A Novel Technique for Determination of Residual Direct-Current Voltage of Liquid Crystal Cells with Vertical and In-Plane Electric Fields

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Abstract: Generation of residual direct-current (DC) voltage (V_{\text{rDC}}) induces serious image sticking of liquid crystal displays (LCDs). In this study, a novel technique to determine the V_{\text{rDC}} of LC cells is proposed. We found that the V_{\text{rDC}} could be determined from a current-voltage (I-V) curve obtained by the application of triangular voltage. In the case of a vertically aligned twisted nematic (VTN) mode LC cell, where a vertical electric field is applied, the I-V curve shows maximum and minimum current peaks owing to rotation of an LC director, and the V_{\text{rDC}} is able to be determined from an average value of the two peaks. On the other hand, in the case of a fringe field switching (FFS) mode LC cell, where an in-plane (lateral) electric field is applied from comb electrodes, the current peaks derived from the rotation of the LC director do not appear. Therefore, we could not adopt the same way with that of the VTN mode LC cell. However, we found that there were two minimum current peaks derived from minimum capacitances of the FFS mode LC cell, and could determine the V_{\text{rDC}} by using these two current peaks. The proposed technique would be useful for the evaluation of the V_{\text{rDC}} of the LCDs, where the electric field is applied both vertically and laterally.

Keywords: liquid crystal display; residual direct-current voltage; I-V curve; triangular voltage application; vertically aligned twisted nematic (VTN) mode; fringe field switching (FFS) mode

1. Introduction

In recent years, the progress for the display performance of liquid crystal displays (LCDs) is remarkable with high contrast ratio, wide viewing angle, and fast response owing to significant advancement of liquid crystal (LC) alignment control technology [1–5]. Therefore, the application of the LCDs extends to many fields: smartphone, watch, tablet, television, automobile display, and so on. With the significant progress of the above image quality, there is a possibility that quite a small level of image defect becomes observable [6–10]. Image sticking is a particularly serious problem because the human eye generally distinguishes quite a small level of image sticking. Hence, a solution to this problem is necessary. It is known that image sticking is the phenomenon in which the previous pattern is visible whilst the next pattern is addressing [11]. One of the reasons for the image sticking of the LCDs is the generation of residual direct-current voltage (V_{\text{rDC}}) [12–18]. The V_{\text{rDC}} is the internal voltage being generated in the LC cell and is estimated to be derived from the following mechanisms [14–18]. One of the mechanisms is that an impurity ion in an LC layer of an LC cell adsorbs on a surface of an alignment layer under application of external DC offset voltage, and then the adsorbed ion does not desorb from the surface for a long period even after the DC offset voltage is removed [14–17]. Hence, the adsorbed ion on the surface of the alignment layer is one of the roots of the V_{\text{rDC}}. The other mechanism of the V_{\text{rDC}} is the generation of charged voltage in the LC cell, as depicted in Figure 1 [18]. The LC cell generates the charged voltage by the application of the DC voltage because both the LC layer and the alignment...
So far, several measurement techniques have been proposed for the evaluation of \( V_{rDC} \), as listed in Table 1. One is the capacitance-voltage (C-V) hysteresis technique: the \( V_{rDC} \) is determined by the C-V curve shift after applying the DC voltage [19,20]. In this technique, square wave voltage is applied to the LC cells [19]. The second technique is the flicker minimization technique: the \( V_{rDC} \) is determined by minimizing an optical flicker by optimizing the DC offset voltage [16,21]. The last one is the dielectric absorption technique: the \( V_{rDC} \) is determined by the residual charged voltage after application of the DC voltage and its discharged process [18]. In these techniques, we usually used the flicker minimization technique for evaluation of the \( V_{rDC} \) of the LC cells such as twisted nematic (TN), electrically controlled birefringence (ECB), vertically aligned (VA), and VA-TN (VTN) mode cells because this optical evaluation technique was empirically coincidence with the image sticking of the LCDs. Figure 2a shows an example of the flicker generation due to the \( V_{rDC} \). Though the LC cell is applied AC voltage without the DC offset, the existence of the \( V_{rDC} \) induces frequently different voltage applications to the LC layer. Therefore, the transmittance changes frequently, inducing the flicker. However, the flicker is not detected when the \( V_{rDC} \) is 0 V, as shown in Figure 2b. Regarding this technique, there is a problem that it is not easy to determine the accurate \( V_{rDC} \) because the flicker is gradually shifted during the adjustment of the flicker minimum point. In particular, it is extremely difficult to determine the \( V_{rDC} \) by this technique for the LC cell with the lateral electric field such as in-plane switching (IPS) or fringe-field switching (FFS) modes because the generation of the flicker is derived not only from the \( V_{rDC} \) but also from a flexoelectric field [22–27]. In this study, we will focus on the \( V_{rDC} \), and the purpose is to propose an alternate technique to determine the \( V_{rDC} \) of the LC cell especially with the lateral electric field more accurately. In particular, we will focus on the FFS mode because most of the LCDs adopted in various applications are the FFS mode. The proposed technique is the current-voltage (I-V) curve shift technique by the application of a triangular voltage to the LC cells. By applying the triangular voltage to the LC cell, the current shift can be monitored owing to capacitance shift, resistance originated from Ohm’s law, and motion of

