

Continuous liquid crystal pretilt control through textured substrates

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(Received 13 September 2004; accepted 27 October 2004)

Reliable control on the pretilt alignment of nematic liquid crystal (LC) in the 30°–50° range is a well-known challenge. An unconventional approach, involving microtextured surfaces with domains favoring dissimilar LC alignments, has recently demonstrated applicability in bi- and tristable displays. These textured domains realize the so-called frustrated boundary condition in which the LC elastic energy built-up (frustration) can drive the LC alignment into macroscopic uniformity. Here we show that one can harness the frustrated boundary to achieve variable LC pretilt control up to 40°. © 2004 American Institute of Physics. [DOI: 10.1063/1.1833552]

When subject to an inhomogeneous surface anchoring field, nematic liquid crystal (LC) elasticity governs the LC local director not to vary faster than the extrapolation length l_e , equal to the ratio of the LC elastic constant to the strength of the surface anchoring field.¹ Typical values of extrapolation length are about 1 μm . Consider inhomogeneous alignment patterns comprising square domains with local preferred alignment directions alternating between x and y , as shown in Fig. 1(a). At very large pattern period P , the LC alignment on the pattern is expected to copy the pattern inhomogeneity. The exception occurs within l_e from the interface between two adjacent domains, where the LC alignment must undergo a gradual transition from one orientation to the other [see left of Fig. 1(b)]. At very small $P \leq l_e$, the interfacial regions would occupy a substantial portion of the domain area, so that the LC configuration is highly homogenized in the $\phi=45^\circ$ azimuthal direction, as shown on the right of Fig. 1(b), verified experimentally.^{2–5} Homogenization of the LC alignment reduces the elastic strain energy of the LC and leads to a rise in the LC azimuthal surface energy, as the LC orientation is misaligned from the locally preferred direction. If the rise in surface energy is large enough, the LC system may lower its total energy further by undergoing an orientation transition at some critical value of the periodicity P^* , into an alignment state with uniform finite pretilt.^{5,6} Here we demonstrate that by adjusting the surface anchoring energy—achievable by varying the groove depth D of the surface pattern⁷—the pretilt angle at the orientation transition can be controlled.

Surface microtextures were fabricated on silicon by atomic force microscopic (AFM) local oxidation,^{5,8} comprising square domains of parallel grooves oriented along x and y in alternations with period $= 0.8 \mu\text{m}$ ($< P^*$). Groove depth D was varied from 13 to 34 nm. The patterned substrates were then made into LC display cells with the opposite substrate being glass coated with a polyimide layer unidirection-

ally rubbed along y . Nematic LC 5BC was filled into the cells at 40 °C above the nematic–isotropic transition temperature by capillarity. Shown in Fig. 1(c) are optical images of these cells between crossed polarizers. As D increases, the cell changes steadily from yellow to green. Generally, the optical property of a LC cell depends on its overall phase retardance, $R = 2\pi\langle\Delta n\rangle d/\lambda$, where d is the cell thickness, λ is light wavelength, and $\langle\Delta n\rangle$ the average difference in refractive index of the LC cell for e - and o -waves, which decreases monotonically from maximum to zero when the LC pretilt increases from 0° to 90°. The observed color change in Fig. 1(c) thus reflects a decreasing $\langle\Delta n\rangle$, that is, the average LC pretilt increasing with increasing D . We measured optical reflection spectrum for each cell between crossed and parallel polarizers, and divided the former by the latter to eliminate extraneous effects due to spectral response of the measurement setup. The resulting normalized spectra of the equal-thickness $D=13$ and 26 μm cells are shown in Fig. 2 (solid lines). The data clearly show the spectrum greenshifts as D is increased. The fast oscillations in the spectrum arise from optical interference within the cell gap (Fabry–Perot fringes). We modeled the measured spectra by the 4×4 matrix method—which essentially builds solutions to the Maxwell's equations for LC cells with uniform xy director field and arbitrary configurations along z —and deduced the LC pretilts on the checkerboards by comparing with the experiment.⁵ In Fig. 3 are plotted the LC pretilts thus deduced versus the value of D (solid circles). The noted rise in LC pretilt with increasing D is consistent with the observation.

