Effects of Dispersed Carbon nanotubes on Electro-Optic Characteristics and Orientation of Liquid Crystal in the In-Plane Switching Cell

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Abstract
To understand effects of carbon nanotubes (CNTs) dispersed in nematic liquid crystal (NLC) on electro-optic characteristic and orientation of the LC, we CNT-doped homogeneously-aligned NLC cells driven by in-plane field have been fabricated. The CNTs were aligned with a LC director from the initial state to below critical ac field, whereas the CNTs disturbed the LC director field above critical ac field. We observed motional textures in the form of vertical stripes in the local area between electrodes, which were associated with a deformation of the LC director orientation. This indicates that CNTs start vibrating three dimensionally with translational motion. Further, the hysterisis studies of voltage-dependent transmittance under dc electric field show that the amount of residual dc, which is related to image sticking problem in liquid crystal displays, is greatly reduced due to ion trapping by CNTS while keeping operating voltage and response time about the same compared to the un-doped LC cell.

1. Introduction
Carbon nanotubes have been extensively investigated due to their new functional performances and technological importance. One of the bottleneck technologies is an alignment of nanotubes in a desired way. Recently, the long axes of CNTs are known to align paralle l to the nematic LC director n.[1-3] The conductivity measurement also proves an electrically controlled reorientation of CNTs from planar (homeotropic) to homeotropic (planar) in nematic LC using a vertical field.[3] Another trial reported that a minute addit ion of carbon nanosolids, such as C60 and mutiwalled CNTs in a twisted nematic LC affects the electro-optical properties of the cell when a dc voltage is applied.[4]

Recently, we observed that CNTs can be dispersed in a nematic LC medium, and that the CNTs aligned parallel to the LC director in a bulk cell, either homogenously, or homeotropically, without disturbing the LC director field when its concentration is less than 0.01 wt.%.[2] Further, when a critical vertical electric field was applied, the CNTs experienced a dielectric torque and started to vibrate.[2]

In this paper, we report that the CNTs can undergo in-plane switching in a homogenously aligned nematic LC according to the applied in-plane electric field, and that when a critical in-plane field is applied, the CNTs start to vibrate with translational motion perturbing the LC directors between electrodes.[5] Furthermore, the hysteresis and electro-optic studies of voltage-dependent transmittance under dc and ac electric field carried out to find the effects of CNTs.

2. Experimental Condition
Figure 1 shows a cell structure of the CNT-doped LC cell. The LCs were homogenous, and a small quantity of the single-walled CNTs (SWNTs), 5×10^{-4} wt %, was doped in LC.[4] The diameter ranged from 4 to 10 nm with wide distribution of CNT length from 0.1 to 1.5 μm (the most probable SWCNT length was 250 nm), which was observed from atomic force microscopy (AFM: Seiko SPA-400). The inter-digitated opaque electrodes composed of aluminum existed only on the bottom substrate with an electrode width of 10 μm, and a distance of 30 μm between electrodes, where both electrodes served as source and common electrodes. Owing to the electrode structure, the horizontal field (E_y) is mainly generated between electrodes, when the bias voltage is applied. For a cell fabrication, a homogenous alignment layer (AL-16139 from Japan Synthetic Rubber Co.) was first spin-coated with a thickness of 800 Å on an electrode-patterned glass substrate. A rubbing process on the substrate was then performed to align the nematic LC. The same alignment layer and rubbing was performed on another glass substrate without an

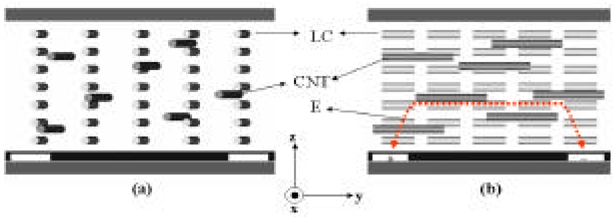

Figure 1. Schematic of the cell structure of CNT-doped nematic LC cell in the off (a) and on (b) state.

