Liquid crystal pretilt angle control using nanotextured surfaces

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A scalable and economical method to control the pretilt alignment of nematic liquid crystal (LC) to ~45° has long been sought as it constitutes the foundation of some key technologies of LC displays. We demonstrate that nanotextured surfaces fabricated by mixing horizontal and vertical polyimides allow complete LC pretilt control from ~0° to 90°. Devices made with these surfaces show response times four times superior to the state-of-the-art panel. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2206067]

I. INTRODUCTION

A central element to liquid crystal display (LCD) is the alignment layers controlling the LC orientations on the panel surfaces. At present, a technology gap exists for attaining LC pretilt angles in the 30°–60° range although it has long been recognized that large pretilt angles, around 45°, can lead to fast response time and power-saving bistable bend-splay displays. While numerous methods for generating large pretilt alignments were proposed,[1–9] none has been adopted in manufacturing. Here we show that nanotextured alignment layers comprising domains of horizontal and vertical polyimides can fill this technology gap. The alignments produced are robust, reproducible, and scalable. We demonstrate successful realization of a zero-bias bend display by using these alignment layers, which shows an unprecedented response time of 2 ms.[10]

Consider a surface consisting of simultaneous vertical (V) and horizontal (H) LC alignment domains with a common preferred azimuthal direction ϕ. In general, the LC alignment near the surface varies according to the V and H domains, unless the domain sizes are too small for the surface anchoring energy to withstand the LC elastic recoil due to the alignment inhomogeneity. Away from the surface, the alignment inhomogeneity evens out, leading to a uniform pretilt angle. The complete three-dimensional LC configuration can be modeled through minimization of the total energy of the system, $F_{\text{tot}}(\boldsymbol{n})$. For a semi-infinite space filled with LC above $z=0$,[11]

$$F_{\text{tot}}(\boldsymbol{n}) = \int\int\int_{\text{volume}} F_e(\boldsymbol{n}) d^3\boldsymbol{r} + \sum_i \int\int_{z=0} f_i(x,y) \frac{W_{0i}\sin^2(\theta-\theta_{0i})}{2} dxdy, \quad (1)$$

where $\boldsymbol{n}(\boldsymbol{r})$ denotes the LC director field $\equiv(\phi,\theta(\boldsymbol{r}))$ at position $\boldsymbol{r}$, $f_i(x,y)$ is unity if (x,y) is in domain i ($i=\text{V},\text{H}$) and zero otherwise, W_{oi} is the polar surface anchoring energy of domain i, and $F_e(\boldsymbol{n})$ is the Frank-Oseen elastic energy:

$$F_e(\boldsymbol{n}) = \tfrac{1}{2}[K_{11}(\nabla\cdot\boldsymbol{n})^2 + K_{22}(\boldsymbol{n}\cdot\nabla\times\boldsymbol{n})^2 + K_{33}(\boldsymbol{n}\times\nabla\times\boldsymbol{n})^2], \quad (2)$$

where K_{11}, K_{22}, and K_{33} are the splay, twist, and bend elastic constants, respectively. Imagine the domains to be patchy and periodic over a $\lambda\times\lambda$ area as that shown in Fig. 1(a) where the area fraction f of the V domains assumes 0.875. The calculated director field for this case (assuming the azimuthal ϕ alignment to be $\parallel x$) in the $y=0$ plane subject to the strong anchoring limit (wherein the extrapolation lengths $\equiv K_{11}/W_{0i}$ are $\ll\lambda$)) is shown in Fig. 1(b). Evidently, the LC director near $z=0$ undertakes an abrupt change from V to H at the domain boundary, but smoothens out rapidly along $+\mathbf{z}$; a uniform alignment is achieved within a distance $\leqslant 0.25\lambda$.

