilt angle using blended polymers for homogenous and homeotropic alignment [18]. For the cell fabrications, the vertical alignment layer is coated on top and bottom ITO-coated glass substrate with thickness of 700 Å. The rubbing direction of the cells was in parallel directions on both top and bottom substrate. The two substrate were assembled to give a similar cell gap of 4.5 μm in four test cells. And then the LC with negative dielectric anisotropy of −4 and birefringence (Δn) of 0.077 at 589 nm was filled into the cell at room temperature. The test cells made were observed under optical polarizing microscopy by applying a sine wave voltage of 60 Hz.

3. Results and discussion

Fig. 1 shows two possible deformations of the LCs as a function of the applied voltage for a parallel rubbed vertically aligned cell. Before voltage is applied, the cell indicates the LCs are almost vertically aligned on substrates and when voltage is applied above threshold voltage (V_{th}), the first configuration can be made that the LCs tilt downward and twist 180° from top to bottom substrate as shown in Fig. 1a. When a pulse voltage is applied above the V_C, the second configuration can be made that the LCs deform to splay structure with no twisting, where the mid-director lies parallel to substrate and around it. Splay configuration of the LCs has hybrid structure with mirror symmetry from center of the cell when a pulse voltage higher than the V_C is applied. With further increasing voltage above V_S, the L_C tries to orient more parallel to the substrate, as shown in Fig. 1b.

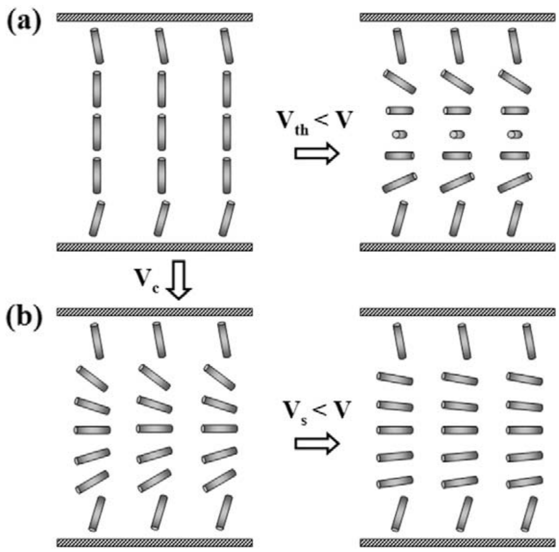

Fig. 1. Two possible deformations of the LCs as a function of the voltage applied for a parallel rubbed vertically aligned cell: (a) from vertical to 180° twist and (b) from vertical to OCS and then to homogeneous one after V_S.

The theoretical values of Gibbs free energy can be obtained by calculating the elastic and electric deformation energy of liquid crystal cell as function of applied voltage [19]. The definition is as follows in terms of the Gibbs energy

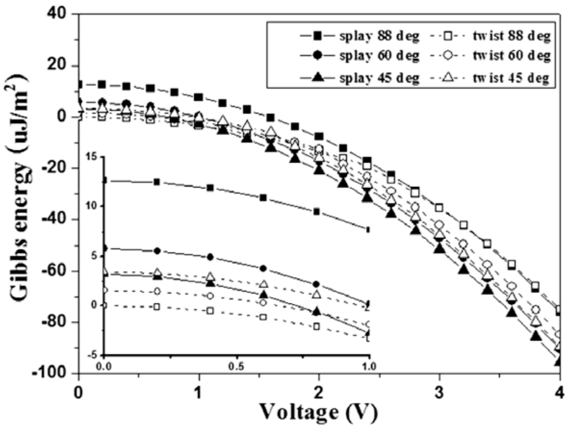

Fig. 2. Calculated voltage dependent Gibbs free energy curve of the splay and twist as a function of the pretilt angle in the OCS cell.

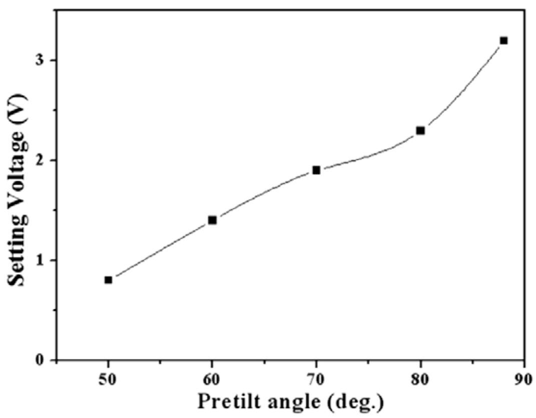

Fig. 3. Calculated setting voltage as a function of the pretilt angle in the OCS cell.

