A self-aligned multi-domain liquid-crystal display on polymer gratings in a vertically aligned configuration

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Abstract — We report on a new method of fabricating a vertically aligned multi-domain liquid-crystal display (LCD) using surface-relief gratings. A linear array of surface-relief gratings was produced by using a photosensitive polymer material coated on glass substrates by the illumination of the UV light through a photomask. The LCD cell was assembled with two substrates with polymer gratings in such way that the grating vectors were orthogonal to each other. In this LCD configuration, the nematic molecules were reoriented by distortions of an external electric field at the grating surfaces to make four different domains. The LC cell with self-aligned four domains shows excellent extinction in the off-state and wide-viewing characteristics in the on-state.

Keywords — Wide viewing, photopolymer, surface relief grating, vertical alignment.

1 Introduction

Recently, various techniques for improving the viewing properties of liquid-crystal displays (LCDs) have been devised, such as the birefringence compensation method,1 the multi-domain method,2-8 the in-plane-switching method,9 etc. Among them, the multi-domain method is the most widely used technology since the light transmitted through each pixel is simply averaged over sub-domains where the LC molecules are aligned along different directions domain by domain. However, such technology involves complex processes, for example, multiple rubbing and many elaborate wet processes.

In this paper, we propose a wide-viewing-angle LCD structure possessing two arrays of photopolymer gratings arranged orthogonal to each other. In the-off state of the proposed structure, the nematic molecules align mostly perpendicular to the cell surface and they are reoriented by distorted electric fields at the grating surfaces to make four different domains. The LCD cell shows excellent extinction in the off-state and the wide-viewing characteristics in the on-state.

2 Basic concept of a wide-viewing-angle configuration

We first executed two-dimensional numerical simulations to understand the molecular distribution on the surface-relief grating. The commercial program, DIMOS (Autronic-Melchers GmbH), was used for calculations. The LC parameters used for the calculations are as follows: the three elastic constants are $K_{11} = 14.5 \times 10^{-12}$ N, $K_{22} = 6.2 \times 10^{-12}$ N, and $K_{33} = 12.6 \times 10^{-12}$ N. The two dielectric con-

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Two-dimensional numerical simulations of the molecular distribution on the grating surface: (a) 1 V, (b) 3 V, and (c) 5 V. Thick white long dashes represent LC molecules and thin white lines represent electrical equi-potential lines, respectively.}
\end{figure}

stants are $\varepsilon_\parallel = 3.3$ and $\varepsilon_\perp = 6.3$. The refractive indices are $n_o = 1.488$ and $n_e = 1.586$, respectively. The dielectric relief gratings are assumed to be present on only one substrate. The amplitude of the grating is 1.6 $\mu$m, the periodicity is
400 μm, the dielectric constant is 4.6, and the cell gap is 5 μm. All the LC molecules are vertically aligned under no applied voltage. As shown in the Fig. 1(b), under an applied voltage, the LC molecules are tilted away from the surface normal mainly due to the distorted electric field at the surface. Under high voltage, the LC molecules are aligned along the grating vector. In this case, a two-fold symmetrical molecular distribution can be obtained since the one-dimensional dielectric grating surface is used. Therefore, when two grating surfaces, orthogonal to each other, are used four-fold symmetry can be produced. Figure 2 shows the basic concept of our device. It is clear that the nematic molecules align perpendicular to the cell surface in the-off state. Under an applied voltage, the molecules are reoriented by the distorted electric field at the grating surfaces to make four different domains.

### 3 Experimental

For fabricating the surface-relief gratings, the UV curable photopolymer (NOA65, Norland Products Inc.) was used. The polymer was spin-coated on indium tin oxide (ITO) coated glasses under 3000 rpm for 300 sec. As shown in Fig. 3, the photopolymer layer was irradiated by UV light from a Xe–Hg lamp with 125 mJ/cm² through a chromium photomask having striped apertures of 200 μm wide. The striped apertures were arranged in a period of 400 μm wide. The photopolymer was subsequently illuminated with the same power of the UV light with no photomask. The homeotropic polyimide, JALS 2021-R1 (Japan Synthetic Rubber Co.), was spin-coated onto the photopolymer surface. The cell was assembled with two grating surfaces such that the grating vectors were orthogonal to each other. The cell thickness was maintained using glass spacers 5 μm thick. The cell was filled with a nematic liquid crystal, EN37 (Chisso Petrochemical Co.), which had a negative dielectric anisotropy ($\varepsilon_\perp = 6.3$, $\varepsilon_\parallel = 3.3$). Note that the material parameters of EN 37 were used in numerical simulations. Microscopic textures were observed as a function of the applied voltage of a bipolar square waveform at a frequency of 1 kHz (for AC driving) under an optical polarizing microscope (Optiphot-pol2, Nikon). For measuring the electro-optic (EO) properties of the cell, an LCD characterizing system (DMS, Autronics Co.) with a white light source was used. All measurements were carried out at room temperature.

