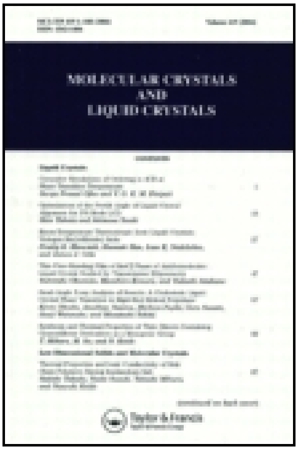

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OPTICAL TRANSMISSION AND POLARIZATION SWITCHING PROPERTIES OF A FERROELECTRIC LIQUID CRYSTAL CELL WITH A STABLE TWISTED STATE

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Optical Transmission and Polarization Switching Properties of a Ferroelectric Liquid Crystal Cell with a Stable Twisted State

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Ferroelectric liquid crystal cells with a stable twisted state were prepared. Dynamic processes of molecular reorientation in a stable twisted state under an applied electric field have been investigated by observing the optical transmittance and polarization switching current with simultaneous observation of the texture change.

Keywords: ferroelectric liquid crystal; twisted states; optical transmittance; polarization switching

1. INTRODUCTION

Ferroelectric liquid crystals have a helicoidal structure in the chiral smectic C (SmC*) state. In a thin cell, the helicoidal structure is suppressed by the boundary surfaces and the surface stabilized states are fabricated. In the surface stabilized ferroelectic liquid crystals (SSFLC) six stable states have been reported: uniform right (UR), uniform left (UL), twisted right (TR1 or TR2) and twisted left (TL1 or TL2).[1,2] The uniform state UL (or UR) has an uniform up (or down) polarization, and the molecules are uniformly tilted from the smectic layer normal to the left (or right) in the top-view. In a slightly thick cell such as 5 μm, a twisted state (TL or TR) is stabilized.[3,4] In TL (or TR) state, the rotational sense of the projection of the director onto the glass surface is left-handed (or right-handed) from the top to the bottom surfaces. The TL and TR states are further distinguished by the sense of rotation of the c-director: one is counter clockwise (TL1 and TR1) and the other is clockwise (TR2 and TL2) from the top to the bottom surfaces.[5,6] Molecular reorientational processes under triangular waves and rectangular pulses have been carried out by many researchers, however, there still remains a little ambiguity in the switching processes in the specimens with stable twisted sates.[2,7]

In this paper dynamic processes of molecular reorientation in specimens with a stable twisted state under an applied electric field have been investigated by observing the optical transmittance and the polarization switching current with simultaneous observation of the texture change.

2. EXPERIMENTAL

The ferroelectric liquid crystal CS-1024 (Chisso Co. Ltd.) undergoes the phase transition sequence: Cr.→SmC*→SmA→N*→Iso. at −12℃, 62.9℃, 82.6℃ and 89.9℃, respectively. The spontaneous polarization is −46.9 nC/cm^2 and tilt angle is 25° at 25 ℃. The helical pitches are 20 μm at 25℃ (SmC*) and 50 μm at 83℃ (N*). The liquid crystal was filled in ITO coated glass cells (EHC) with cell thickness 2 μm, 5 μm, and 10 μm. The glass surfaces were spin coated with polyimide (Hitachi Kasei LH-1400) and got rubbed (anti-parallel). Monodomain samples were prepared by cooling down slowly (about 48 h) from the isotropic phase to the Sm A phase with applying an ac electric field (1 Hz, $\pm$2V/μm).

Molecular reorientational processes of the SSFL cells under triangular waves and rectangular pulses have been investigated by observing the switching current and transmitted light intensities. The current induced by triangular waves was transformed to a voltage by a standard resistance and stored in a digital storage oscilloscope (Kikusui COR-5501), then processed by a personal computer. The transmitted light was detected by a phototransistor and stored in a digital oscilloscope. Triangular waves and rectangular pulses were generated by a function synthesizer (NF Electronic Instrument 1917) and amplified by a power amplifier (NF Electronic Instrument 4005). The experimental setup is shown in Figure 1. The texture changes associated with switching under low frequency triangular waves were observed with an optical microscope (Nikon Labophoto2-POL) equipped with a video system.