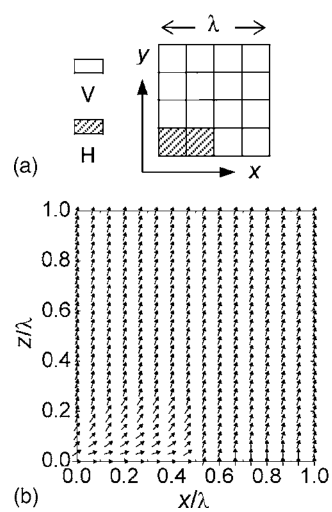

FIG. 1. (a) Distribution of the V and H domains on the unit cell of the model surface pattern with $f=0.875$. (b) The simulated director field in the $y=0$ plane for the surface pattern shown in (a).

Details of this calculation are contained in a separate publication.[11] It was shown that the uniform LC pretilt increases almost linearly with f, independent of the ratio W_{0V}/W_{0H}. Since the result demonstrated no dependence on the finer details of the surface pattern such as the shape of the domains, it is expected that the result should be applicable to irregular surface patterns possessing a uniform length scale λ. For typical values of W_{0i} ($\approx 10^{-4}-10^{-3}\ \mathrm{J\,m^{-2}}$) and K_{11} ($\approx 10^{-11}$ N), the strong anchoring limit ensues for $\lambda \gg 0.01-0.1\ \mu$m.

II. SAMPLE PREPARATION

To realize the alignment surfaces, we exploit phase separation that might happen in a homogeneous blend film of immiscible H and V polyimides (PIs) or their precursors. Commercial V PI and H PI precursors purchased from Japan Synthetic Rubber Co., with nominal LC pretilts of 88° and 6°, respectively, were dissolved and diluted in the standard solvent provided by the company, allowing the components to mix. But any mixtures of V and H aligning materials that phase separate upon curing should work.[12] The resulting solution was used to form the alignment film on indium tin oxide (ITO) coated glass by spin coating. The film was then preannealed at 90 °C for 5 min followed by hard baking at 230 °C for 90 min where most imidization took place. During this heating process, the PI precursors phase separate into micro/nanodomains rich in either PI or PI precursor before imidization completes. To produce LC azimuthal alignment in the PI film, we rub the film surface with a rayon cloth as in standard industrial processing. The rubbing direction defines the LC pretilt direction in individual PI domains. (Note that the pretilt angles suggested by the manufacturer are measured from the rubbing direction.) The use of PIs with pretilts not equal to 0° and 90° avoids bistability between pretilt states symmetric about the surface normal, which could cause undesirable multidomain formation. The LC alignment produced by this method was found to be insensitive to the freshness of the rayon cloth.

III. RESULTS AND DISCUSSION

Figure 2(a) shows the optical micrographs of a series of PI films we made with V-PI wt % ranging from 1.1% to 7.4%, rubbed, and a thin layer of nematic LC deposited on top. With the setup illustrated, the dark regions are the V domains while the lighter regions are the H domains. As the wt % of the V PI increases from 0, the film surface morphology changes from homogeneously scattered micro/nanodomains of the V PI in a continuous H matrix to a Voronoi network of the V PI in a matrix of the H PI, and finally to homogeneously scattered H domains in a continuous V matrix. Topographic atomic force microscopic (AFM) images of the samples as shown in Fig. 2(b) provide further details of the sample surface. For example, the surface of the 2.7 wt % sample actually comprises a Voronoi network with nanometer wide threads of the V PI that cannot be resolved by optical microscropy. The area fraction f of the V PI on the film surface is plotted versus the V-PI wt % in Fig. 2(c). It is interesting to note that the initial variation is rapid, almost

