Effects of carbon nanotubes on electro-optical characteristics of liquid crystal cell driven by in-plane field

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(Received 12 November 2006; accepted 12 February 2007; published online 19 March 2007)

Homogeneously aligned nematic liquid crystal (LC) cells doped with carbon nanotubes (CNTs) driven by an in-plane field were fabricated and their electro-optic characteristics were investigated. The effective cell retardation values showed no difference between doped and undoped LC cells in the absence of electric field. However, in the presence of electric field, it was smaller in the CNT-doped cell than in the undoped cell, resulting in the decrease of transmittance. Furthermore, the CNT-doped cell exhibited a slight increase in the driving voltage due to the increase of the twist elastic constant (K_{22}) and the decrease in the decay response time due to the decrease in the rotational viscosity (γ) and γ/K_{22} compared to the undoped cell. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2714311]

In liquid crystal displays (LCDs), the physical properties of LC are important factors because the electro-optic characteristics of LCDs such as the driving voltage, transmittance, and response time strongly depend on the physical properties of the LC. Over the last ten years, the physical properties of LCs, particularly superfluorinated LC mixtures, have been greatly improved such that the rotational viscosity of LC with a positive dielectric anisotropy ($\Delta\varepsilon$) decreases from over 100 to below 80 mPa s for television (TV) applications to achieve a fast response time.[1] In addition to the fast response time, the LCD should exhibit high image quality in all viewing directions for TV applications. Several LC modes such as in-plane switching (IPS),[2,3] fringe-field switching (FFS),[4,5] and multidomain vertical alignment including patterned vertical alignment[6,7] have been proposed and commercialized. Among such modes, the homogeneously aligned LC rotates almost in plane in the IPS and FFS modes, thereby exhibiting a high intrinsic image quality in wide viewing angles. In both modes, a thin cell gap (d) is essential for achieving fast response time. However, in the IPS mode, the cell gap decreases with increasing operating voltage (V_{op}). Under these conditions, LC with a high $\Delta\varepsilon$ must be used, which increases the rotational viscosity of LC intrinsically. This means that there is a limitation in that all the physical properties of LC cannot be satisfied simultaneously according to the requirements of LCDs because each of the physical properties has a trade-off relationship.

Recently, new approaches such as the doping of nanoparticles such as MgO,[8] $BaTiO_3$,[9] $Sn_2P_2S_6$,[10] and carbon nanotube (CNT)[11–16] into LC was proposed to overcome the limitations of the physical properties of LC. We also reported the effect of CNTs in the twisted nematic (TN)-LC device, and claimed that the CNT-doped cell reduces the residual dc and improves the response time.[17–19] In the TN-LCD, the 90° twisted LC is driven by a vertical electric field, while in the IPS-LCD, the homogeneously aligned LC is driven by an in-plane field. Up to now, the CNT effects on the electro-optic characteristics of the IPS mode have never been reported.

Figure 1 presents the cell structure of the CNT-doped IPS cell. The signal and common electrodes exist only on the bottom glass substrate with an electrode width of 5 μm and a distance (l) of 10 μm between electrodes. They are composed of aluminum and transparent electrodes, respectively. Due to the electrode structure, the horizontal electric field (E_y) is mainly generated between electrodes when a voltage is applied. For an alignment layer, a homogeneous alignment layer (JALS-204 from Japan Synthetic Rubber Co.) was spin coated on the patterned electrode at bottom and top glass substrates with a thickness of 800 Å. The rubbing process on both substrates was performed in the antiparallel direction to align the nematic LC with an angle of 70° with respect to E_y. The cell was then assembled to give d=3.5 μm, where the plastic balls were used to keep d. Finally, the LC with positive dielectric anisotropy from Merck Co. ($\Delta\varepsilon$=7.4, Δn

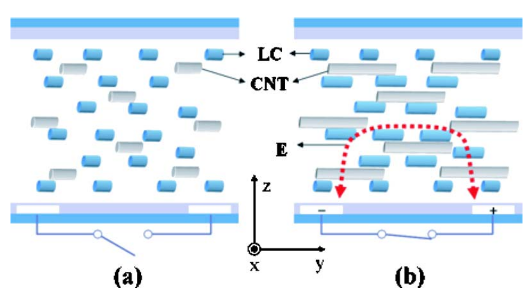

FIG. 1. (Color online) Schematic of the cell structure of the CNT-doped nematic LC cells in (a) off and (b) on states.

