Effect of the Surface Dielectric Layer on the Electro-Optical Performances of Liquid Crystal Devices

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Abstract

We studied the dielectric layer effect on the electro-optical (EO) properties of liquid crystal (LC) devices together with numerical simulations. Recently, it has been reported that the surface dielectric layer affects significantly the EO performances of LC microlens arrays and wide-viewing LC displays. it is found that the operation voltage of the LC device decreases with increasing the dielectric constant or with decreasing the thickness of the dielectric polymer layer. The experimental data agree well with theoretical results predicted in a simple dielectric model within the continuum formalism.

1. Introduction

Liquid crystals (LCs) have been extensively studied for technological applications, such as LC displays and photonic components, as well as scientific interest because of a variety of physical phenomena and electro-optic (EO) effects. Basically, conventional LC devices are fabricated using indium-tin-oxide (ITO) glass substrates on which an alignment layer is prepared to have the optical anisotropy. For tailoring the EO effect of the LC for specific applications, hybrid LC devices with functional polymers have been recently proposed for LC displays [1-3] and microlens arrays [4]. Most of the previous works have been focused on composite film structures where the LC was embedded in the polymer matrices or networks to produce the scattering type EO switching [5]. For wide-viewing LC displays, a periodic array of surface relief gratings was produced on a photo-controllable polymer layer to form self-induced four-domain structures in each pixel of the LC device [2]. However, the effect of such dielectric layer with photo-controllable surface relief on the EO properties of the LC device has not been fully understood so far. In this work, we present experimental results for the dielectric layer effect on the EO properties of the LC devices together with numerical simulations. The photo-controllable polymer was used as a dielectric material on which the alignment agent of the LC was prepared. The thickness of the dielectric polymer layer was varied to find the relationship between the operation voltage or the Fredericks threshold [6] and the dielectric parameters of the LC and the polymer. It was found that the experimental data agree well with theoretical results predicted in a simple dielectric model within the continuum formalism.

2. LC Cell with Functional Polymer Layer

In this work, we simply consider a 1-dimensional system in which the thickness of each layer is uniform in the xy-plane. The schematic structure of the LC cell with functional polymer layer (FPL) is illustrated in Fig. 1.