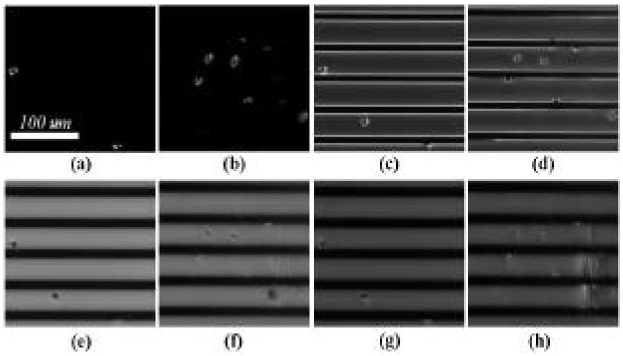

Figure 2. Optical microphotographs for cells with LC only and CNT-doped LC cell when applied voltages are 0 V_{rms} ((a) and (b)) and 10 V_{rms} ((c) and (d)), 60 V_{rms} ((e) and (f)) and 120 V_{rms} ((g) and (h)), respectively.

electrode. Two substrates were assembled to give a cell gap (d) of 9 μm, where the plastic balls were used to maintain the cell gap. Finally, the super-fluorinated LC mixture, with a positive dielectric anisotropy from Merck Co. ($\Delta\varepsilon$ = +7.4, Δn = 0.088 at λ = 589 nm), was filled at room temperature by the capillary action. The LC cell without the SWNTs was also fabricated with a cell gap of 8.8 μm. In both cells, the LC directors were aligned to 80° with respect to the horizontal field.

3. Result and Discussion

The fabricated test cells were observed under optical polarizing microscopy by applying a sine wave voltage of 60 Hz, and the voltage-dependent textures were compared to the LC cell without SWNTs. Figure 2 shows optical microphotographs as a function of the applied voltage for both cells. In the device, the normalized transmittance is proportional to $\sin^2(2?(V))\sin^2(pd?n_{eff}(V)/?)$, where ? is a voltage-dependent angle between the LC director and crossed polarizer axes, and $d?n_{eff}$ is also a voltage-dependent effective cell retardation value.[6] Without a bias voltage, the optic axis of the LC director coincides with one of the crossed polarizers (? = 0°). Thus, the cells appear to be black. However, in a dark state, several spots appeared which originate from the director deformation around the spacers (see Fig. 2(a) and 2(b)). This indicates that the long axis of SWNTs was aligned parallel to the LC director n, which was correlated well with the previous reports.[1-3] By increasing the voltage up to 10 V_{rms}, the LC director rotated in plane due to a dielectric torque, and transmittance started to occur continuously. In the device, the twist deformation mainly occurred with most twisted angles around the mid- layer, since the LCs at both surfaces were strongly anchored, like in the in-plane switching LC cell.[6] The interesting feature is that any difference between the pure LC and the SWNT-doped LC cells was not observed, as shown in Fig. 2(c) and 2(d). This confirms that the SWNTs also rotate, while the LC director rotates. Otherwise, the luminance difference between areas in the SWNT-doped cell should have existed, since the unrotated SWNTs disturb the continuous LC deformation layer by layer. Previous work reported that for fields larger than about 1.8 V μm^{-1}, the SWNTs were oriented parallel to the field, overcoming the orientational influence of the grooved surface.[1] However, the results inform that the orientation of SWNTs in the plane can be controllable at much lower critical field than that with an assistance of twist deformation of LC layers. With further increasing voltage to 60 V_{rms} and then to 120 V_{rms}, more LC layers tried to orient parallel to the horizontal electric field. In the LC cell, the transmittance change only occurred in relation to the variation of $\sin^2(2?(V))\sin^2(pd?n_{eff}/?)$, which is time-independent, as shown in Fig. 2(e) and 2(g). However, in the SWNT-doped LC cell, the transmittance change between electrodes started to occur at 60 V_{rms} in the form of vertical stripes (see circles), and appeared to be very clear with an increased number of the vertical stripes at higher voltages, in directions parallel to the horizontal electric field, as shown in Fig. 2 (f) and 2(h). Furthermore, the width and size of the vertical stripes was not uniform, and fluctuated with time. In some cases, the vertical stripes moved to and pro between electrodes. Nevertheless, these textures were not observed under dc electric field.

