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Self-formation of microdomains by the topographical and fringe field effects in a liquid crystal display with dielectric surface gratings

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We report on the self-formation of microdomains by the topographical and fringe field effects in a twisted nematic liquid crystal display (LCD) with dielectric surface gratings (DSG). A regular array of the DSG produces periodically aligned microdomains in each pixel because of the topographical alignment of the LC and the spatial variations of the effective voltage across the LC layer. The mutual optical compensation within each pixel is naturally achieved and thus the range of viewing in the LCD is significantly extended without complex surface treatments. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1510156]

One of the most widely used liquid crystal displays (LCDs), the twisted nematic (TN) LCD, has suffered from poor viewing properties that originate intrinsically from the asymmetrical nature of the LC alignment irrespective of the driving scheme whether a passive multiplexing or an active matrix driving is employed.[1] Various methods have been developed to solve the narrow viewing problem of the LCDs. For example, multidomains are often used for compensating the optical asymmetry in each pixel.[2] For obtaining such multidomains in each pixel, at least two easy directions should be generated for the surface alignment of the LC.[3] However, the surface treatment usually involves complex processes such as multiple rubbing and photoexposure.

Recently, in the vertically aligned LCD configuration, the distortions of the electric potential in the LC layer have been utilized for creating symmetric elastic distortions of the LC so that a wide viewing characteristic of the LCD is achieved.[4,5] Since no complex surface treatment for the LC alignment is involved, these methods are known to be simple and cost effective. The electric potential distortions are produced by patterned (or nonplanar) electrodes[4] or a two-dimensional array of dielectric surface relief structure.[5] These distortions can be denoted by the electrode fringe field (EFF) and the grating fringe field (GFF), respectively. Although the GFF effect is expected to play an important role in the LCDs, the GFF effect has not been well understood so far. Moreover, an attempt to combine the GFF effect with the topographical alignment of the LC[6,7] has not been made yet. Therefore, it is important to explore the possibility of using dielectric surface gratings (DSG) on a planar electrode to produce the topographical alignment of the LC as well as the GFF effect.

In this work, we propose a concept of spontaneously forming periodic microdomains in each pixel of the TN LCD with the DSG when the GFF effect is combined with the topographical alignment of the LC. In such a self-forming microdomain structure, the range of viewing in the LCD is expected to be greatly extended since the mutual compensation of the optical retardation is naturally achieved in each pixel. Basically, the strengths of the topographical and the GFF effects are governed by both the geometrical factors and the dielectric property of the DSG. The periodicity of the DSG should be on the order of 1 μm to produce a uniform alignment of the LC by the topographical effect.[6,7] Since the GFF effect depends on the dielectric properties of the DSG relative to the LC, the GFF effect may be described in terms of a scaled quantity, ξ, defined as the effective voltage per unit thickness across the DSG, V_{DSG}/h, scaled by the effective voltage per unit thickness across the LC layer, V_{LC}/ℓ, where h and ℓ are the thickness of the LC layer and the height of the DSG on the substrate, respectively.

We first derive an expression for ξ in terms of the effective dielectric constant of the LC layer (ϵ_{LC}) and that of the DSG (ϵ_{DSG}). Consider that both h and ℓ are periodic in x as shown in Fig. 1. Assuming that no polarization of the LC appears on a macroscopic scale, the electric displacement has only the z component, D_z, that is uniform. Under these circumstances, the effective voltages per unit thickness, V_{DSG}/h and V_{LC}/ℓ, are simply proportional to $D_z/\epsilon_{\mathrm{DSG}}$ and $D_z/\epsilon_{\mathrm{LC}}$, respectively. This directly leads to $\xi=\epsilon_{\mathrm{LC}}/\epsilon_{\mathrm{DSG}}$. Since the value of ξ is periodic with the DSG along the x

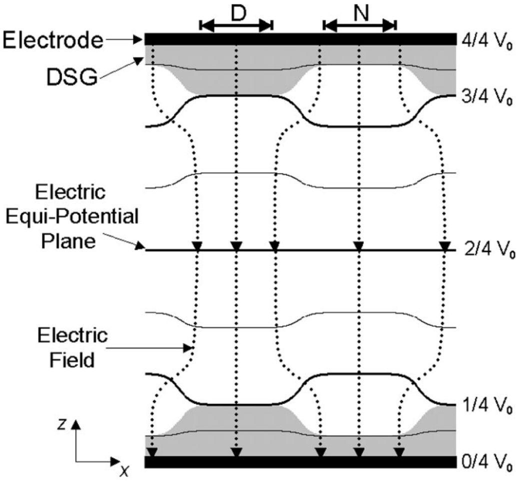

FIG. 1. The cross-sectional view of the spatial variations of V_{LC} and the fringe field lines produced by the GGF effect of $\xi=3.0$.