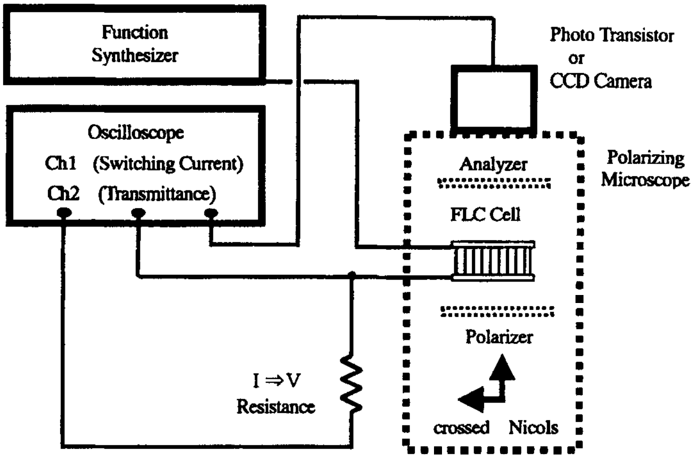

FIGURE 1 Experimental setup for measuring light transmittance and switching current.

3. RESULTS

The texture of the SSFLC cell was examined under crossed Nicols by a polarizing microscope. The texture was almost uniform over the cell and sometimes contained zigzag domains. In the present experiment the specimens with a monodomain state was used. The specimen showed pale pink (or pale purple) and the color alternated when the cell was rotated by the apparent cone angle (2θ). The present SSFL cell did not become dark under crossed Nicols but became almost dark at the position where the angle between the polarizer and analyzer made 2θ (apparent cone angle). This suggests that molecules should be not uniformly oriented; they are tilted to the opposite direction at the upper and bottom surfaces.

In the present specimen the almost dark state was achieved by rotating the analyzer by 40° in clockwise from the crossed position. This indicates that the specimen has the twisted left structure (TL).[5] Though the specimen did not become dark under the zero bias field condition, they became dark by applying $\pm 2V/\mu m$ bias fields under crossed Nicols, where the sign of the voltage was taken positive if the voltage increased from the upper to the bottom surfaces of the cell. The uniform left (UL) and the uniform right (UR) states were produced by application of the positive and negative fields, respectively.

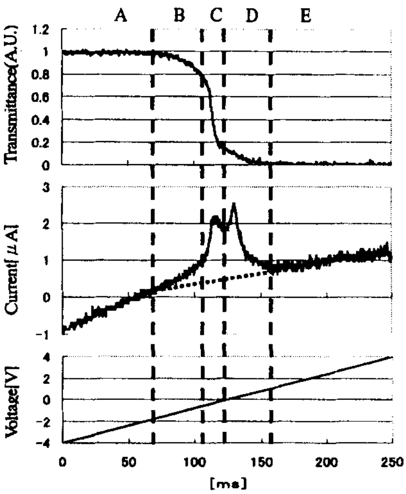

FIGURE 2 Field-induced switching current and light transmittance under the triangular waves (2Hz, ±4V). The A and E represent the states UR and UL, respectively. The B,C and D represent the transition between UR→TL2, TL2→TL1 and TL1→UL, respectively.

The switching current and the transmitted light intensities of the TL cell (2 μm) under triangular waves (2Hz, ±4V) were investigated. Typical traces of field-induced current and light transmittance are shown in Figure2. The polarizer and analyzer were arranged to give a dark position of UL (uniform left). The transmittance was normalized between the dark and the bright states. The current due to the polarization realignment in the present SSFLC cell showed two peaks. On the other hand transmittance of the light showed a sharp bend around zero electric field.