In order to understand the motion of SWNTs according to the horizontal field, especially without

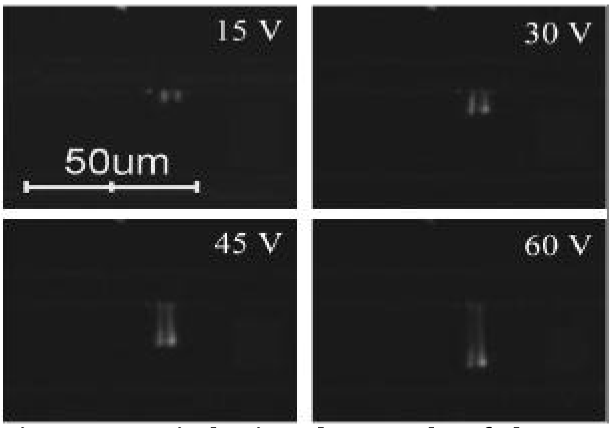

Figure 3. Optical microphotographs of the CNT-doped LC cell describing generation of two vertical stripes with increasing voltage.

accompanying twist deformation of the LC layers, we fabricated cells, where the rubbing direction is perpendicular to the electrode direction (E_y// n). In the pure LC cell, the LC layers did not experience twist deformation with bias voltage until a high voltage of 120 V_{rms} is applied. The CNT-doped cell also showed a clear dark state at an initial state. However, when the applied voltage was 15 V_{rms}, the light transmittance started to occur in patterns of two short vertical stripes with a dark line between them, as shown in Fig. 3. Interestingly, one end of the stripes was fixed near the electrodes initially, and then the height of the vertical stripes increased, as the applied voltage increased. The height of the stripe was saturated at about 60 V_{rms}, until it outreached the size of the electrode distance. According to detailed observations, the height of the stripes was not related to the length of CNTs, since in a cell with an electrode distance of 10μm, the height became 10μm. Once they became a certain size, a translational motion along the field direction occurred between electrodes and a few of them jumped over the electrodes. Such a motion of the SWNTs disturbed the LC director orientation, resulting in the generation of transmittance.

Now, we describe a schematic modeling for an origin of vibrational and translational motion of the SWCNTs dispersed in LC medium. In the model, we assume that the SWCNT possesses a permanent dipole moment **p** with a rod-like shape. This assumption is quite reasonable, since the SWCNTs were stirred in nitric acid such that the nanotubes are easily functionalized by carboxylic and hydroxyl groups.[7] Under an external electric field $\mathbf{E}_{ext}$, the nanotube will experience a torque $\mathbf{N} = \mathbf{p} \times \mathbf{E}_{ext.}$ In our system, the field changes polarity with a frequency of 60 Hz, and the field intensity is not uniform along *y* and *z* directions, that is, $\mathbf{E}_{ext} = (E_y\ \mathbf{j} + E_z\ \mathbf{k}) \sin ?t$. Consequently, this oscillating field causes a vibrational motion of the SWCNT. If the SWCNT does not hold the permanent dipole moment, no net torque will exert on SWCNT under ac field and therefore no vibrational motion will be induced. In addition, a net force **F** on the dipole exists such that $\mathbf{F} = (\mathbf{p} \bullet \nabla)\mathbf{E}_{ext}$[8], resulting in a translational motion of the SWCNTs. Both torque and net force exerting on the SWCNTs increase with increased applied voltage, and they are time- and positional dependent, causing the appearance of such textures in which *?* and $d ? n_{eff}$ of LC layers vary as a function of time.

