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Chiral-Doped Optically Compensated Bend Nematic Liquid Crystal Cell with Continuous Deformation from Twist to Twisted Bend State

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We have fabricated a nematic liquid crystal (LC) cell associated with the transition of the liquid crystal director from a twist to a twisted bend alignment, where an initial transition voltage is not required unlike in the case of the conventional optically compensated bend (OCB) cell. For the device which is initially in the twist state, the molecular deformation occurs continuously from twist to bend alignment without forming nucleations with increasing voltage and initial setting voltage for transition. The device exhibits a wide viewing angle with compensated films and a fast response time of less than 10 ms.

KEYWORDS: nematic liquid crystal cell, optically compensated bend, chiral dopant

Currently, liquid crystal displays (LCDs) are widely used in notebook computers and monitors. Recently, application of the LCD has extended to the area of television use. However, since the LCDs are nonemitting displays and the liquid crystal itself is viscous liquid, the response time including all grey levels is in the range of 5–100 ms for nematic liquid crystals, which is insufficient for video rate display. The response time mainly depends on the rotational viscosity, the cell gap and the display mode. Among several display modes, the optically compensated bend (OCB) or π cell is known to exhibit a fast response time of less than 10 ms in all grey levels, which is favorable for video rate display, and a wide viewing angle with a compensated film.[1–6)] In the conventional OCB cells, the LC director is in splay alignment in the initial stage and when the voltage is applied to the cell, it transforms to the bend state. However, time is required for the transition from the splay to the bend state, which takes more than 3 s. Furthermore, once the voltage from the bend state is relaxed to zero, the LC director changes from the bend to the twist state, and finally the splay state, again taking a transition time more than a few seconds. Such complexity of the dynamics and initial setting voltage for the transition from the splay to the bend state renders the device difficult to apply to commercial displays, though it shows a high speed. Recent results are also reported with an initial transition time of less than 3 s, achieved by applying a high direct current voltage.[7,8)]

In this study, we propose a new device that does not require an initial transition time, by adding a suitable amount of chiral dopant to a parallel rubbed cell. Depending on the ratio of cell gap (d) to chiral pitch (p), the initial state can be either twist or splay. In particular, for the cells within the range of $0.2 < d/p < 0.4$, the LC director initially coexists in the twist and splay states, changes to the bend state when sufficiently high voltage is applied for some time, and then remains in the twist state permanently after the voltage is decreased below the threshold. This device shows a very fast response time of less than 10 ms and a wide viewing angle with compensated films. Here, we study the dynamics of chiral-doped OCB (C-OCB) cells and their electro-optic characteristics.

Figure 1 shows a schematic of the molecular dynamics of the C-OCB cell by simulation where $p = 25\,\mu$m and the pretilt angle 5° for $d = 8\,\mu$m. Below the threshold voltage

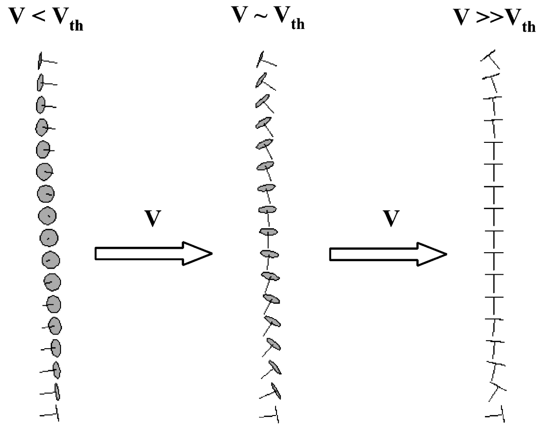

Fig. 1. Deformations of the LC molecules of the C-OCB cell with increasing applied voltage.

(V_{th}), the LC director is in the twist state and at $V \sim V_{th}$, the LC molecules start to tilt up in a twisted bend formation; with further increase in voltage much greater than V_{th}, they deform to an almost bend state like that in the OCB cell but with a twist of the optic axis by 180°. The deformation of the LC director occurs continuously, and the bright and dark states can be obtained in twisted bend state by adjusting the applied voltage.