A typical example of the texture change under triangular waves is shown in Figure 3. Typical states from (1) to (9) were observed in the process of the field induced molecular reorientation. Four stable states, UR (1), TL1 (3), TL2 (7) and UL (9), are assigned as shown in Figure 3. Details of the assignment will be discussed in the next section. The texture changed from the state UR to the state UL with varying the applied voltage from –4V to 4V. In the processes from (2) to (3), the spot-shaped domains appeared on the bottom surface. In the processes from (3) to (7) formation of domains were observed. In the processes from (7) to (8) spot-shaped domains were observed on the upper surface. When the applied voltage was removed at the states (1) or (9) the texture relaxes to the stable states (3) or (7).

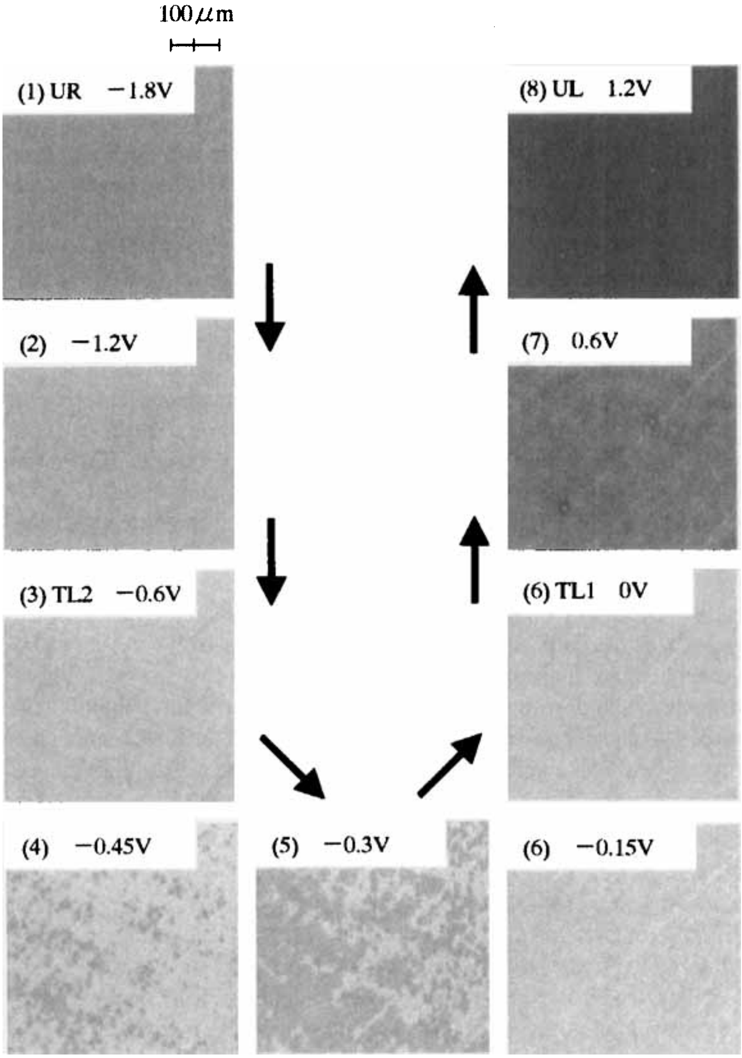

FIGURE 3 Texture-change in the cell (2 μm) with a stable twisted structure under the triangular waves (2Hz, ±4V).

See Color Plate XI at the back of this issue.