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axis, the spatial average of ξ over x is physically meaningful. The dimensionless dielectric parameter ξ is then given by

$$\xi = \frac{\langle \epsilon_{\mathrm{LC}} \rangle}{\epsilon_{\mathrm{DSG}}}. \tag{1}$$

The bracket denotes the spatial average over x. The parameter ξ can be used for describing the main features of the GFF effect created by a DSG in the LC cell. In fact, a subtle change in the GFF effect can be precisely controlled by the change in $\langle \epsilon_{\mathrm{LC}} \rangle$ to ϵ_{DSG}. For $\xi \approx 1$, no GFF effect will exist and only the topographical alignment of the LC will appear as a function of the periodicity of the DSG. However, for $\xi \gg 1$, a strong GFF effect is produced while for $\xi \ll 1$, a GFF effect resembling the EFF effect of a nonplanar electrode is expected. Note that for $\xi > 1$, the spatial variations of the effective voltage across the LC layer (V_{LC}) due to the GFF effect are enhanced. A typical example of spatial variations of V_{LC} and the resultant fringe field lines in the LC cell with the DSG of $\xi = 3.0$ are shown in Fig. 1. The DSGs in "D" and those in "N" are the hills and the valleys. And the dimensionless height of the D region and that of the N region, scaled by the cell thickness, are 1/8 and 1/20, respectively.

We now examine the GFF effect on the Fredericks transition in the TN cells for two cases of $\xi > 1$ and $\xi < 1$. The cell parameters are assumed to be $h_D = 0.5$ μm, $h_N = 0$, and $\ell_D = 5.5$ μm, giving $\ell_N = 6.5$ μm which is the cell thickness. The dielectric constant of the DSG material, AZ-6612 of Clariant Co., is $\epsilon_{\mathrm{DSG}} = 5.1$. For the cell of $\xi > 1$, the material parameters of a commercial LC (ZLI-4900-100 of Merck Co.) are used: the dielectric constants $(\epsilon_\perp, \epsilon_\parallel) = (7.9, 37.7)$ at 1 kHz and the elastic constants $(K_1, K_2, K_3) = (16.3, 9.5, 23.3)$ in unit of 10^{-7} dyn. The value of ϵ_{LC} increases with V_{LC} from 7.9 to 37.7, giving $1.55 \leqslant \xi \leqslant 7.39$. For the cell of $\xi < 1$, the same material parameters other than the dielectric constants $(\epsilon_\perp, \epsilon_\parallel) = (2.1, 5.1)$ at 1 kHz are used. This means that ξ varies from 0.42 to 1.00 with increasing V_{LC}. Using the earlier parameters, we carried out numerical simulations to study the GFF effect on the Fredericks transition in the TN cells with the DSGs of two different ξ's. A commercial LCD simulator, LCD Master of Shin Tech Co., was partly utilized for the numerical simulation. In Fig. 2, the midplane tilt angle in the D region, θ_D, and that in the N region, θ_N, are plotted as a function of the applied voltage V_0 scaled by the Fredericks threshold $V_{\mathrm{th},N}$ in the N region. For the cell of $\xi > 1$ (ZLI-4900-100), the actual value of V_{th} is found to be 1.00 V in D and 0.78 V in N. For the cell of $\xi < 1$, the values of V_{th} are 2.67 V in D and 2.48 V in N. It should be emphasized that the difference in the midplane tilt angle between D and N, $\Delta\theta$, increases with V_0, reaches a maximum, and eventually vanishes in the high voltage limit. Moreover, $\Delta\theta$ for $\xi > 1$ is always larger than that for $\xi < 1$ because of the enhanced spatial variations of V_{LC}. As will be discussed later in Fig. 4, self-formed microdomains will be observed only for $\xi > 1$.