Data shown in Fig. 3 can be understood by considering the surface potential $W(\theta, \phi)$ of LC anchoring on a surface with orientation (ϕ, θ) which can vary on the xy plane. The potential possesses the general form⁵

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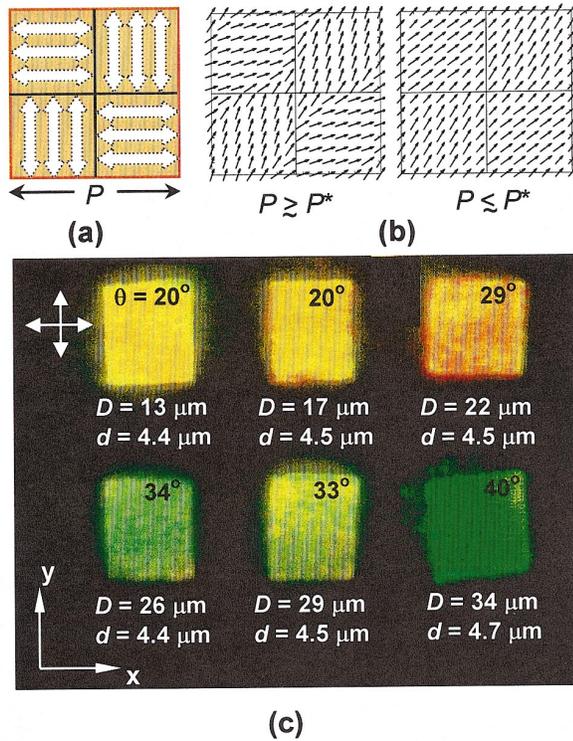


FIG. 1. (Color) (a) Schematic of a square inhomogeneous alignment pattern with adjacent domains preferring orthogonal alignment directions. (b) A sketch of the planar LC configuration in inhomogeneous alignment pattern as that in (a) (left) above and (right) below the transition period P^* for LC pretilt jump. (c) Optical images of the LC cells, made of checkerboard grooved patterns with D varied from 13 to 34 μm , between crossed polarizers. The double-headed arrows indicate the orientations of the polarizer (along y) and analyzer (along x). The patterns are mostly $\sim 23 \times 25 \mu\text{m}^2$ in size. The quoted values of d and θ were deduced by model-fitting the normalized reflection spectra of each cell.

$$W(\theta, \phi) = \frac{1}{2}W_\phi \cos^2 \theta \sin^2[\phi - \phi_0(x, y)] + \frac{1}{2}W_\theta^{(2)} \sin^2 \theta + \frac{1}{4}W_\theta^{(4)} \sin^4 \theta, \quad (1)$$

where the W are constants, and ϕ_0 is the local preferred azimuthal orientation (identical to the spatially varying local groove orientation). The preferred LC pretilt innate to the substrate is denoted 0° . With $W_\theta^{(2)}=0$, $W_\theta^{(4)}=1.5 \times 10^{-5} \text{ J/m}^2$, and $W_\phi=1.0 \times 10^{-5} \text{ J/m}^2$, we found that a frustrated boundary model—one that seeks the optimal LC configuration through minimization of the total LC energy

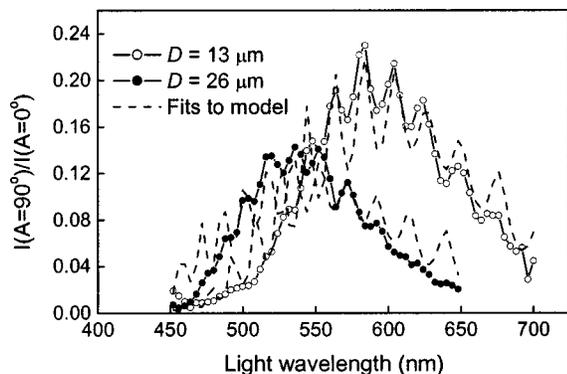


FIG. 2. Normalized reflection spectra of the $D=13$ and $26 \mu\text{m}$ cells. Solid lines are measurements. Dashed lines are simulations. The entrance polarizer was along y during measurement.