The time evolution of optical transmittance and the switching current due to the molecular reorientaion in the TL cell (2 μ m) under the symmetric rectangular pulses (-2V→2V→-2V) and (-1V→1V→-1V) of 0.1 Hz at upward and downward jumps are shown in Figure 4(a) and 4(c) and Figure 4(b) and 4(d), respectively. The polarizer and analyzer were arranged to give a dark position of UL (uniform left). The transmittance was normalized to be zero and one at the dark and bright states, respectively. The start position of the time-scale was chosen at the upward jump of the symmetric square waves. At the upward jump (-2V→2V), the transmittance decreased exponentially with time as shown in Figure4(a). The switching current showed a sharp jump just after application of the voltage and then immediately decreased as shown in Figure 4(c). The sharp jump was assigned to the process of charge accumulation to the cell capacitor.[8] Then the current increased gradually and made a peak around the time where the transmittance started to increase. The slow response was assigned to the process of the polarization realignment. At the downward jump (2V→-2V) the behavior of the transmittance and the switching current as shown in Figure 4(b) and 4(d) are almost the same as those observed in Figure 4(a) and 4(c), though the transmittance increased and the direction of the current was opposite. On the other hand, when the symmetric rectangular pulses with smaller amplitude (-1V→1V→-1V) were applied, the transmittance and switching current varied gradually at both upward and downward jumps as shown in Figures 4(a) and 4(c), and Figures 4(b) and 4(d). According to the observation of the texture under the triangular waves, the voltage ($\pm$1V) is lower than the threshold to induce the uniform states but strong enough to induce TL2→TL1 or TL1→TL2 transformations. The switching current and transmittance due to TL2→ TL1 and TL1→TL2 transitions were observed at the upward and downward jumps, respectively, as shown in Figure 4. The polarizer and analyzer were arranged to give the dark state of UL. The transmittance was normalized to be zero at UL state and one at UR state. In the processes of TL2→TL1 and TL1→TL2 transitions, the scattering of light in the cell was observed without polarizer or analyzer, transmittance varied partly due to the scattering of light in the specimen. The transmittance decreased from 0.8 to 0.2 at upward jump (-1V→1V) and increased from 0.2 to 0.8 at the downward jump (1V→-1V). Small switching current was observed at both upward and downward jumps, respectively.

The time evolution of optical transmittance and the switching current due to the molecular reorientation at the upward and downward jumps of

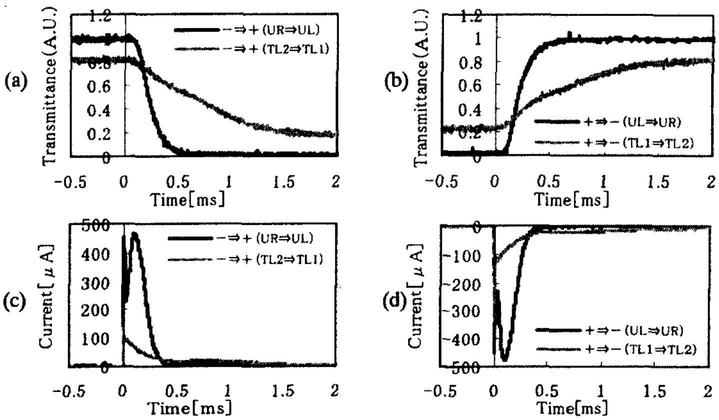

FIGURE 4 Optical transmittance and switching current under the symmetric rectangular pulses (-2V→2V→-2V or -1V→1V→-1V). The responses to the rectangular pulses are represented with dark (-2V→2V→-2V) and light (-1V→1V→-1V) line, respectively. Optical transmittance (a) at the upward (-2V→2V or -1V→1V) jump and (b) at the downward (2V→-2V or 1V→-1V) jump. Switching current (c) at the upward (-2V →2V or -1V→1V) jump and (d) at the downward (2V→-2V or 1V→-1V) jump.