Based on the earlier ideas, we fabricated our TN cell with the DSG of $\xi > 1$. The periodicity of the DSG was 6.0 μm. The widths of the hills and the valleys of the DSG were 2 and 4 μm, respectively. The measured parameters were $h_D = 0.79$ μm and $h_N = 0.28$ μm. Note that the DSG layer in N was not completely etched out during the etching process so that practically $h_N \neq 0$. The materials being used for the LC and the DSG were ZLI-4900-100 and AZ-6612. The TN cell was obtained by assembling two DSGs perpendicular to each other with no additional alignment layer and injecting the LC into the cell. The cell gap was 6.8 μm, giving $\ell_D = 5.22$ μm and $\ell_N = 6.24$ μm. Figure 3 shows a photograph of the TN cell taken under crossed polarizers at $V_0 = 2.1$ V ($\xi = 3.8$). Clearly, an array of self-formed microdomains in each pixel can be seen and the transmitted light intensity through the cell varies periodically with the DSG. As shown in Fig. 3, each unit cell consists of four bright domains in the corners (D), one dark domain in the center (N), and four gray domains (S) at the sides. The DSG configurations in D, S, and N are two-sides occupied, one-side occupied, and not occupied, respectively. In other TN cells with the DSG of the periodicity longer than 10 μm, no uniform microdomain array was observed under an applied voltage. This is consistent with the fact that the DSG with long periodicity is not capable of aligning the LC by the topographical effect.[7]

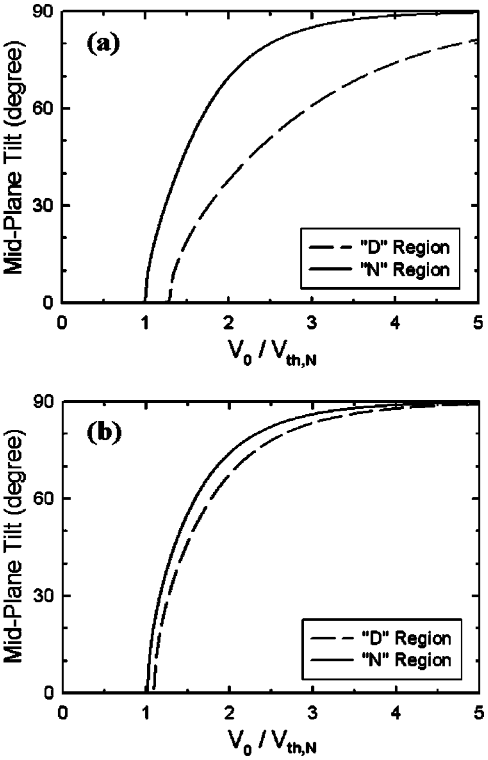

FIG. 2. The midplane tilt angle in D and that in N as a function of the applied voltage V_0 scaled by the Fredericks threshold $V_{\mathrm{th},N}$ in N for (a) $\xi > 1$ and (b) $\xi < 1$. The self-formed microdomains are expected in (a).

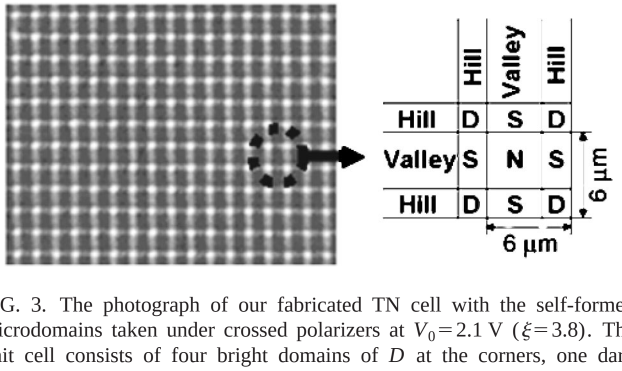

FIG. 3. The photograph of our fabricated TN cell with the self-formed microdomains taken under crossed polarizers at $V_0 = 2.1$ V ($\xi = 3.8$). The unit cell consists of four bright domains of D at the corners, one dark domain of N in the center, and four gray domains of S in the sides.