With understanding of the SWNT characteristics under in-plane field, we investigated its effect on the electro-optic and residual dc characteristics of the cells. First of all, the voltage-dependent transmittance (V-T) under ac electric field was measured for both SWNT-doped and pure LC cells with cell gap of 3.1 μm (d ? n = 0.27 μm), as shown in Fig. 4. The threshold voltage and the operating voltage are exactly the same each other for such low concentration of the SWNTs. similar in both cells. Next, we investigated the response time in 8 grey levels, in which the applied voltages are the same each other for both cells. The rising and decaying times associated with transition from fully dark to white state and vice versa are 17.3 ms and 18.9 ms in the pure LC cell, respectively, while they are 17.5 ms and 19 ms in the SWNT-doped cell. Furthermore, the grey scale response times also show similar difference, indicating that such concentration

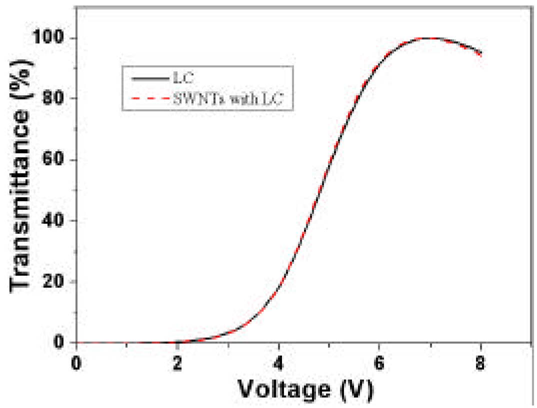

Figure 4. Measured voltage-dependent transmittance curves.

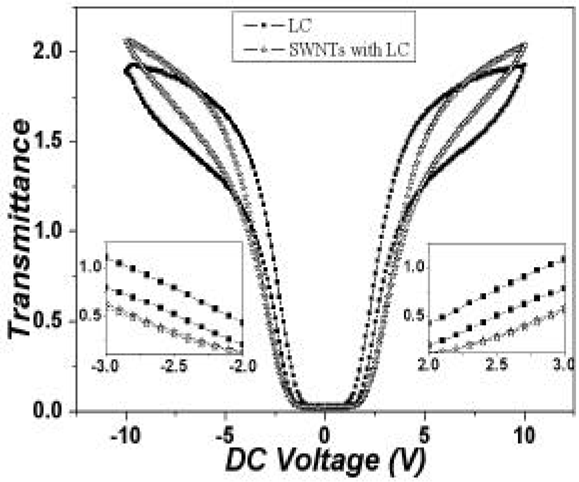

Figure 5. Measured voltage-dependent transmittance hysteresis curves for pure LC and SWNT-doped IPS cell.

of the SWNTs do not affect the response time, greatly. Finally, the residual dc which is still a crucial problem causing an image sticking in the IPS LCDs is measured through voltage-dependent transmittance (V-T) hysteresis curves, as shown in Fig. 5. The dc voltage was swept from 0 to +10 V, and then changed from +10 V to –10 V, and finally from –10 V to 0 V, with an each step of 0.1 V. This reveals that in the pure LC cell, the amplitudes of hysteresis at V_{10}, V_{50}, and V_{90} (here, the subscript indicates a relative transmittance with respect to the maximum transmittance) were about 0.38, 0.71, and 3.4 V at both positive and negative cycles, respectively, while they were about 0.04, 0.3, and 1.6 V in the SWNT-doped cell. Further, we tested residual dc even in the TN cell with various concentrations of CNTS, and the results showed that it is greatly reduced in the CNT-doped cell.

Now, a question arises why the existence of SWNTs dispersed in nematic LC medium reduces the residual dc. We presume that in the pure LC cell, the atom size of ions must be trapped at an interface between LC and alignment layer during applied dc voltage, while in the SWNT-doped cell, the SWNTs attract small ions due to the existence of dipole field and resides between LC layers so that less ions are trapped at the interface.

4. Summary

For the first time, we have reported the CNT-doped homogenously aligned nematic LC cell driven by an in-plane field. As the LC director rotated in plane by the horizontal field, the CNTs also rotated in plane. When a critical field was applied, the CNTs started vibrating in in a confined area between electrodes with translational motion. Further, the electro-optic measurements of voltage-dependent transmittance, response time, and V-T hysterisis confirm that the operating voltage and response time remain about the same, however, surprisingly; the residual dc is greatly reduced in the CNT-doped cell. We believe that this work may have a great impact to reduce the residual dc which is a long standing problem in the conventional TFT-LCDs and also suggest that the residual dc in an active area can be reduced by introducing ion-trapping sites such as CNTs in a non-active area of the LCDs.

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