Electro-optic characteristics of carbon nanotube-doped liquid crystal cell driven by in-plane switching and fringe-field switching

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Abstract

Effects of carbon nanotube (CNT) on the in-plain switching (IPS) and fringe-field switching (FFS) modes were investigated. The studies show that the CNT-doped LC cells exhibit lower transmittance but faster response time than those in the pure LC cell. Interestingly, the CNT-doped IPS and FFS modes show different characteristic in effects of operating voltage.

1. Introduction

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 last 10 years, the physical properties of LCs, particularly superflurinated LC mixtures (SFMs) have been greatly improved such that the rotational viscosity of LC with a positive dielectric anisotropy ($\Delta\varepsilon$) decreases from over 100 mPa·s 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], fringe-field switching (FFS) [3], and multi-domain vertical alignment (MVA) including patterned VA (PVA) [4] 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 and FFS 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 that the doping of nanoparticles such as MgO [5], $BaTiO_3$ [6], $Sn_2P_2S_6$ [7], and CNT [8-10] into LC was proposed to overcome the limitations of the physical properties of LC. We 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 [11]. Also, we found out that in the IPS mode, CNT-doped LC cell is reduced effective birefringence compare to pure LC cell [12]. In the TN-LCD, the 90^o twisted LC is driven by a vertical electric field while in the IPS and FFS LCD, the homogenously aligned LC is driven by in-plane and fringe field. Up to now, the CNT effects on the electro-optic characteristics of the FFS mode was not reported and compared between two modes.

2. Experimental

Figure 1 presents the cell structure of the CNT-doped IPS cell and FFS cell. In the IPS cells, the signal and common electrodes exist only on the bottom glass substrate with an electrode width of 5 ㎛ and a distance (l) of 10 ㎛ between electrodes. The FFS cells have an electrode width of 4 ㎛ and a distance (l') of 5 ㎛ between electrodes with extra electrode in a plane shape below passivation layer. (that these electrodes exist same position like a IPS cells.)

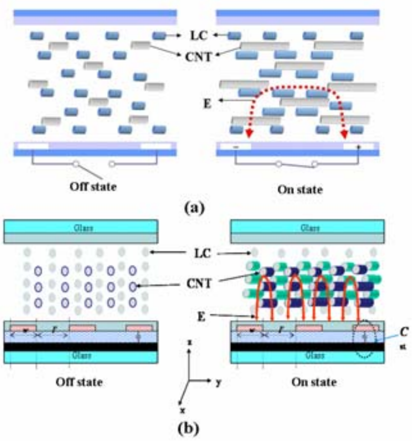

Fig. 1. Schematic of the cell structure of the CNT-doped (a) IPS cell and (b) FFS cell in off and on states

IPS cells are composed of aluminum and transparent electrodes and FFS cells are compose only transparent electrodes, respectively. Due to the electrode structure, in the IPS mode, the horizontal electric field (E_y) is mainly generated between electrodes when a voltage is applied but FFS mode generated all area including on to the electrode. For an alignment layer, a homogenous 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 in the IPS cells. On the other hand, FFS cells have 83° with respect to E_y. The cell was then assembled to give to each other d = 3.5, 3.8 ㎛ in IPS cells and FFS cells, where the plastic balls were used to keep d. Finally, in the IPS cell using the LC with positive dielectric anisotropy from Merck Co. ($\Delta\varepsilon$ = 7.4, Δn = 0.088 at λ = 589 nm, γ= 147 mpa·s) with a small amount (5 x 10^{-4} wt %) of single-wall CNTs (SWCNTs) and FFS cell used the LC with positive dielectric anisotropy from Merck Co. ($\Delta\varepsilon$ = 15.25, Δn = 0.1034 at λ = 589 nm, γ= 143 mpa·s) with a small amount (1 x 10^{-3} wt %) of multi-wall CNTs (MWCNTs) were filled at room temperature by capillary action. For the CNT-doped cells, a small amount of the CNTs was doped into the LC. Undoped and CNT-doped cells were also fabricated, and the electro-optic characteristics were compared.

3. Results and discussion

In the homogeneous cell like a IPS and FFS mode, the normalized transmittance, T / To, is given by $sin^2(2\,\psi(V))\,sin^2(\pi\,d\,\Delta n_{eff}(V) / \lambda)$, 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 optic axis coincident with one of the crossed polarizer axes so that the cell appears black. In the on state, the homogeneous 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 [13].

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 applied voltage, the uniform transmittance was generated, as shown in Fig. 2 and there was no difference among these cells.

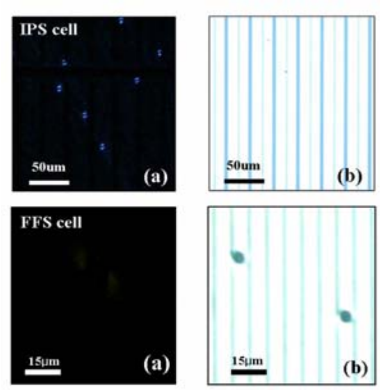

Fig. 2. Polarization microphotographs of (a) off and (b) on stage of the pure and CNT-doped cells

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.