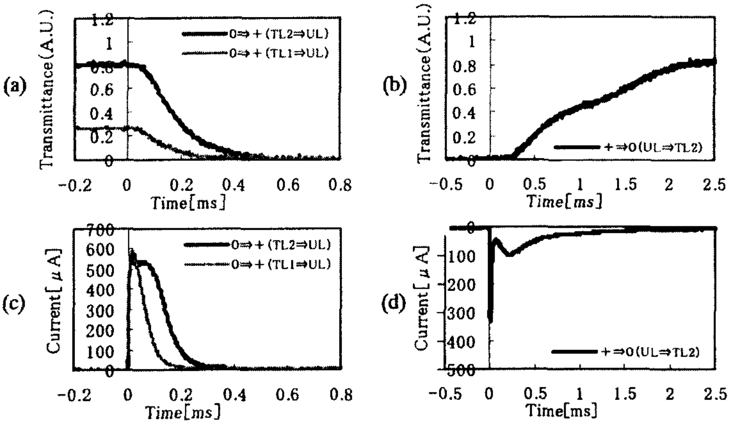

FIGURE 5 Optical transmittance and switching current under the asymmetric pulses (0V→4V→0V) for the specimen with TL1 or TL2 states. The responses for the specimen with TL2 and TL1 states are represented with dark and light lines, respectively. Optical transmittance (a) at the upward (0V→4V) and (b) at the downward (4V→0V) jump. Switching currents (c) at the upward (0V→4V) and (d) at the downward (4V→0V) jump.

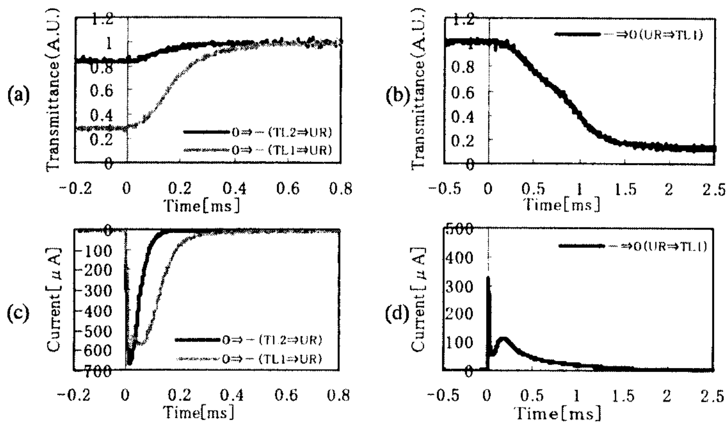

FIGURE 6 Optical transmittance and switching current under the asymmetric pulse (0V →-4V→0V) for the specimen with TL1 or TL2 states. The responses for the specimen with TL2 and TL1 states are represented with dark and light lines, respectively. Optical transmittance (a) at the downward (0V→-4V) jump and (b) at upward (-4V→0V) jump. Switching currents (c) at the downward (0V→-4V) and (d) at the upward (-4V→0V) jump.

the asymmetric rectangular pulses (0V→4V→0V) for the specimen with TL1 and TL2 states are shown Figures 5(a) and 5(c), and Figures 5(b) and 5(d), respectively. The transmittance of the specimen with TL2 state was larger than that of the specimen with TL1 state under zero bias field as shown in Figure 5(a). At the upward jump (0V→4V) the transmittances of both specimens gradually decrease with time. The transitions at the upward jump were assigned to be TL2→UL and TL1→UL, respectively. The switching current for the processes TL2→UL and TL1→UL were not similar as shown in Figure 5(b). The transmittance at the downward jump (4V→0V) exhibited slow two-step responses. The transmittance at the final state was 0.8. The transitions at the downward jump for the specimens with TL1 or TL2 were the same and assigned to be UL→TL2. The switching current showed a small peak around the time where transmittance started to increase as shown in Figure 5(d).