The cell consists of two glass substrates that are

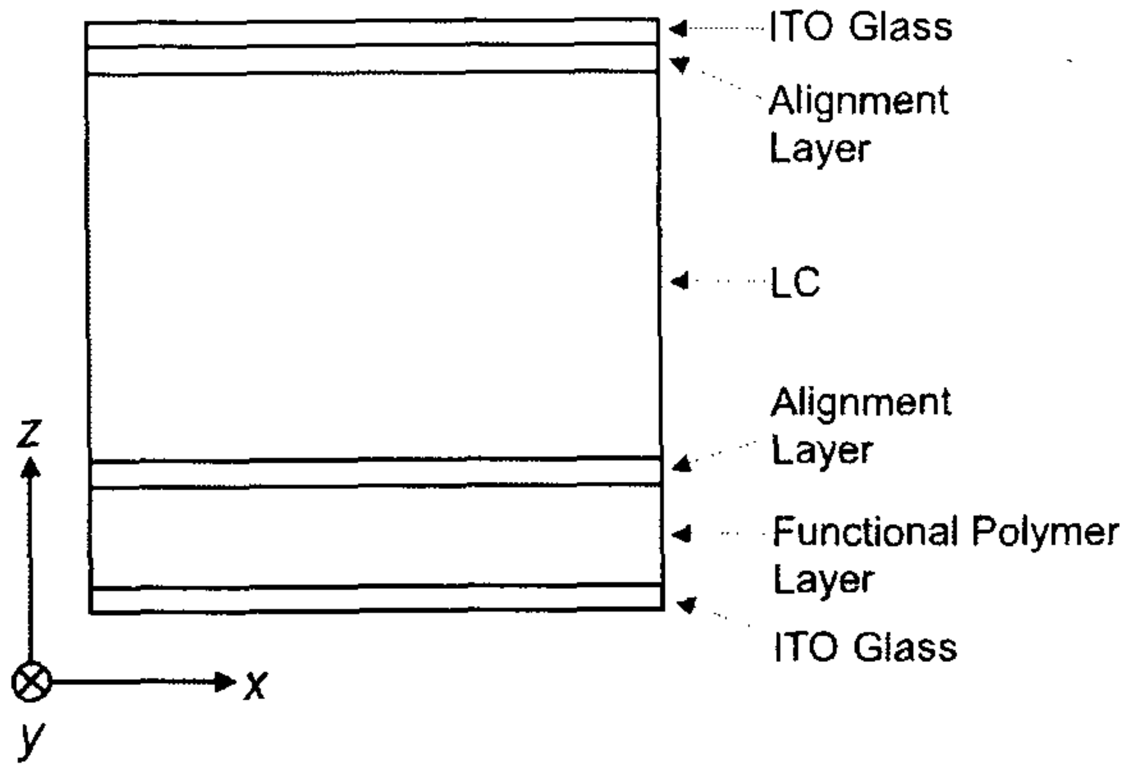

Fig. 1 The LC cell structure having a functional polymer layer and the coordinate system.

coated with ITO. On one of the substrate, the FPL was prepared. An alignment layer coated on the top of the FPL produces uniform homeotropic alignment of the LC molecules, i.e., the molecular director is aligned perpendicular to the substrate surface. Generally, the dielectric constant of the alignment layer is much larger than those of the LC and the FPL. In addition, the thickness of the alignment layer is very thin. Therefore, we only take the LC and the FPL into account for our purpose.

In Fig. 1, the tilt angle (θ) of the LC is varied along the *z*-axis and the twist angle (φ) in the *xy*-plane is fixed. Taking the director vector as $\hat{n} = (\cos\theta\cos\varphi, \cos\theta\sin\varphi, \sin\theta)$, the resultant free energy density is expressed as [6]

$$f = \frac{1}{2}K_1(\nabla\cdot\hat{n})^2 + \frac{1}{2}K_2(\hat{n}\cdot\nabla\times\hat{n})^2 + \frac{1}{2}K_3(\hat{n}\times\nabla\times\hat{n})^2 + \frac{1}{2}\varepsilon\vec{E}\cdot\nabla V, \qquad (1)$$

where K_1, K_2, K_3 are the elastic coefficients, $\vec{E}$ is the electric field, V is the voltage, and ε is the dielectric constant. Minimizing the above free energy density Eq. (1), we obtain the Euler-Lagrange equation [6] that gives a numerical solution for each set of the cell parameters. For calculating the electric potential at the LC/FPL interface, we utilize the constraint that the normal components of the electric displacement must be continuous at the interface.