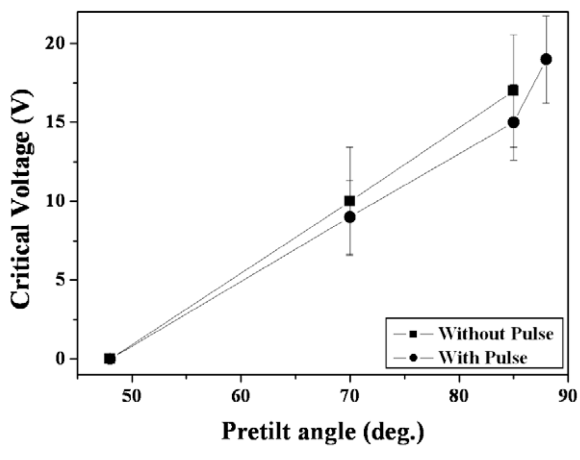

Fig. 4. Measured critical voltage as a function of the pretilt angle in the OCS cell.

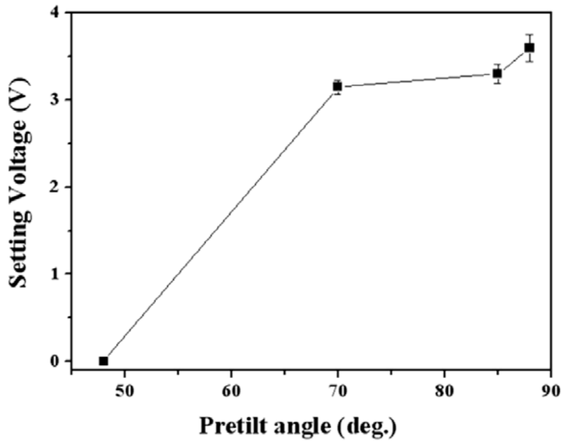

Fig. 5. Measured setting voltage as a function of the pretilt angle in the OCS cell.

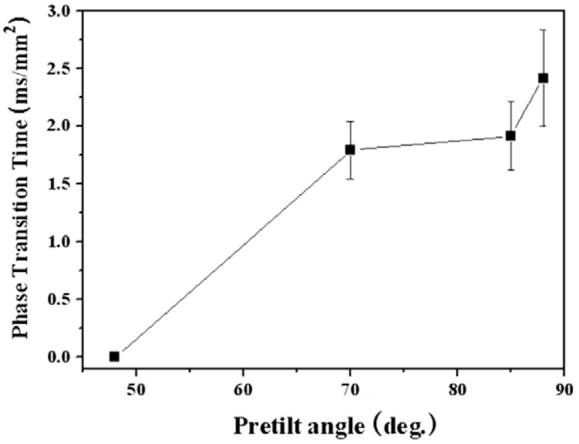

Fig. 6. Phase transition time as a function of the pretilt angle in the OCS cell.

$$Gibbs\ energy = f_{elastic} - f_{electric}$$

and the elastic energy:

$$f_{\mathrm{elastic}} = \frac{1}{2}[K_{11}(\nabla \cdot n)^2 + K_{22}(n \cdot \nabla \times n)^2 + K_{33}(n \times \nabla \times n)^2]$$

where K_{11}, K_{22} and K_{33} are the splay, twist and bend elastic constants, respectively. And the electric energy is given by

$$f_{electric} = \frac{1}{2} E \cdot D$$

This field induced reorientation of the liquid crystal is referred to as the Freedericksz transition [19].

Fig. 2 shows calculated voltage dependent Gibbs free energy curve of the splay and twist as a function of the pretilt angle in the OCS cell. For a cell with $\theta_P = 88°$, the Gibbs free energy appeared that the twist state is more stable than the splay state up to 3.3 V and with further increasing voltage, the Gibbs free energy of the splay state is more stable than twist state as shown in Fig. 2. For a cell with $\theta_P = 60°$, when the voltage is larger than 1.3 V, the splay state shows lower Gibbs free energy than that in the twist state. For a cell with $\theta_P = 45°$, from initial state, the splay state is more stable than the twist state. In the calculation, the defined V_S can be the voltage at which both Gibbs free energy in splay and twist state is the same each other, and the calculated V_S decreases with decreasing θ_P, as shown in Fig. 3.