The time evolution of optical transmittance and the switching current at the downward and upward jumps of asymmetric pulses (0V→-4V→0V) for the specimen with TL1 and TL2 states are shown in Figures 6(a) and 6(c), and Figures 6(b) and 6(d), respectively. At the downward jump (0V→

-4V) the transmittance gradually increased with time for both specimen with transmittance 0.2 (TL1) and 0.8 (TL2). The behavior of the switching current was almost the same as that observed in Figure 5(b), except the direction of the current. The transmittance at the upward jump (-4V→0V) exhibited slow two-step response. The transmittance at the final state was around 0.2. The transitions at the upward jump for the specimens with TL1 and TL2 were the same and assigned to be UR→TL1. The switching current showed a small peak around the time where transmittance started to decrease. The behavior of the switching current was almost the same as in Figure 5(d), except the direction of the current.

4. DISSCUSSION

The variation of molecular orientational states under applied triangular waves at low frequencies can be assigned with the help of the observation of the textures under a polarizing microscope, transmittances and switching currents. In the present specimen the almost dark state was achieved by rotating the analyzer by 40° in clockwise sense from the crossed Nicols position. This means that the specimen has the twisted left structure (TL).[3] The uniform right (UR) and uniform left (UL) states are induced by applying -2V and +2V bias fields, respectively.

The nine stable states were observed at the switching process under the triangular waves as shown in Figure 3. The states (1) and (9) are assigned to the field induced uniform right (UR) and uniform left (UL) states, respectively. Because both (1) and (9) states become dark under crossed Nicols and the extinction position between two states is equal to the cone angle. The states (3) and (7) are assigned to TL2 and TL1 states, respectively. Because the states (3) and (7) did not become dark under crossed Nicols but became almost dark by rotating the analyzer by 40° in clockwise, respectively.[2] The two twisted left states (TL1 and TL2) will be equivalent for the applied field without taking into account of the molecular pre-tilt at the surfaces. It is suggested that a selective pre-tilt at the top and bottom surfaces gives the lateral driving force between TL1 and TL2. Taking into account of the pre-tilt angle at the top and bottom surfaces and color change, the state (3) and (7) are assigned to be TL1 and TL2, respectively.[9] Therefore, the molecular reorientational sequence of the liquid crystal cells with the stable twisted state (TL) under triangular waves (-4V→4V) is revealed to be UR→TL2→ TL1→UL. A schematic illustration of the molecular reorientaional processes under application of triangular waves is shown in Figure 7, where a low pre-tilt angles at the top and bottom surfaces are assumed. If the effect of the molecular pre-tilt at the top and bottom surfaces are taken into account, formation of the chevron structure in the specimen will be expected.[10] The contribution of the chevron structure to the polarization switching process will not be essential, thus the chevron structure was not taken into the consideration.

Let us further consider the molecular reorientational processes, the transmittance and switching current induced by triangular waves and rectangular pulses. There are three switching processes under triangular waves: UR→TL2, TL2→TL1 and TL1→UL. According to the texture observation the boundary motions are classified into two kinds. In the processes from (2) to (3), the spot-shape domains appeared on the bottom surface, on the other hand, in the processes from (7) to (8) spot shape domains on the upper surface. These processes are assigned to a reversion of c-director on the top (UL→ TL1) and bottom (TL2→UR) surfaces accompanying a surface disclination motion.[11,12] In the processes from (3) to (7) formation of domains was observed.

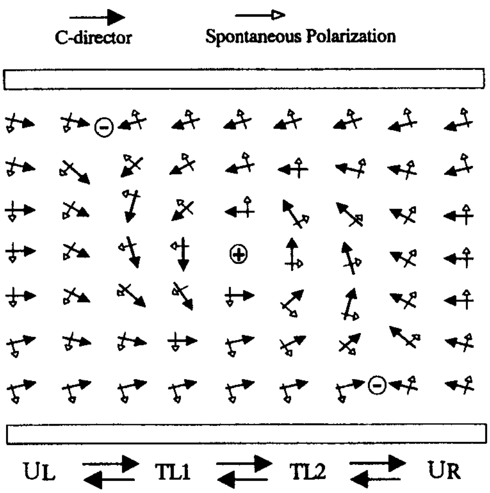

FIGURE 7 A schematic illustration of the molecular reorientational processes under application of triangular waves. Voltage at the upper substrate is kept 0V. The surface disclinations on the upper and the bottom surfaces are represented by (-). The 2π twist disclination between TL1 and TL2 states is represented by (+) in the center.