### 4 Results and discussion

#### 4.1 Surface-relief grating

When the photopolymer was illuminated with UV light passing through the photomask, the photopolymerization process began at positions corresponding to the apertures. Then, the difference in the monomer density between the illuminated regions and unilluminated regions caused the diffusion effect to move unpolymerized monomers into the illuminated region during the polymerization process so that the surface-relief grating was formed. The amplitude of the resultant solidified polymer was about 1.6 μm. The expression for the diffusion process can be written as

$$\frac{\partial \phi_m(x,t)}{\partial t} = \frac{\partial}{\partial x} \left[ D(x,t) \frac{\partial \phi_m(x,t)}{\partial x} \right] - F(x,t)\phi_m(x,t),$$

$$\frac{\partial \phi_p(x,t)}{\partial t} = F(x,t)\phi_m(x,t).$$

In the above expression, $\phi_m(x,t)$ is the monomer concentration, $\phi_p(x,t)$ is the polymer concentration, $F(x,t)$ is the polymerization rate and is related to the power of the illuminated UV light, and $D(x,t)$ is the diffusion constant. Figure 4(a) shows the numerical simulation of the grating amplitude as a function of the illumination time. Clearly, the numerical simulations agree well with the main features of the experimental results as a function of the illumination energy. In our experiment, the illumination energy was varied by changing the illumination time for fixed UV power. It
is then concluded that the grating amplitude can be controlled by adjusting the irradiation energy.

4.2 Electro-optic properties

Figure 5 shows the microscopic textures of our cell under crossed polarizers at different applied voltages. It is clear that the four-domain structure is naturally formed due to the distorted electric field. However, the effective voltages across the LC layer are different from region to region, thus the operating region is also different. The expression for the effective voltage can be written as

\[ V_{\text{effective}} = V_{\text{applied}} \left(1 + \frac{\varepsilon_{\text{LC}} V_{\text{applied}} d_{\text{polymer}}}{\varepsilon_{\text{polymer}} d_{\text{LC}}\varepsilon_{\text{LC}}} \right)^{-1}. \]

In the above expression, \( V_{\text{applied}} \) is the applied voltage to the cell, \( d \) is the thickness of each material at the local region, and \( \varepsilon \) is the dielectric constant. Under no applied voltage, the LC molecules are homeotropically aligned so that a dark state similar to a conventional vertically aligned (VA) structure is obtained. When the voltage is applied, the distorted electric field is produced due to the presence of the dielectric gratings. Since the two surface-grating vectors of the cell are orthogonal to each other, the distorted electric field has a four-fold symmetry with respect to the center of each unit domain. Figure 6 shows the normalized EO transmittance when a bipolar square waveform at a frequency of 1 kHz is applied to the cell. The driving voltage is somewhat higher than that of a conventional VA cell mainly due to the existence of the dielectric layer. The dashed line represents the numerical simulations of the LC cell with no dielectric layer. The open circles represent the experimental results of our device and the solid line is the least-square fit to the experimental data. For fitting, the surface grating
was assumed to be a flat dielectric layer over the whole region, \(d_{LC} = 6.25 \mu m\), and \(d_{polymer} = 3.15\).

Figure 7 shows the viewing-angle dependence of the luminance. The luminance has a high-symmetry property, meaning that the directional dependence of the viewing property is almost negligible. This is due to the natural appearance of the self-aligned multi-domain structure in our cell.

5 Conclusion

We have demonstrated a new wide-viewing LCD mode in a self-aligned multi-domain configuration. We have fabricated a rubbing-free homeotropic cell using two grating surfaces such that the grating vectors are orthogonal to each other. The new mode presented here shows excellent extinction in the off-state and the symmetric wide-viewing property in the on-state.

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References


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