![Figure 1](image-url)
the LC directors [18]. Therefore, the $I-V$ curve obtained by the application of the triangular voltage gives us various properties of the LC cell.

Table 1. Conventional evaluation techniques for $V_{\text{rDC}}$.

| Measuring method | C-V Hysteresis [19,20] | Flicker Minimization [16,21] | Dielectric Absorption [18] (Refer to Figure 1) |
|------------------|------------------------|-----------------------------|-----------------------------------------------|
| Measurement item | Electrical              | Optical                     | Electrical                                   |
|                  | Shift of C-V curve      | Offset voltage to minimize optical flicker | Change of electrical potential |
| Correlation with the image sticking | High                  | High                        | Middle                                        |
| Convenience for measurement | Easy                  | Difficult                    | Easy                                          |
| Adaptivity to the LC cells with vertical electric field (TN, ECB, VA, VTN modes) | Applicable             | Applicable                    | Applicable                                    |
| Adaptivity to the LC cells with in-plane electric field (IPS and FFS modes) | No Data                | Difficult                    | Applicable                                    |

Figure 2. Schematic illustrations for (a) the generation of the flicker due to generation of $V_{\text{rDC}}$, and (b) the minimization of the flicker.

2. Two Types of the LC Cells

We selected two types of LC cells; one is the VTN mode cell where the electric field is applied vertically, and the other is the FFS mode cell where the electric field is applied laterally on one substrate with electrodes. These are shown in Figure 3a,b, respectively.
In the case of the VTN mode LC cell, LC directors inside the LC layer rotate vertically and uniformly due to the application of voltage (Figure 3a). On the other hand, the FFS mode LC cell shows the lateral rotation of the LC directors only in the neighborhood area of the electrodes under application of the voltage (Figure 3b) [5,28]. The different behaviors of the LC directors in two LC modes are explained in the following. In the case of the VTN mode, the electric field appears uniformly and symmetrically in the LC layer as the simulation result is shown in Figure 4a,b. The physical properties of the LC material used for this simulation are listed in Table 2, and the layer thickness and pretilt angle of the LC materials are 4.0 μm and 88.5°, respectively. In contrast, the electric field appears non-uniformly for the FFS mode, and then the distribution of the LC director under application of the voltage is non-uniform in the in-plane area, as shown in Figure 5a,b. The simulation was performed under the line/space = 3.5 μm/4.5 μm, the dielectric constant of the passivation layer is 7, and its thickness is 200 nm. In this simulation, the same LC material as that of the VTN mode is used, and the pretilt angle is 0.1°. The density of the electric field in the neighborhood area of the electrodes is high, and that of the electric field around the opposite substrate is low. In other words, the electric field of the LC cell with the comb electrodes shows non-uniform and asymmetry.

Figure 3. (a) The LC cell with vertical electric field owing to the upper/lower electrodes, and (b) the LC cell with the in-plane electric field owing to the comb electrodes on one side of the pair of the substrates.