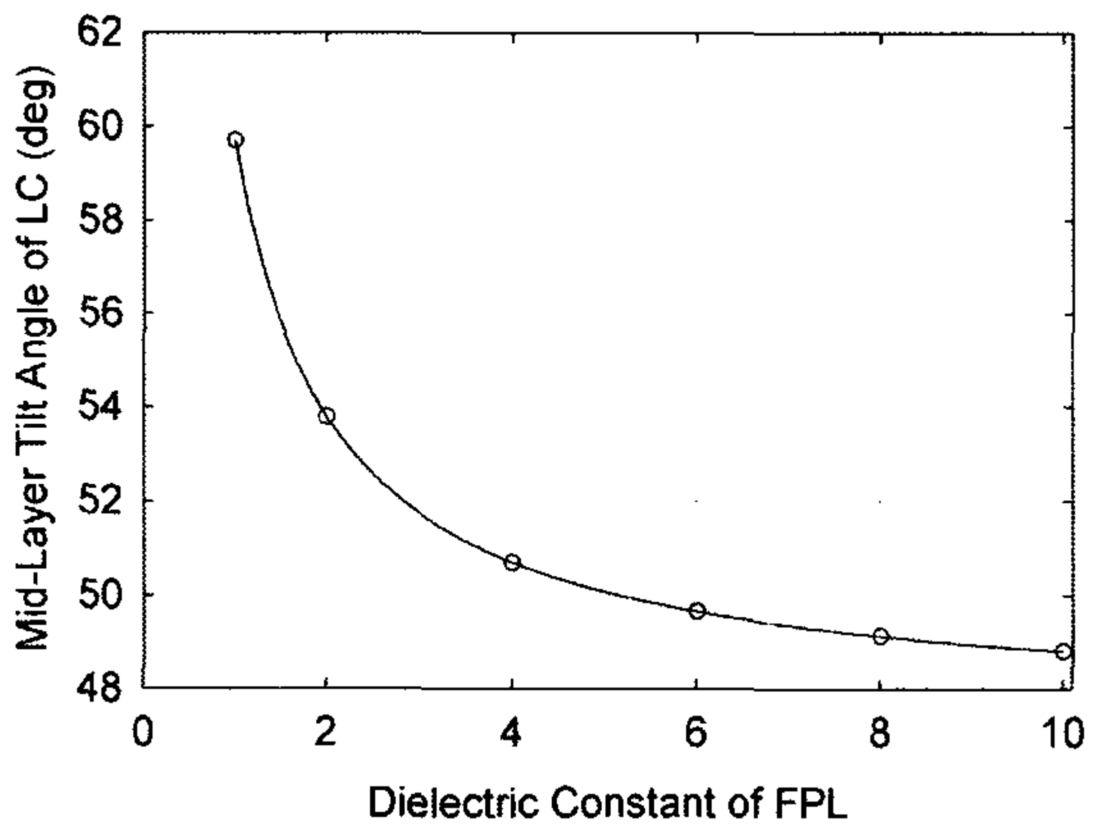

Fig. 2 Calculated mid-plane tilt variations of the LC for various dielectric constants of FPL.

In order to obtain the director profiles, we executed numerical simulations based on an iterative finite-difference method [7]. The material parameters of the LC are $\varepsilon_\perp = 6.3$, $\varepsilon_\parallel = 3.3$, $k_1 = 14.5\times10^{-12}$ N, $k_2 = 6.2\times10^{-12}$ N, and $k_3 = 12.7\times10^{-12}$ N [8]. Initially, the LC molecules are vertically aligned ($\theta \approx 89.9°$) and they become to be parallel to the substrate under the applied voltage. Fig. 2 shows the mid-plane tilt angle variations of the LC for various dielectric constants of the FPL at $V = 5$ V. In this case, both the LC layer and the FPL are assumed to be 5 μm thick. It was found that the dielectric layer effect of the FPL vanishes in the high limit of the dielectric constant of the FPL, meaning that the director profile approaches that of no FPL case. Fig. 3 shows the mid-plane tilt angle variations of the LC as a function of the thickness of the FPL when the dielectric constant of the FPL is 5. As expected, the mid-plane tilt angle of the LC increases with the thickness of the FPL.