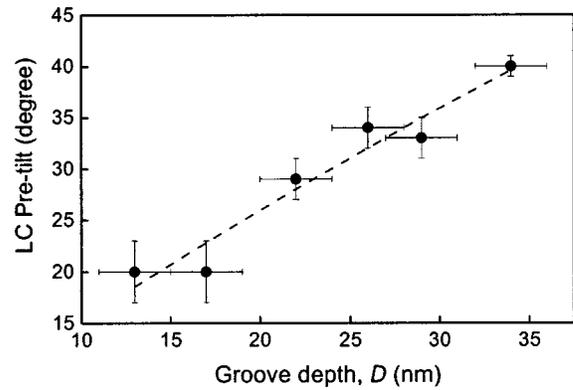


FIG. 3. Plot of LC pretilt against groove depth. Solid circles are data. Dashed line is obtained by calculations with the frustrated boundary model assuming the azimuthal surface energy to vary as D^2 (see Ref. 5 for details).

(=sum of LC elastic and surface anchoring energies)—could produce a 40° pretilt jump in checkerboard microtextured substrates with $D=34 \text{ nm}$ below $P^*=1 \mu\text{m}$.⁵ Since the azimuthal orientation of the LC in the uniform state is close to 45° everywhere [Fig. 1(b)], one is justified to use $W(\theta, \phi=45^\circ)$ to estimate the surface anchoring potential of the uniform alignment state. By assuming the values of W for $D=34 \text{ nm}$ quoted above and that W_ϕ scales as D^2 in accordance to the theory for grooved surfaces,⁷ we use Eq. (1) to calculate $W_\phi(\theta, \phi=45^\circ)$ for different D between 10 and 35 nm and plot the result in Fig. 4. It is interesting to note that all the displayed surface potential curves exhibit a minimum at values of θ corresponding well with the measured LC pretilts shown in Fig. 3. Indeed, they are in exact agreement with the simulated LC pretilts by the frustrated boundary model (dashed line in Fig. 3). Previous study found that the D^2 scaling of W_ϕ could fail at sufficiently large D ($\geq 32 \text{ nm}$),⁹ whereas we also found the measured LC pretilt (data not shown) to deviate from the trend shown in Fig. 3 for $D > 35 \text{ nm}$. Occurrence of a minimum in $W_\phi(\theta, \phi=45^\circ)$ at finite θ is what drives the LC pretilt jump at P^* . By increasing D , the azimuthal surface energy component of $W_\phi(\theta, \phi=45^\circ)$ [i.e., the first term of Eq. (1)] increases in proportion causing the minimum position of $W_\phi(\theta, \phi=45^\circ)$ to shift to higher θ . Physically, increase in D increases the

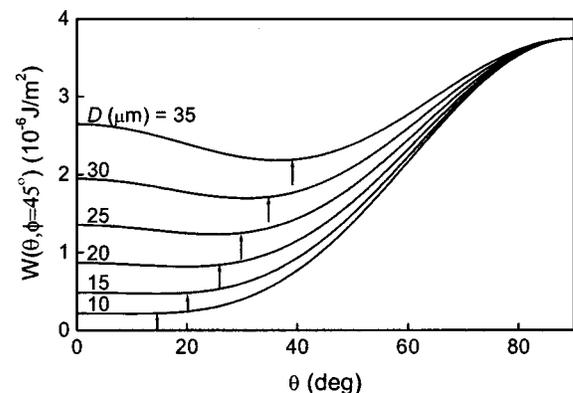


FIG. 4. Surface potentials of uniform LC states, $W(\theta, \phi=45^\circ)$, on checkerboard grooved patterns with different groove depths obtained from Eq. (1) assuming $W_\theta^{(2)}=0$, $W_\theta^{(4)}=1.5 \times 10^{-5} \text{ J/m}^2$, and $W_\phi=1.0 \times 10^{-5} \text{ J/m}^2$ at $D=34 \mu\text{m}$, and $W_\phi \propto D^2$. The arrows indicate the minimum of the curves.

azimuthal surface energy of the $\phi=45^\circ$ uniform alignment state. This explains why the deeper the grooves were made, the further the LC director tilted away from the patterned surface.

In conclusion, we have demonstrated continuous variation of the LC pretilt with groove depth. While the surface patterns demonstrated were fabricated by AFM nanolithography, our approach is amenable to alternative techniques such as photoalignment that are more apt for mass production. The latter has been used for making multidomain LC displays, which is however used for a different purpose; namely, to widen the viewing angle,⁹ and require the size of the constituent alignment domains to be about 10–100 μm . In comparison, that required for the present application is smaller in the micron order, but is still well within the scope of existing lithographic techniques.

This work is supported by Research Grant Council of Hong Kong through project no. HKUST6115/03E.

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