Figure 4. (a) The electric field distribution of the LC cell with the upper/lower electrodes, and (b) the LC director distribution of the VTN mode.
Table 2. Physical properties of the nega-LC material used in this study.

| Property          | Value       |
|-------------------|-------------|
| $T_{NI}$ (°C)     | 90          |
| $\epsilon_\parallel$ | 3.6        |
| $\epsilon_\perp$  | 7.8         |
| $\Delta\epsilon$  | -4.2        |
| $\Delta n$        | 0.083       |
| $\rho$ (Ω cm)     | $1.8 \times 10^{13}$ |

Figure 5. (a) The electric field distribution of the LC cell with the comb electrodes, and (b) the LC director distribution of the FFS mode. (Red lines mean equipotential lines.).

Figure 6 indicates the simulation result for rates of change of $dC/dV$ as a function of the applied voltage in the VTN and FFS modes. The VTN mode shows a sharp and large peak at around 2.5 V, whereas the FFS mode shows only a small peak at around 1 V. This indicates that, in the VTN mode, the sharp increase for the capacitance of the LC cell appears due to response of the LC director under application of the voltage. On the other hand, in the FFS mode, only the slight increase for the capacitance of the LC cell appears probably due to the non-uniform electric field.

Figure 6. Simulation result for the rates of change of $dC/dV$ in VTN and FFS modes as a function of applied voltage ($C_0$ is a capacitance of the cell with no applied voltage).
3. Preparation of LC Cells

The fabrication procedure of the VTN-LC cell is in the following. First, the polyimide material for the VA mode, purchased from JSR Corporation, was coated on a pair of glass substrates carrying transparent indium-tin-oxide (ITO) electrodes on the whole area. Then, linearly-polarized UV of 20 mJ/cm² was irradiated at a 30 °C atmosphere from an oblique direction for obtaining a slightly inclined pretilt angle [29,30]. Two glass substrates were assembled together for showing π/2 twist configuration of the LC directors with seal adhesive. The cell gap was maintained at 4.0 μm with glass fiber, and the LC material with negative dielectric anisotropy (nega-LC; Table 2) was injected into the empty cell by vacuum filling method, being obtained the VTN-LC cell.

In the case of the FFS-LC cell, horizontal alignment material purchased from JNC Corporation was coated on the pair of the substrates for the FFS mode. One side of the substrates carries the comb ITO electrode and a passivation layer, and the other substrate does not carry any electrode. The line and space of the electrodes were 3.5 μm and 4.5 μm, respectively. The thickness and dielectric constant of the passivation layer were 200 nm and 7.5, respectively. The linearly-polarized UV of 5 J/cm² was then irradiated from the normal direction to the substrates. Two glass substrates were assembled together with the seal adhesive. The cell gap was maintained at 4.0 μm, and the nega-LC material, whose physical properties are shown in Table 2, was injected into the empty cell by the same method described above. Finally, we obtained the FFS-LC cell. The parameters of the LC cells are listed in Table 3. Specific capacitance (“C”) and resistance (“R”) of the LC cells were determined by the current-voltage (I-V) curve by the application of 30 Hz triangular voltage from −10 V to +10 V at 25 °C. Voltage holding ratios (VHRs) were determined during an open-circuit of 16.61 ms after application of ±5 V for 60 μs, at 70 °C, with a 6254 type VHR meter developed by Toyo Corporation [18]. The specific capacitance of the VTN-LC cell is five times larger than that of the FFS-LC cell. On the other hand, the specific resistance of the VTN-LC cell is between 1/4 and 1/5 compared with that of the FFS-LC cell. This is probably due to the difference in the average distance of the electrodes between the VTN-LC and FFS-LC cells. The VHRs for both LC cells were almost equal, assuming that the amount of impurity ion in the LC layers of both LC cells are almost equal, as presented in Table 3.

Table 3. Parameters of the LC cells (VTN-LC cell * 1 and FFS-LC cell * 1) used in this study.

|                     | VTN-LC Cell | FFS-LC Cell |
|---------------------|-------------|-------------|
| d (μm)              | 4.0         | 4.0         |
| C * 2 (nF) / 25 °C  | 1.3         | 0.28        |
| R (GΩ) * 3 / 25 °C  | 0.76        | 3.68        |
| VHR/70 °C           | 98.4        | 98.1        |

*1 Electrode area is 1 cm². *2 Capacitance “C” is determined by the average capacitance value when +10 V is applied and −10 V is applied. *3 Resistance “R” is determined from the average slopes of positive and negative sides when −10 V and +10 V are applied.