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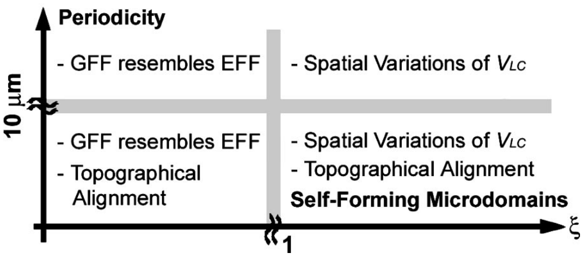

FIG. 4. The criteria for the self-forming microdomains by the topographical alignment and the grating fringe field effect of the DSG in the plane of the periodicity and the dimensionless dielectric parameter ξ.

The criteria for self-forming microdomains are given in terms of the periodicity of the DSG and the magnitude of ξ in Fig. 4. In order to obtain the topographical alignment of the LC and the spatial variation of V_{LC}, the periodicity should be on the order of 1 μm and the dielectric parameter should be $\xi > 1$. The periodic microdomains will be spontaneously formed only in this case. As shown in Fig. 4, a GFF effect resembling the EFF effect of a nonplanar electrode occurs for $\xi < 1$, and the topographical alignment effect disappears with increasing the periodicity above 10 μm.[7] The criteria presented here should provide a basis for tailoring the electro-optic performances of the LCDs by adjusting the geometrical factors and the dielectric parameters of the DSG.

In Fig. 5, the gray scale representation of the isoluminance maps of a conventional TN cell (cell gap: 6.3 μm, cell I) and our fabricated TN cell with the DSG (cell II) are shown with the positive vertical viewing direction[1] denoted by $\hat{s}$. The luminance in the normal direction of cell II at $V_0 = 2.1$ V ($\xi = 3.8$) corresponds to the gray level of 45% in the normally white mode. For cell I, the same gray level is obtained at $V_0 = 1.5$ V. The Fredericks thresholds for cell I and the N region of cell II are found to be about 0.79 and 0.86 V, respectively. The luminance in the normal direction is set as 100% in each gray scale representation. For the cell I shown in Fig. 5(a), a dark region is found to be as wide as ±80° with respect to $\hat{s}$. For cell II shown in Fig. 5(b), however, the bright region is far extended and the dark region is as narrow as ±25° with respect to $\hat{s}$. Note that, in Fig. 5(b), the minimum luminance of the dark region is larger than 30% of the luminance in the normal direction, which greatly eliminates the contrast inversion of TN mode. This agrees well with our numerical simulations.[8] It is then concluded that the self-formed microdomains in each pixel play a critical role on extending the range of viewing in the LCDs.

In summary, we have demonstrated that the self-formation of periodic microdomains is predominantly governed by the geometrical factors of the DSG and the dielectric parameters of both the LC and the DSG. The self-formed microdomains in each pixel of the TN cell with the DSG should be useful for eliminating the contrast inversion of the TN mode.

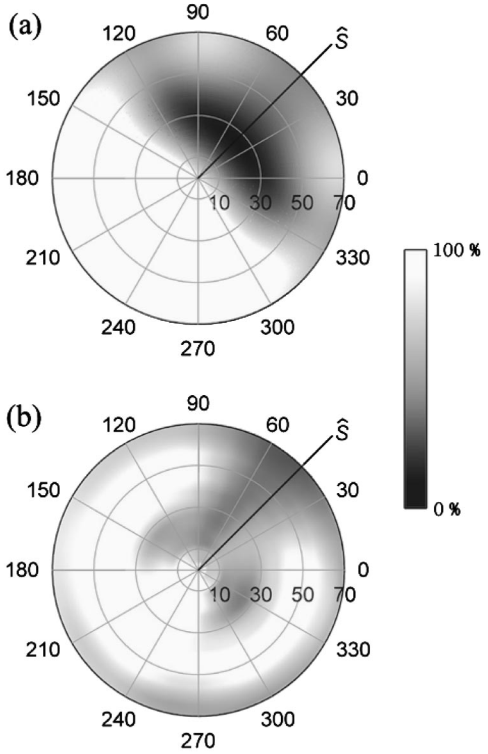

FIG. 5. The gray scale representation of the isoluminance maps of (a) a conventional TN cell at $V_0 = 1.5$ V and (b) our fabricated TN cell with the DSG at $V_0 = 2.1$ ($\xi = 3.8$) for the given gray level of 45% in the normally white mode.

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