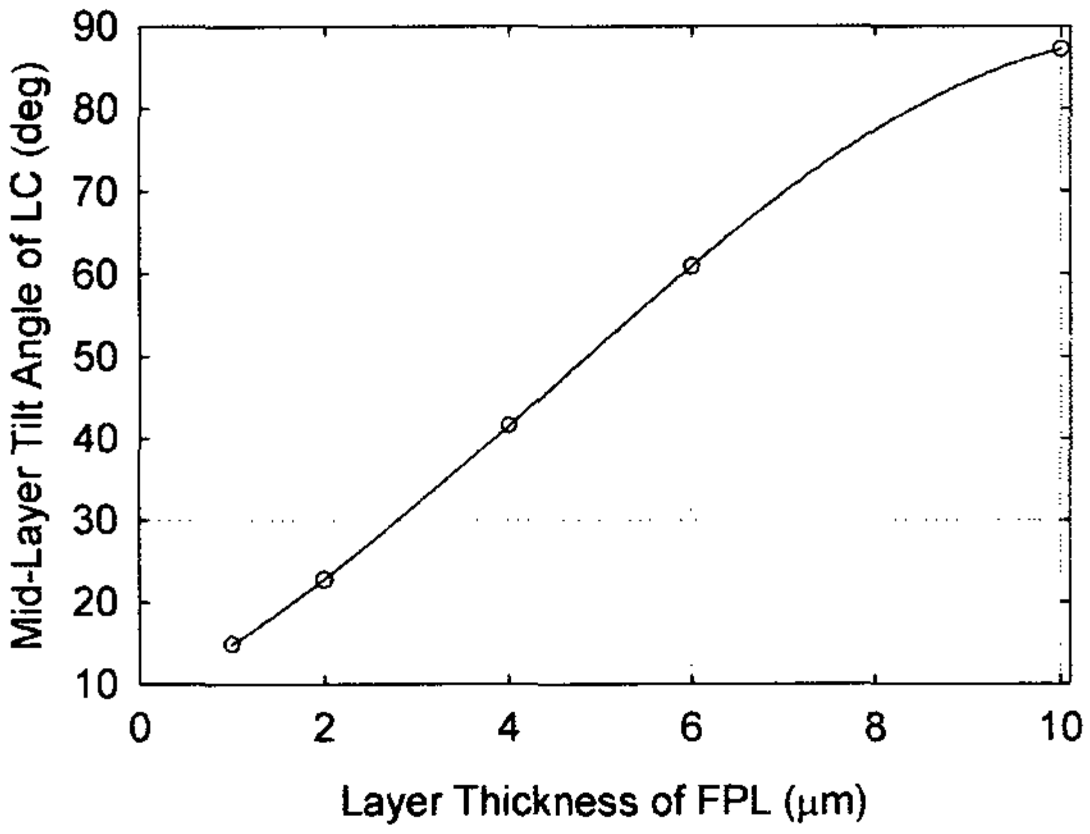

Fig. 3 Calculated mid-plane tilt variations of the LC as a function of the thickness of FPL

4. Experimental

For producing the FPL, the ultraviolet (UV) curable photopolymer of NOA65, obtained from Norland Products Inc., was used. The polymer was spin-coated onto the ITO glass substrates. The thickness of the polymer was controlled by the time duration of spin-coating at the speed of 3000 r.p.m.. The photopolymer was illuminated with the UV light at 200 mJ/cm^2 for full photo-crosslinking of the polymer. By monitoring the transmitted intensity in a wide range of the input wavelength, the thickness of the polymer was determined. Fig. 3 shows the measured thickness of the FPL as a function of the time duration of spin-coating at the speed of 3000 r.p.m. The polyimide, JALS 2021-R1 of Japan Synthetic Rubber Co., was prepared on the top of the photopolymer layer and on the bare glass substrate for homeotropic alignment of the LC. The LC cell was filled with a commercial nematic liquid crystal, EN37 of Chisso Petrochemical Co., and the cell gap was maintained using glass spacers of 5 μm. A He-Ne laser of 632.8 nm was used for measuring the EO transmittance as a function of the applied voltage under crossed polarizers. All the measurements were carried out at room temperature.