4. Measurement of VA-LC Cell

4.1. I-V Curve

Figure 7 indicates the I-V curve of the VTN-LC cell obtained by the application of the 30 Hz triangular voltage from −10 V to +10 V at 25 °C. The slope of the I-V curve indicates an inverse of the resistance between the electrodes [18]. Generally, the slope of the I-V curve becomes small with increasing the resistance of the LC cell. The distance between the positive and negative current sides is attributed to the capacitance of the LC cell [18]. This increases with increasing the absolute value of applied voltage because the LC material shows the anisotropy of the dielectric constant [18]. Moreover, one can observe the maximum current peak in the range from +4 V to +7 V, and the minimum current peak in the range from −7 V to −4 V. These two peaks are attributed to a rotation of the LC director due to the anisotropy of the dielectric constant [18].
The 50% transmittance [14–16]. The and the alternate current (AC) voltage was 3.3 V at 30 Hz, which is the AC voltage shown in Figure 8b. The voltages of the maximum and minimum current peaks are +5.69 V and −5.25 V, respectively. By using these two current peaks, the triangular voltage from −7 V to −4 V. These two peaks are attributed to a rotation of the LC director

4.2. Determination of V_{rDC}

For the determination of the $V_{rDC}$ from the $I$-$V$ curve, the maximum and minimum current peaks derived from the rotation of the LC director are used. Before the application of DC offset voltage for stress, we can estimate that the $V_{rDC}$ does not generate ($V_{rDC} = 0$ V). Figure 8a shows the $I$-$V$ curve of the VTN-LC cell before application of the DC offset voltage, and we can observe the maximum and minimum current peaks at +5.38 V and −5.38 V, respectively. By using these two current peaks, the $V_{rDC}$ can be determined from the average value, which is 0.00 V. In the next step, the DC offset voltage of +5 V for 180 min (3 h) was applied to the cell for the stress, and then the $I$-$V$ curve was measured, which is shown in Figure 8b. The voltages of the maximum and minimum current peaks are +5.69 V and −5.25 V, respectively. The result that two current peaks are shifted indicates that the $V_{rDC}$ is generated by the application of the DC offset voltage. We determined that the $V_{rDC}$ was 0.22 V from the average voltage of the two current peaks. The determination of the $V_{rDC}$ by using this method would be reasonable because the rotation of the LC director is induced by the application of the voltage to the LC layer. In the case that the internal DC voltage is generated in the LC layer, the application voltage to the cell would be shifted. We decide to call the method the “$I$-$V$ curve shift” technique.

![Figure 7. $I$-$V$ curve for the VTN-LC cell and illustration of capacitance $s (C_\perp$ and $C_\parallel$), resistance (R), and maximum and minimum current peaks; the triangular voltage from −10 V to +10 V was applied with 30 Hz at 25 °C.](image1)

![Figure 8. $I$-$V$ curves for the VTN-LC cell (a) before and (b) after application of the +5 V DC offset voltage for 3 h (180 min) as the stress test; (condition of the measurement) the triangular voltage from −10 V to +10 V was applied with 30 Hz at 25 °C.](image2)
4.3. Comparison of $V_{rDC}$ Determined by I-V Curve and Flicker Minimization

The comparison of the $V_{rDC}$ determined from the I-V curve shift technique proposed in this report and the flicker minimization was carried out under application of the DC offset voltage as the stress. Figure 9 presents the time profile $t$ of the application voltage to the LC cell for the stress test. The DC voltage applied to the LC cell was fixed at +5 V, and the alternate current (AC) voltage was 3.3 V at 30 Hz, which is the AC voltage showing the 50% transmittance [14–16]. The I-V curves obtained by the application of the triangular voltage before and after application of the DC offset voltage are presented in Figure 10. The current maximum and minimum peaks are gradually shifted toward high voltage, indicating that the $V_{rDC}$ is generated under application of the DC offset voltage to the VTN-LC cell and that the $V_{rDC}$ is gradually increased with increasing the period of the stress.