We have constructed several cells to investigate the dynamics and electro-optic characteristics of the C-OCB cells, varying the chiral pitch given the cell gap. To fabricate the C-OCB cells, layers 400-Å thick indium-tin-oxide (ITO) was deposited on the bottom and top glass substrates with an area of 3.2 cm^2, the alignment layer from Nissan Chemicals Co. (SE-5291) was coated on both substrates to a thickness of 1000 Å and the rubbing was done in parallel directions. The pretilt angle generated by the rubbing is 6°. Two glass substrates were then assembled to give the cell gap of 8.0 μm. The liquid crystal with positive dielectric anisotropy ($\Delta n = 0.13$ at $\lambda = 550$ nm, $\Delta\varepsilon = 8.0$ at 1 kHz) was used and filled at room temperature. The chiral dopant was mixed with the LC to give chiral pitch 10 μm, 20 μm, 25 μm, 30 μm, 35 μm and 40 μm, that is, the values of d/p of about 0.8, 0.4, 0.32, 0.27, 0.23, and 0.2, respectively, and they were compared with the undoped cell.

We examined the configuration of the LC director of the cells after filling and also performed a simulation to see which

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configuration is in the stable state by calculating the Gibbs free energy with increasing d/p for given chiral pitch. According to the simulation results, when the value of d/p is higher (lower) than 0.26, the twist (splay) state is stable, as shown in Fig. 2. In the splay state with chiral pitch, the twist and tilt angles of the LC molecule in the center remain zero whereas in the twist state they are not zero and thus the continuous deformation of the LC molecules with increasing voltage is possible. However, in the experimental results, both states coexist in about equal proportions when the cell has a d/p value of 0.32. For the cells with $d/p = 0.27$ and 0.23, the splay state mainly exists except in a few tiny areas near spacers after filling at room temperature. However, only the splay state exists when the cells are cooled down to room temperature after being heated above the clearing point. Next, we applied voltage to each cell and observed the texture with an optical polarizing microscope to verify the transition time from initial alignment to twisted bend state and the nucleation of domains. Here, we define the configuration of the LC director as the splay state if we observe the dark state and as the twist state if we cannot observe it by rotating the optic axis of the crossed polarizers. Furthermore, the greenish and yellowish colors of the cell were defined to have the configurations of splay and twist states, respectively, as in the conventional OCB cell.

For the cell with $d/p = 0.32$, the coexistence of both states changes to the twisted bend state after applying a high voltage of 10 V for a few seconds and relaxes to the twist state when the voltage returns to zero. Then, the initial twist state changes to the twisted bend state without any nucleation or transition time with further increase in voltage. For the cells with $d/p = 0.27$ and 0.23, the LC molecules that are initially in the splay state change to the twisted bend state with increasing applied voltage beyond the threshold. However, transition time is required from the initial state to the twisted bend state, depending on applied voltage. Also, when the voltage returns to zero from high voltage for the twisted bend state, the twist state dominates over the whole electrode area and remains permanently. Nevertheless, outside the electrodes, the splay state still exists and there is a discontinuous boundary between the two states. As the value of d/p increases from 0.23 to 0.27, the boundary between the splay and the twist states becomes sharp, and further, the twist state is extended outside the electrode. In any case, no invasion of the splay state from the edge to the active area occurs permanently. We measured the transition time for the cell with $d/p = 0.32$ ($p = 25\,\mu$m). When the voltage of 7.5 V is applied, the duration from initial alignment to twisted bend state is about 30 s and the alignment relaxes to the twist state immediately when the voltage is returned to zero. For a cell with no chiral dopant, 10 s is necessary when the same voltage is applied, but it returns to the splay state in a transition time of about 120 s when the bias voltage is zero. It is obvious that the initial transition time from the splay to the bend state depends on applied voltage, that is, a higher voltage yields a shorter transition time. Although the cell with $d/p = 0.32$ still requires transition time from the splay to the twisted bend state, once it is initially in the twisted state, continuous transition from the twist to the twisted bend state occurs by increasing the applied voltage. Such dynamic behavior of the device renders it easy to fabricate a LCD without requiring an initial setting voltage in the conventional OCB cell. When the pitch of the cell is 40 μm, the dynamic behavior is about the same as in a conventional OCB cell, and thus finally the splay state was stable in the off state. The range of d/p that is initially in the twist and splay mixed state, but changes to the twist state after the voltage is reduced from the twisted bend state is $0.2 < d/p \leq 0.32$, based on the experimental results. We have also examined the cell with $p = 10\,\mu$m. In this case, the LC molecules are twisted at about 360° and fingerprint textures occur with increasing voltage, and thus the cell is not suitable as the light modulator.