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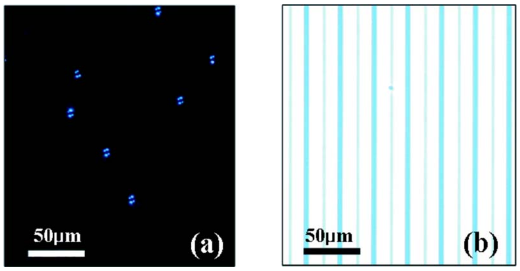

FIG. 2. (Color online) Polarization microphotographs of (a) off and (b) on states of the pure and CNT-doped IPS cells.

=0.088 at λ=589 nm, and K_{22}=5.1 pN) with a small amount (5×10^{-4} wt %) of single-walled CNTs (SWCNTs) (Ref. 17) was filled at room temperature by capillary action. For the CNT-doped cells, a small amount (5×10^{-4} wt %) of the SWCNTs was doped into the LC. An undoped (C-1) and CNT-doped (C-2) cells were also fabricated, and the electro-optic characteristics were compared.

In the IPS cell, the normalized transmittance, T/T_0, is given by $\sin^2(2\psi(V))\sin^2(\pi d\Delta n_{\text{eff}}(V)/\lambda)$, where ψ is a voltage-dependent angle between the transmission axes of the crossed polarizers and the LC director, Δn_{eff} is the effective birefringence of the LC layer dependent on voltage, and λ is the wavelength of incident light. Therefore, in the off state, the LC was aligned homogeneously with its optical axis coincident with one of the crossed polarizer axes so that the cell appears black. In the on state, the in-plane field rotates the LC director, giving rise to transmittance. However, in the on state, the Δn_{eff} is known to be changed such that it reduces to 80% of the original value at V_{op}, which gives the maximum transmittance.[20]

We first observed the pure and CNT-doped LC cell under the polarizing optical microscopy before and after applying voltage. In the off state, no defects related to the CNT bundles were observed; instead, only light leakage due to the existence of spacers was observed and in the on state with 7 V, the uniform transmittance was generated, as shown in Fig. 2, and there was no difference between the two cells. Here, the wide and narrow dark lines originated from an opaque electrodes and the insufficient rotation of the LC director above the transparent electrode.

The voltage-dependent transmittance (*V*-*T*) curves after applying a square wave voltage of 60 Hz with an increasing step of 0.1 V were measured using a halogen lamp, as shown in Fig. 3. The transmittance (3.75%) of C-2 at maximum value was slightly lower than that (3.86%) of C-1, and V_{op} of C-2 (7.55 V) was slightly higher than that of C-1 (7.35 V). The *V*-*T* curves using another LC mixture exhibited the same