![Figure 9. Square waveform of the applied DC offset voltage to the LC cell as the stress test.](image)

![Figure 10. I-V curve shift of the VTN-LC cell with a parameter of time $t$ applying +5 V DC offset voltage as the stress test; the triangular voltage in the range from −10 V to +10 V was applied with 30 Hz at 25 °C.](image)

In Figure 11, the $V_{rDC}$ values determined both from the I-V curve shift and flicker minimization are plotted as a function of time $t$. The time dependence of the $V_{rDC}$ determined from the I-V curve shift is nearly coincident with the $V_{rDC}$ determined from the flicker minimization. Therefore, the proposed technique, the I-V curve shift technique, is useful for the evaluation of the $V_{rDC}$ of the LCDs. Furthermore, we are convinced that the proposed technique would be more convenient than the flicker minimization because the measurements of the I-V curve are automatically performed by using the instrumental setup developed by the Toyo Corporation [18].
5. Measurement of FFS-LC Cell

5.1. I-V Curve

Figure 12 indicates the I-V curve of the FFS-LC cell obtained by the application of the 30 Hz triangular voltage at 25 °C. The applied voltage is swept between −10 V to +10 V. The behavior of the FFS-LC cell is different from that of the VTN-LC cell. The I-V curve of the FFS-LC cell does not show any specific maximum and/or minimum current peaks. We consider that the current value derived from the rotation of the LC director is so small that no current peak is observed. The rotation of the LC director seems to be slight and limited to the narrow area of the electric field because the electric field concentrates only around the electrodes, as shown in Figure 4. Though we cannot observe maximum and minimum current peaks, a slight shift of the current derived from the anisotropy of the dielectric constant is observed in Figures 12 and 13.

Figure 12. Typical I-V curve for the FFS-LC cell; the triangular voltage from −10 V to +10 V was applied with 30 Hz at 25 °C.
5. Measurement of FFS-LC Cell

5.1. I-V Curve

Figure 12. The I-V curve for the FFS-LC cell (a) before and (b) after application of the +5 V DC offset voltage for 3 h (180 min) as the stress test; (condition of the measurement) the triangular voltage from −10 V to +10 V was applied with 30 Hz at 25 °C.

5.2. Determination of $V_{rDC}$

Regarding the FFS-LC cell, the maximum and minimum current peaks did not appear, as described previously. Thus, we considered another method for determining the $V_{rDC}$ from the I-V curve. As shown in Figure 13, two slight minimum current peaks were observed, which are +1.94 V and +0.06 V, respectively. Therefore, the average voltage, which is the $V_{rDC}$, becomes 1.00 V. The result indicates that the $V_{rDC}$ is gradually increased with increasing the stress time. This is the same tendency with the result of the VTN-LC cell, implying that the stress time can also be determined by using the $V_{rDC}$.

Figure 13. I-V curves for the FFS-LC cell (a) before and (b) after application of the +5 V DC offset voltage for 3 h (180 min) as the stress test; (condition of the measurement) the triangular voltage from −10 V to +10 V was applied with 30 Hz at 25 °C.

The rotation of the LC director seems to be slight and limited to the narrow area of the electric field because the electric field concentrates only around the electrodes, as shown in Figure 4. Though we cannot observe maximum and minimum current peaks, a slight shift of the current derived from the anisotropy of the dielectric constant is observed in Figures 12 and 13. In the case of the FFS-LC cell, the current minimum peaks are gradually shifted toward high voltage, indicating that the $V_{rDC}$ can also be determined by using the method of the I-V curve.
observed for the positive and negative sides. In Figure 13a, two minimum current peaks for the positive and negative sides are +0.72 V and −0.74 V, respectively. The average value of these two voltages is −0.01 V, which is the $V_{rDC}$ before application of the DC offset voltage. Then, the DC offset voltage of +5 V for 180 min was applied to the cell, and the $I$-$V$ curve was measured, as shown in Figure 13b. Two minimum current peaks were also observed, which are +1.94 V and +0.06 V, respectively. Therefore, the average voltage, which indicates the $V_{rDC}$, becomes 1.00 V. The result indicates that the $V_{rDC}$ of the LC cell with the in-plane electric field can be determined by the method of the $I$-$V$ curve obtained by the application of the triangular voltage.