Figure 3 shows a cell configuration with simplified LC director at an applied voltage greater than V_{th}. In the device, the top and bottom substrates were rubbed in parallel directions on the horizontal plane and one of the transmission axes of the crossed polarizers forms an angle of 45° with respect to the rubbing direction. At $V \gg V_{\mathrm{th}}$, the LC layers can be simplified into three layers, two tilt-up directors plus one ver-

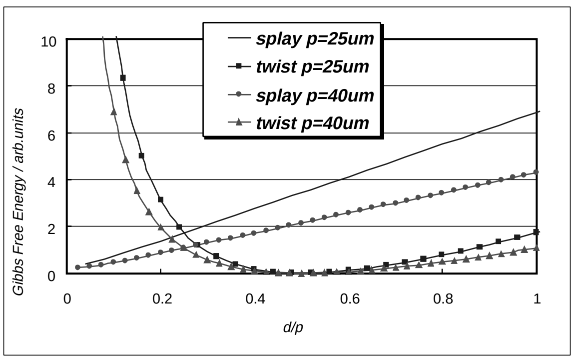

Fig. 2. Gibbs free energy as a function of the d/p ratio when the LC molecules are in splay or twist state for two different chiral pitchs.

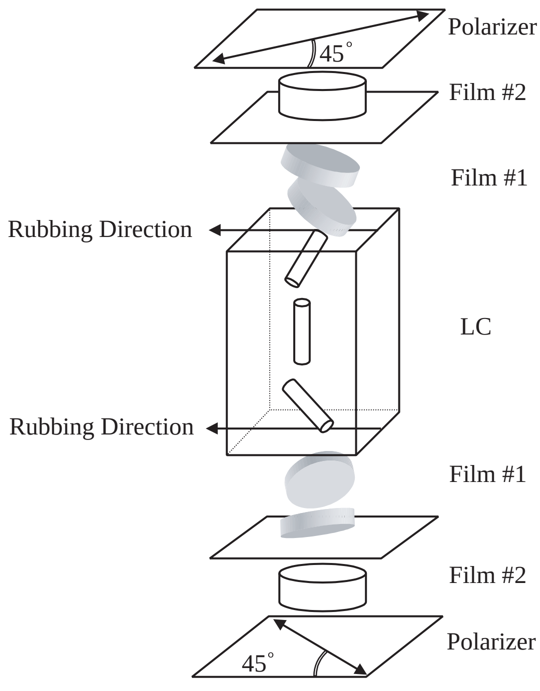

Fig. 3. Cell configuration of the C-OCB cell with compensation films. The negative birefringent discotic films are inserted between the polarizers and cell to obtain a dark state.

tically aligned layer around the middle of the cell (see Fig. 1). Generally, in OCB and C-OCB cells, compensation films are necessary to obtain a dark state. From our simulations, we found that three films are necessary to reduce the light leakage in the dark state, that is, two discotic negative birefringence films (film #1) with tilted optic axis with birefringence at normal direction ($R_{th} = 110$ nm, optic axis $= 22.5°$ from the normal direction),[6] and two negative birefringent films (film #2) with a retardation value, $(n_x - n_z)d = 300$ nm (from Nitto Denko Co.), are inserted as indicated in Fig. 3.

For electro-optic measurement, the LCD-7000 (Otsuka Electronics Co., Japan) is used. From the equipment, the halogen lamp was used as a light source and a square wave, 60 Hz voltage source from the function generator was applied to the sample cell. The light passing through the cell was detected by a photomultiplier tube. Figure 4 shows the voltage–dependent transmittance (V-T) curves of the cells ($d/p = 0.32$) initially in the twist state with and without the optical compensated films. With the compensating films, the dark state was obtained at 7.2 V. In the V-T curves, an initial optical bouncing occurs due to the twist- to–twisted-bend transition. We have measured the contrast ratio (CR) while varying the viewing angle, as shown in Fig. 5. The CR in

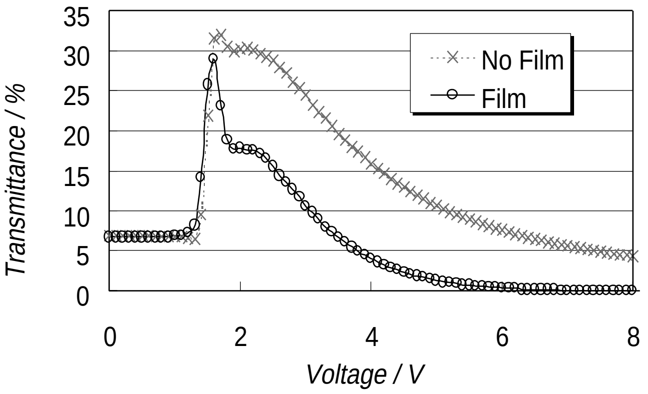

Fig. 4. Voltage-dependent transmission curves of C-OCB cell with and without compensation films.