Fig. 4 shows measured V_C as a function of the pretilt angle in the OCS cell. For the cell with $\theta_P = 88°$, the OCS domain is not generated without applying pulse voltage and even relatively a high pulse voltage 19 V is required to generate the OCS domain. And for the cell with $\theta_P = 85°$, the OCS domain is generated at 17 V even not at pulse voltage and if applying pulse voltage, 15 V generates the OCS domain. When θ_P is 70°, the cell shows a low V_C at both without pulse (10 V) and with pulse (9 V), whose voltage is much lower than the previous cells. However, for the cell with $\theta_P = 48°$, the LC configuration in the initial state can be considered a splay structure with no twisting of the LC. When the cell is rotated 45° (that is, the rubbing axis of the cell makes a 45° angle with the transmission axes of the crossed polarizer), the dark state of the cell appears to be white, and again becomes dark when it is rotated 90°. Also, in order to prove a splay structure in initial state, we tried to understand calculated Gibbs free energy curve of the twist and splay state as a function of a θ_P by computer simulation, as shown in Fig. 2. The result was that the splay state is more stable than the twist state when θ_P of the cell is 45°. This indicates that if θ_P was lower, the OCS state can be obtained at lower VC.

We experimentally confirmed that V_S and phase transition time which is time to change from vertically aligned state to splay state, are reduced with decreasing the θ_P, as shown in Figs. 5 and 6. Nevertheless, the V_S is still larger than 3 V for $\theta_P = 70°$, meaning that to obtain a low driving voltage cell, the θ_P should be lower than 70° and the $\Delta\varepsilon$ of the LC should be larger than −4. Overall, the experimental results are similar to those in simulations, such that those results clearly confirm a tendency that the lower surface tilt angle, the less V_C for the cell to form the OCS orientation is required, which is consistent with θ_P–V_S behavior in calculated results.

Fig. 7 shows measured gray-to-gray response time according to 6-gray levels in the OCS cell. In this case, the LC medium exists under crossed polarizer with its optic axis making 45° with respect to

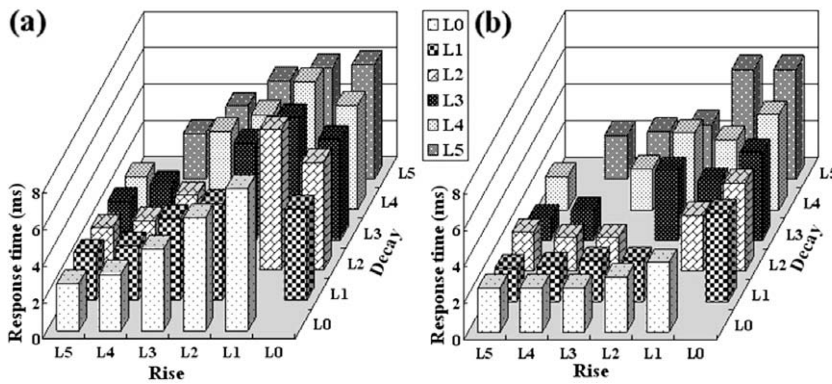

Fig. 7. Measured gray-to-gray response time of according to 6-gray levels in the OCS cell: (a) $\theta_P = 88°$ and (b) $\theta_P = 48°$.

the polarizer axis. Therefore, the transmittance change is proportional to $\sin^2(\delta/2)$, where δ is phase difference. In case of pretilt angle 88°, the response time is under 8 ms at all gray scales, although the viscosity of LC is very large (γ = 171 mPa s). Similarly, the cell with pretilt angle 48° shows faster response time, too. Especially, the cell with low surface tilt angle shows faster rising response time than that with high surface tilt angle, especially at low gray level because the LC reorients with little elastic deformation responding to the field.

4. Conclusions

In this study, we have found that VS and phase transition time can be reduced by decreasing θ_P based on simulations and experiments in the optically compensated splay cell. Besides, the response time becomes more faster with decreasing θ_P. Consequently, these indicate that the more θ_P decreases, the easier OCS state can be obtained at lower V_C and with reduced phase transition time. Furthermore, we have also confirmed that the OCS state can be made initially when θ_P is close to 45°.

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