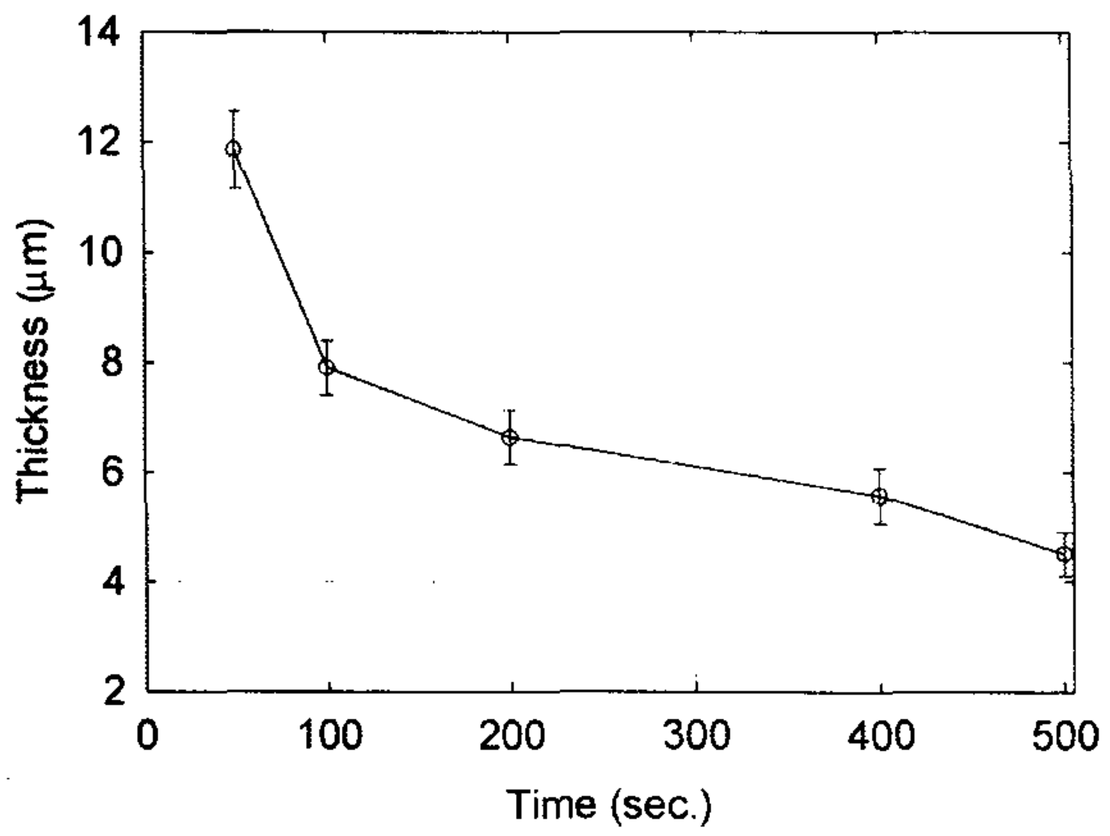

Fig. 4 The layer thickness of the ptotopolymer as a function of the time duration of spin-coating at the speed of 3000 r.p.m.

5. Results and Discussions

Figure 5 shows the EO transmittance of the LC cell with the FPL as a function of the applied voltage. The open symbols and solid lines represent the experimental data and numerical simulations in our dielectric model, respectively. It is clear that both the Fredericks threshold and the amount of the phase retardation strongly depend on the FPL. The Fredericks threshold becomes large with increasing the thickness of FPL. For understanding the dielectric layer effect, we introduce a concept of the effective voltage across the LC cell as follows.

$$V_{LC} = V_{applied}\left(1 + \frac{d_{FPL} / d_{LC}}{\varepsilon_{FPL} / \varepsilon_{LC}}\right)^{-1}, \qquad (2)$$

where $V_{applied}$ is an externally applied voltage and d is the layer thickness. Note that the scaled dielectric constant and the scaled thickness of the FPL by those of the LC layer primarily govern the effective voltage across the LC layer. Therefore, it is desirable to have a small value of d_{FPL} / d_{LC} and a large value of $\varepsilon_{FPL} / \varepsilon_{LC}$ to lower the operation voltage of the LC cell. Therefore, a precise tuning of the material parameters of the FPL should be required for given surface relief structures on the FPL. Moreover, the geometrical factors of the surface relief structures in the FPL such as the shape, the periodicity, and lattice structure should be taken into account for designing practical LC devices.