5.3. $V_{rDC}$ as a Function of Stress Time Measured by I-V Curve

The stress test was performed under application of the +5 V DC offset voltage for 180 min, using the FFS-LC cell. The time profile of the stress test is the same as that of Figure 9. The $I$-$V$ curves before and after application of the DC offset voltage are presented in Figure 14. In the case of the FFS-LC cell, the current minimum peaks are gradually shifted toward high voltage, indicating that the $V_{rDC}$ is gradually increased with increasing the stress time. Figure 15 indicates that the $V_{rDC}$ is a function of the stress time, $t$. The result indicates that the $V_{rDC}$ of the FFS-LC cell is gradually increased with increasing the stress time. This is the same tendency with the result of the VTN-LC cell, implying that the $V_{rDC}$ of the FFS mode cell can also be determined by using the $I$-$V$ curve method though it was difficult to determine by the flicker minimization. In the case of the VTN-LC cell, the $V_{rDC}$ determined from the $I$-$V$ curve shift was coincident with the $V_{rDC}$ determined from the flicker minimization technique. Moreover, the $V_{rDC}$ could also be determined for both the VTN- and the FFS-LC cells by the $I$-$V$ curve shift. These results intimate that the $V_{rDC}$ determined from the $I$-$V$ curve shift reflects the internal voltage generated from the adsorption of the ion on the surface of the alignment layer.

![Figure 14. I-V curve shift of the FFS-LC cell with a parameter of time $t$ applying +5 V DC offset voltage as the stress test; the triangular voltage in the range from −10 V to +10 V was applied with 30 Hz at 25 °C.](image-url)
Figure 15. $V_{\text{rDC}}$ of the FFS-LC cell as a function of stress time $t$ applying +5 V DC offset voltage.

6. Characteristics of the $I$-V Curve Shift Technique by the Triangular Voltage Application for Determination of the $V_{\text{rDC}}$

In this study, we proposed a novel technique to determine the $V_{\text{rDC}}$. This is the method to evaluate the $I$-$V$ curves by the application of the triangular voltage after application of the DC offset voltage as the stress. The technique is especially useful for the determination of the $V_{\text{rDC}}$ because we can not only perform it automatically but also evaluate the $V_{\text{rDC}}$ of the FFS mode LC cell, having the lateral electric field. The following table (Table 4) lists the characteristics of the newly proposed technique for the measurement of the $V_{\text{rDC}}$.

Table 4. Proposed evaluation techniques for $V_{\text{rDC}}$.

| Measuring method          | $I$-$V$ Curve Shift                        |
|---------------------------|-------------------------------------------|
| Electrical                | Shift of current maximum and/or minimum   |
| Correlation with the image sticking | peaks                                      |
| Convenience for measurement| High                                       |
| Advantage compared with the other techniques | Convenient and easy                        |
|                           | Could be evaluated for both the LC cells with vertically- and in-plane electric fields |

7. Conclusions

The $V_{\text{rDC}}$ could be determined by the $I$-$V$ curve obtained by the application of the triangular voltage. In the case of the LC cell with the vertical electric field such as the VTN mode, the $I$-$V$ curve shows the maximum and minimum current peaks for the positive and negative sides due to the rotation of the LC director. Therefore, we can determine the $V_{\text{rDC}}$ as the average value of these two current peaks. The result of the $V_{\text{rDC}}$ evaluated by the proposed method is fairly coincident with the $V_{\text{rDC}}$ evaluated by the flicker minimization, which is the optical method. In addition, the proposed method could be applied to the LC cell with the lateral electric field such as the FFS mode though the $V_{\text{rDC}}$ could not be determined by the flicker minimization for the FFS mode LC cell. In the case of the FFS mode LC cell, the $I$-$V$ curve shows two minimum current values due to the minimum capacitances of the positive and negative sides. Thus, the $V_{\text{rDC}}$ can be determined by using these two minimum current values in a similar manner to the VTN mode LC cell. By using the flicker minimization to the FFS mode LC cell, the $V_{\text{rDC}}$ could not be determined because the flicker is generated by not only the generation of $V_{\text{rDC}}$ but also the flexoelectric effect. Thus, our proposed technique would be particularly useful for the LC cell with the lateral electric field. Furthermore, the $I$-$V$ curve shift technique has superior characteristics to conventional techniques as shown in Table 4. We believe that the proposed technique is significantly useful for the evaluation of the image sticking of the LCDs.
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