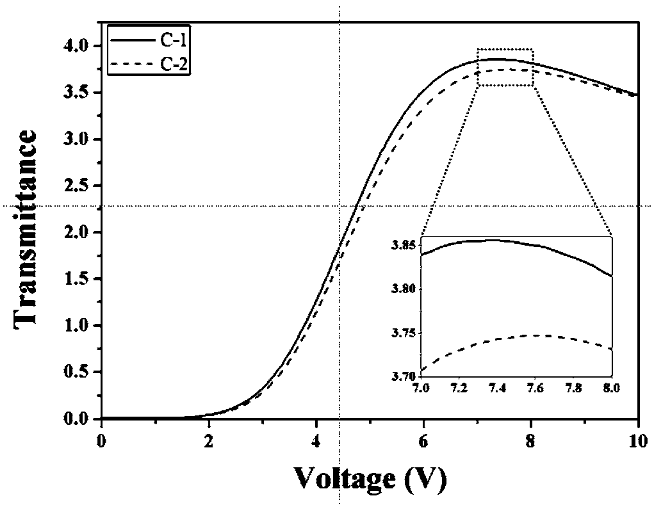

FIG. 3. Measured voltage-dependent transmittance curves of the pure and CNT-doped LC cells.

behavior. In addition, the CNT effects on the physical properties of the LC were investigated. As a result, the clearing temperature T_{ni}, $\Delta\varepsilon$, and Δn remained almost unchanged, while the rotational viscosity γ measured using the transient current method[21] was reduced appreciably (approximately 7.5%) in the CNT-doped LC, as shown in Table I. With an understanding of the CNT effects on the physical properties of the LC, the *V*-*T* curves are analyzed hereafter.

In the IPS cell, the V_{op} in the cell is given by $V_{\text{op}}=\pi l\sqrt{K_{22}/\varepsilon_0|\Delta\varepsilon|}/d$. Since both cells have the same l, d, and $\Delta\varepsilon$ values, the change in V_{op} is mostly affected by K_{22} of the CNT, i.e., the CNT-doped LC may have slightly higher K_{22} than the undoped LC. The length of the CNT on average is much longer than LC and the interaction between LC and CNT is strong with a binding energy of about −2 eV between the LC and CNT.[17,22] The elastic modulus of SWCNTs is much larger than that of LC.[23] The strong interaction between CNTs and LC molecules may then increase the elastic energy of LC molecules and therefore can be attributed to the increase in K_{22} in the CNT-doped LC. With the relationship $K_{22}(\text{C-1})/K_{22}(\text{C-2})=[V_{\text{op}}(\text{C-1})/V_{\text{op}}(\text{C-2})]^2$, we estimated that K_{22} in the CNT-doped LC increased to 5.38, i.e., equivalently to approximately 5.5%.

Since the light absorption of the CNT with such a small amount of doping is negligible, the difference in transmittance is related to the difference in Δn_{eff} in the on state. The effective birefringence of C-1 and C-2 cells as a function of applied voltage was measured to confirm the influence of CNTs on the reorientation of LCs, as shown in Fig. 4.

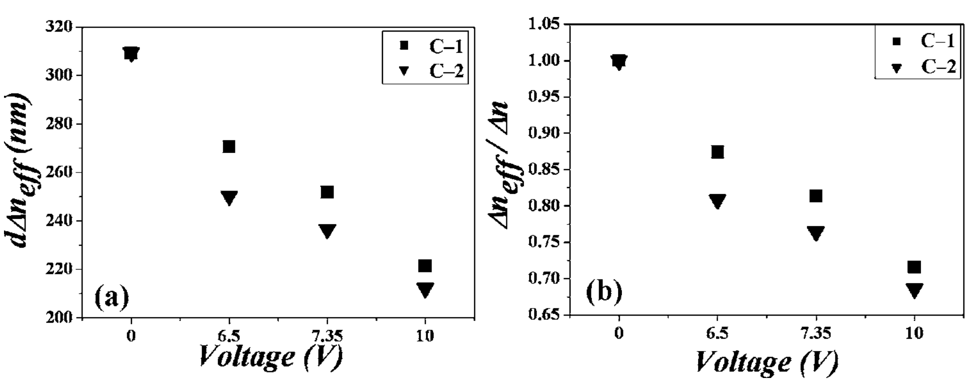

FIG. 4. Measured (a) $d\Delta n_{\text{eff}}$ and (b) $\Delta n_{\text{eff}}/\Delta n$ in the pure and CNT-doped LC cells as a function of the applied voltage.