This process is attributed to an interior $\pm 2\pi$-disclination motion without changing surface molecular orientation (TL2→TL1).[11,12] It has been suggested that proper combination of the cell thickness and surface polar interaction favor the twisted state. In the present FLC, a weak dipolar surface interaction and a choice of cell thickness may favor the twisted state TL.[13]

Under symmetric rectangular pulses, UR→UL or TL1→TL2 processes are induced depending on the strength of the applied voltage as shown in Figures 4 (a), (b), (c) and (d). Under asymmetric rectangular pulses (0V→4V→0V) TL1→UL or TL2→UL transitions are induced at the upward (0V→4V) jump depending on the initial state. The TL1 converted directly to UL, however, TL2 converted to UL state through TL2→TL1 process as can be seen in Figure 5(b). The difference in the molecular reorientational processes between TL2→TL1→UL and TL1→UL is indicated in the switching current as shown in Figure 5(c). The two steps variation of the transmittance at the downward jump clearly showed UL→TL1→T2 processes as shown in Figure 5(b). On the other hand, when the sign of the applied rectangular pulse is reversed, (0V→-4V→0V) TL1→UR or TL2 →UR transitions are induced at the downward (0V→-4V) jump. The two steps variation of the transmittance at upward jump (-4V→0V) as shown in Fig.6(b) is assigned to be UR→Tl2→TL1 transitions. The positive electric field induced the UL state and the UL state relaxed to the TL2 state when the voltage was removed. On the other hand, the negative electric field induced the UR state and the UR state relaxed to the TL1 state when the voltage was removed. The final states are not the same as can be seen in Figure 5(b) and Figure 6(b). This will be elucidated by taking into account of the effect of the depolarization field.[14] In the field induced uniform UR (or UL) state, the spontaneous polarization aligns up (or down) and the surface charge due to the spontaneous polarization is compensated by the charge supplied by the electric source. When the applied electric field is turned off, the surface charge due to the spontaneous polarization no longer compensated and induces the depolarization field which has opposite direction to the spontaneous polarization. The depolarization field drives the spontaneous polarization in the reverse direction. The net polarization (space average of the molecular polarization) of TL1 and TL2 are negative and positive, respectively. The depolarization field drives the UL→TL1→TL2 and UR→TL2→TL1 relaxation processes.

5. CONCLUSIONS

The switching processes of the liquid crystal cell with the twisted state (TL) under triangular waves, symmetric and asymmetric pulses were investigated by observing the light transmittance, switching current and textures.

1) The surface stabilized ferroelectric liquid crystal cell (SSFLC) with stable twisted left (TL) structures were fabricated.

2) The molecular reorientational sequence of the liquid crystal cell with the stable twisted state (TL) under triangular waves (-4V→4V) is revealed to be UR→TL2→TL1→UL→TL1→TL2→UR.

3) There are three switching processes under triangular waves: UR→TL2, TL2→TL1 and TL1→UL. The assignment is consistent with the texture observation.

4) The transition between TL1 and TL2 states occurs continuously. The variation of transmittance in accordance with the state variation will be used as gray scale display.

5) The field induced UL state relaxes to the TL2 state, on the other hand the field induced UR sate relaxes to the TL1 state when the applied fields are turned off. The preferential relaxation phenomena are due to the polarization induced depolarization field.

6) The molecular reorientaionl motion between TL1 and TL2 induces spacial molecular orientatinal disorder in a cell, thus the incident light is scattered. Scattering of the light is observed without polarizer or analyzer.

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