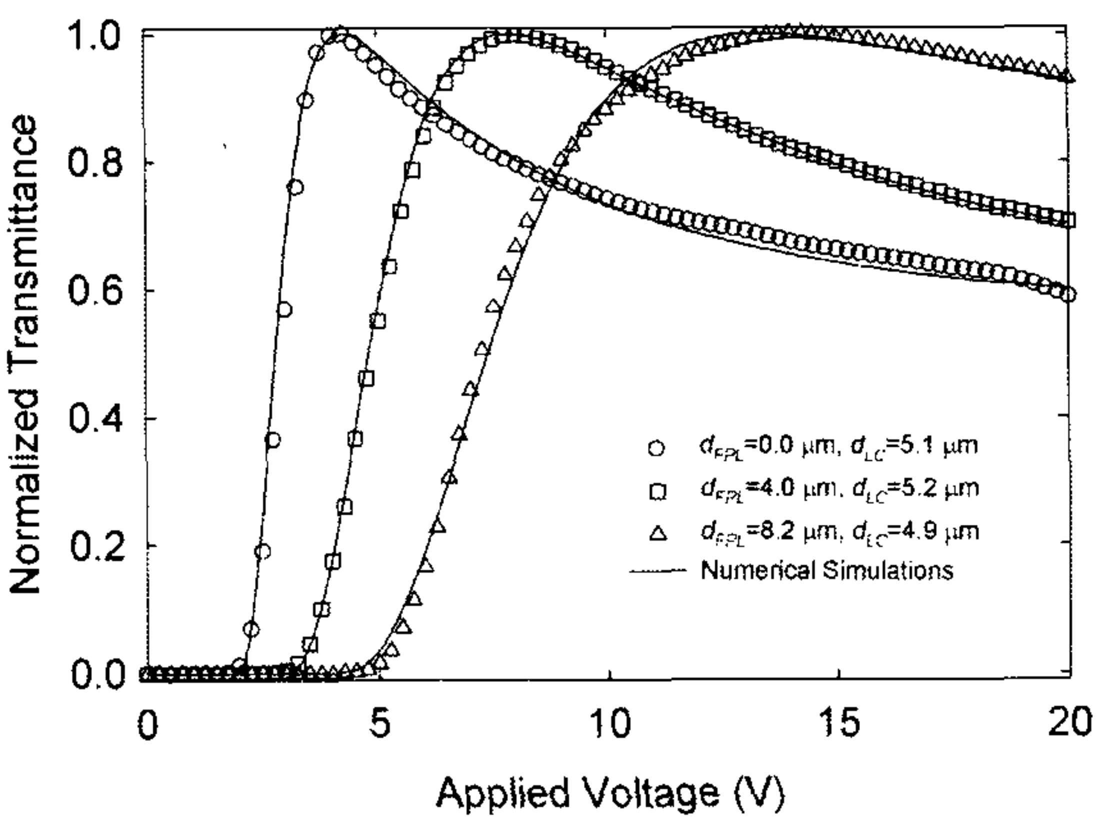

Fig. 5 The normalized transmittance of the LC cell with the FPL as a function of the applied voltage for various FPL thickness. The open symbols and solid lines represent the experimental data and numerical simulations in our dielectric model, respectively

6. Conclusion

We studied the dielectric layer effect on the electro-optic performances of liquid crystal devices with the FPL on the surface. For experiments, the photopolymerizable polymer was used as the FPL and the influence of the dielectric constants and the thickness of the polymer layer on the electro-optic properties of a liquid crystal/FPL composite film was investigated. The experimental data are in good agreement with the numerical simulations in the simple dielectric model. Both the scaled dielectric constant and the scaled thickness of the FPL by those of the LC play a crucial role in determining the operating voltage. In conclusion, the concept of using the FPL would be useful for controlling the EO performances of the LC devices..

7. Acknowledgement

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