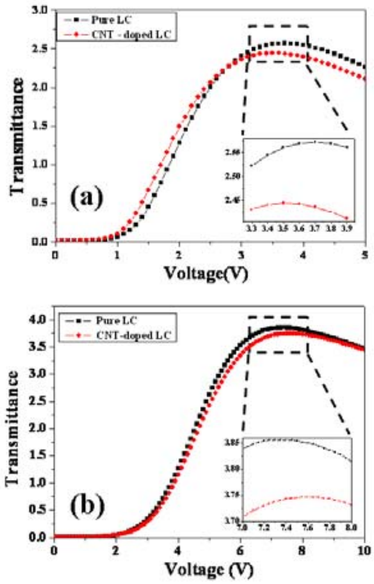

Fig. 3. Measured voltage-dependent transmittance curves of the pure LC and CNT-doped LC cells: (a) FFS cell, (b) IPS cell

The transmittance of CNT doped cells at maximum value was slightly lower than that of pure cells, and V_{op} of CNT-doped LC cell (7.55V) was slightly higher than that of pure LC cell (7.35V) in the IPS cell. However, the FFS cell does not show the same effect like in the IPS cell. Transmittance also slightly reduced in the CNT-doped cell, but V_{op} of CNT-doped LC cell was lower than pure LC cell. The V-T curves using another LC mixture exhibited the same 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 [14] was reduced appreciably (approximately 7.5 % used IPS cell, 5.6% used FFS cell, respectively) in the CNT-doped LC. 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 $V_{op} = \pi\, l \sqrt{K_{22} / \varepsilon_0 |\Delta\varepsilon|} / d$. 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[15]. The elastic modulus of SWCNTs is much larger than that of LC. 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 relationship, K_{22}(C-1)/K_{22}(C-2) = $[V_{op}(C\text{-}1)/V_{op}(C\text{-}2)]^2$, we estimated that K_{22} in the CNT-doped LC increased to 5.38, i.e. equivalently to approximately 5.5 %. However, at the moment we could not explain clearly the origin of decrease in V_{op} compared to that of pure LC cell. In fact, the field density to rotate the LC and switching concept in the FFS mode is quite different from those of the IPS mode, which may give different effects on V_{op}.

Finally, the response time of Pure and CNT-doped cell was measured to identify the effect of the reduced rotational viscosity on the response time of the CNTs-doped LC cell. Fig. 4(a) and (b) present the measured rising time and the decaying time of the IPS cell and FFS cell in eight gray levels by applying a square wave ac voltage with 60 Hz.

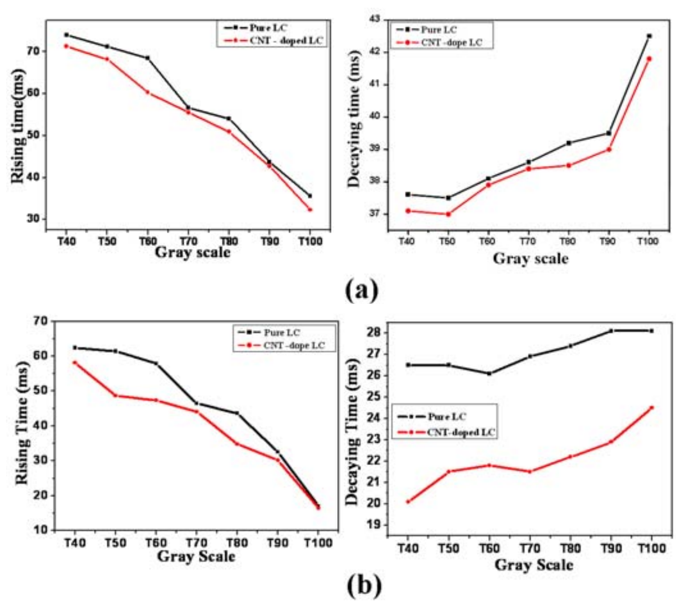

Fig. 4. Measured rising and decaying times of the pure LC and CNT-doped LC cells in the (a) FFS and (b) IPS mode.

Here, the applied voltages for each gray scale were identical for pure and CNT-doped cells. In the case of the rising time, the pure cell reacted slightly faster than the CNT-doped cell. The average decay time in CNT-doped cell was also faster than that in pure cell; the decaying response time in CNT-doped cell was approximately 18% faster in the IPS mode and 12.5% faster in the FFS mode. The decaying time is in general proportional to γ . The rotational viscosity of CNT-doped LC is reduced to compare of the pure LC used to each mode so that it can fast response time in the IPS and FFS cell.

4. Summary

In summary, we have examined the effects of CNTs on a nematic liquid crystal and electro-optical characteristics of the in-plane switching and fringe field switching cells. In the IPS cell, 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. Also CNT-doped FFS cell decreased operation voltage. The physical properties of the LC such as the rotational viscosity were modified by the minute doping of CNTs, which helps improve the response time of the IPS and FFS cell. This opens a possible application of the CNT-doped LC to the IPS and FFS LCD to improve the response time by modifying the physical properties of the LC by CNTs.

5. Acknowledgement

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