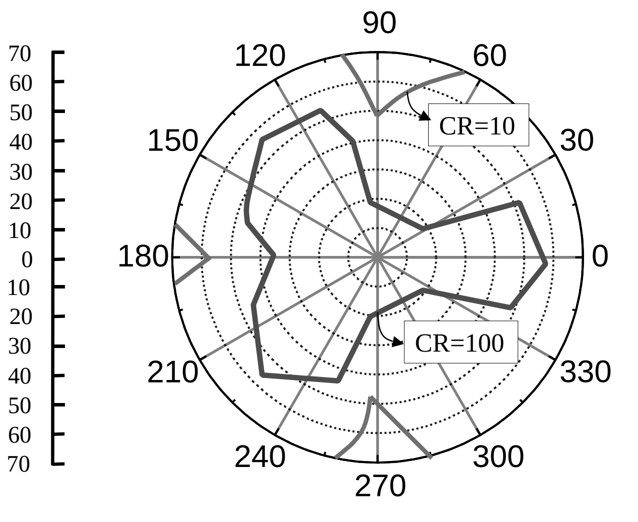

Fig. 5. Iso-contrast plot of the cell with compensation film for $d/p = 0.32$ where the vertical axis indicates a polar angle and 0° of the azimuthal angle is coincident with the rubbing direction.

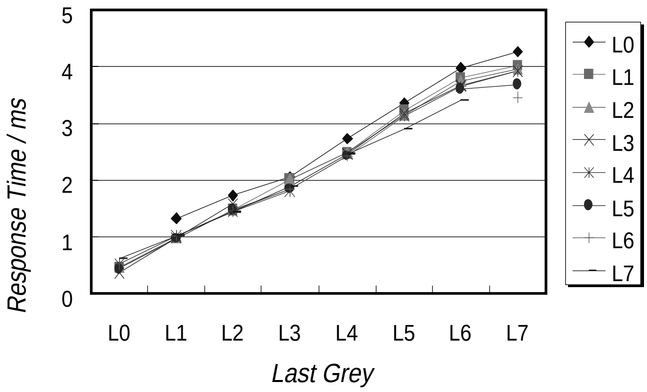

Fig. 6. Response time of the C-OCB cell in 8 grey levels with $d/p = 0.32$, where $L_0 \ldots L_7$ indicate light transmittance in each grey level from the dark to white state.

the normal direction is larger than 200, and the region where the CR greater than 10 is almost over 70° of the polar angle in vertical and horizontal directions indicating that the light leakage is well controlled by the films. This result is better than that of the twist nematic (TN) mode and comparable to that of the OCB cell.[9] However, asymmetry of the region with CR greater than 100 can also be improved with further optimization of the cell parameters and films that match simulation results correctly.[10] We also measured the response time of C-OCB cell in eight grey levels. As indicated in Fig. 6, the response times from fully white (2.5 V) to black (7.2 V) and from black to fully white are 0.6 ms and 4.3 ms, respectively. Furthermore, the eight grey levels from the dark to white state, that is, $L_0 \ldots L_7$, divide the transmittance equally; one grey is fixed and then the transition time from the other greys to the fixed one is measured in 8 grey levels. The response time is less than 10 ms in all grey levels, which is comparable to a conventional OCB cell.[5] However, the light transmittance has a bouncing peak when the LC director changes from dark to white state, which may cause a visual effect like a slow response time so that the study in the driving method is necessary.[10]

In summary, we have proposed a chiral-doped OCB cell and found the cell gap to pitch ratio where especially initially the twist and splay mixed states or the splay state, relaxes to twist state from twisted bend state. The twist state is permanently stable. This enables the device to be easily applicable to thin film transistor (TFT)—LCDs with conventional driving methods. The device also shows a good viewing angle and fast response time of less than 10 ms, favorable for the display at video rate. Further improvements of the device performance are under way.

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