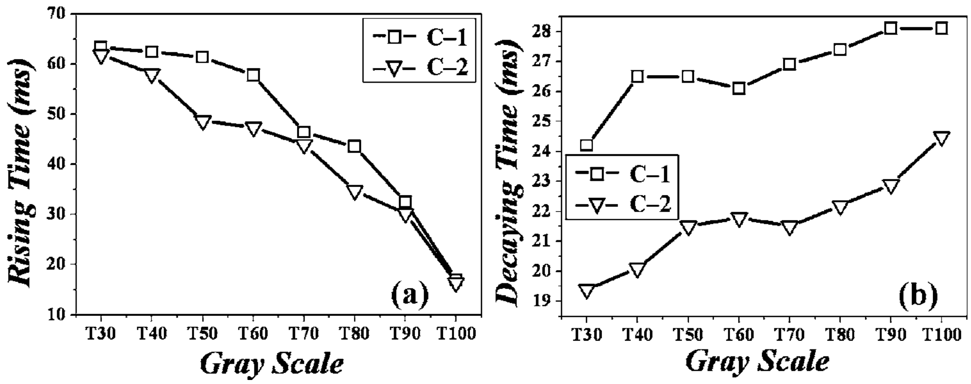

FIG. 5. Measured (a) rising and (b) decaying response times of the pure LC and CNTs-doped LC cells. The numbers in the label of the row axis show the relative transmittance with respect to the maximum transmittance at the normal direction.

The $d\Delta n_{\mathrm{eff}}$ in the off state was identical for both cells as expected. However, it decreased from 309 nm at 0 V to 252 nm (237 nm) at 7.35 V in C-1 (C-2) cell. In terms of $\Delta n_{\mathrm{eff}}/\Delta n$, the ratio at 7.35 V is 0.82 (0.77) in C-1 (C-2) cell. This implies that less number of LC molecules in C-2 cell is twisted than those in C-1 cell in the same voltage.

The response time of C-1 and C-2 cells was measured to identify the effect of the reduced rotational viscosity on the response time of the CNTs-doped LC cell. Figures 5(a) and 5(b) present the measured rising time and the decaying time of the IPS cell in eight gray levels by applying a 60 Hz square wave ac voltage. Here, the applied voltages for each gray scale were identical for both cells. In the case of the rising time, the C-2 cell reacted slightly faster than the C-1 cell. However, when high voltage V_{op} was applied, the difference became minor. The average decay time in C-2 cell was also faster than that in C-1 cell; the decaying response time in C-1 cell was approximately 18% faster. The decaying time is in general proportional to γ/K_{22}. This ratio was approximately 0.0396 and 0.0347 in C-1 and C-2 cells, respectively. The ratio of C-2 cell was decreased by 14% compared with that of C-1 cell, which is in good correlation with the 18% decrease in the measured decaying time.

In summary, we have examined the effects of CNTs on a nematic liquid crystal and electro-optical characteristics of the in-plane switching cells. The effective retardation value of the CNTs-doped LC cell was reduced and its operation voltage was increased slightly compared with that in the pure LC cell. The physical properties of the LC such as the twist elastic constant and the rotational viscosity were modified by the minute doping of CNTs, which helps improve the response time of the IPS cell. This opens a possible application of the CNT-doped LC to the IPS LCD to improve the response time by modifying the physical properties of the LC by CNTs.

This work was supported by LG.Philips LCD [for one of the authors (SHL)], and KRF Grant funded by Korea Government (MOEHRD) (KRF-2005-201-C00012), and in part KOSEF through CNNC at SKKU (YHL).

TABLE I. Change in the physical properties of LC by CNT doping.

	Pure LC	SWCNTs-doped LC
$\Delta\varepsilon$	7.4	7.41
γ (mPa s)	147	136
Δn	0.088	0.0881

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