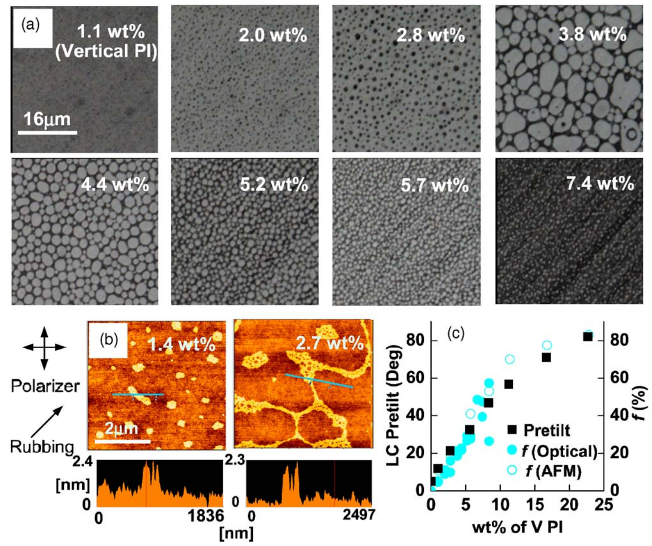

FIG. 2. (Color online) (a) Optical micrographs of the PI blend films with different V-PI wt % as indicated on the upper right. The scale bar shown on the first picture applies to all other pictures. The arrows at the bottom illustrate the optical setup used to take the pictures. (b) Topographic AFM images of the 1.4 and 2.7 V-PI wt % films showing the nanodomains on the film surface. The lighter areas are elevations. The same scale bar applies to both images. The lower panels are cross-sectional profiles drawn along the blue lines shown in the upper main panels. (c) Measured LC pretilt (left axis) as a function of wt % of the V-type PI (squares). Also plotted is the area fraction f (right axis) vs wt % of the V PI according to the optical (solid circles) and AFM (open circles) images.

linear with a slope of 5.4 until the V PI concentration is ~10 wt % whereupon f increases steadily towards 100%. Cross-sectional AFM profiles of the 1.4 and 2.7 wt % samples [Fig. 2(b), lower panels] show the V regions to be elevated by ~2.3 nm from the H regions,[13] whereas the overall thickness of the film is ~7 nm according to ellipsometry. Given the surface V domains to be only 2.3 nm thick, lying on top of a continuous layer of H PI with thickness of approximately 10 nm, the observed initial rise in f can be very well accounted for.

The solid squares in Fig. 2(c) display the measured LC pretilt angle as a function of the V-PI wt % in the blend film. The LC pretilt angle was measured using an 18-μm-cell-gap homogeneously aligned (i.e., antiparallel) test cell in a conventional crystal rotation setup. As seen from the data, LC pretilt angle from nearly 0° to 90° can be generated. Beyond 25 wt % of V PI, the alignment layer essentially gives vertical alignment. This result is in keeping with the f versus V-PI wt % data (the open and solid circles) shown in the same plot, i.e., f saturates to 100% also beyond 25 wt % of V PI. The fact that the two curves overlap with one another by a proper scaling of the f axis as shown in Fig. 2(c) suggests that the LC pretilt varies linearly with f as expected from our calculation.[11]

We also measured the polar anchoring energy of these surfaces using the high voltage method[14] on the same test cells. The anchoring energies measured are in the range of $1-2\ \mathrm{mJ/cm^2}$ which is the same as that of ordinary rubbed PI. Notice that the measured pretilt angle in the present case is that of LC beyond a boundary layer of the order of $\lambda/2\pi$ thick,[11] where the director of the LC is inhomogeneous. Thus

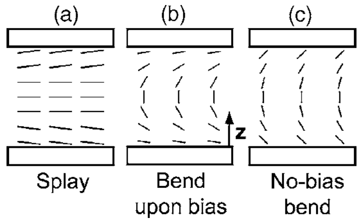

FIG. 3. Three pi-cell configurations: (a) Splay, (b) bend upon external bias, and (c) no-bias bend.

the anchoring energy is that of the boundary layer producing the uniform LC pretilt alignment in bulk. It is important that the domain size be small enough that such boundary layer does not affect the optical property of the LCD. For the 18 μm test cells and for the nanostructures shown in Fig. 2(b), the ~0.75 μm boundary layer can be ignored.

The high-temperature stability of these alignment layers was also checked. We placed a LC test cell in an oven at 100 °C for 24 h and checked that the pretilt angle did not change. In fact, the temperature stability is expected to be good since the component PIs are commercial and have been demonstrated to be steadfast for LCD application.

The availability of a reliable method for manufacturing large LC pretilt angle is important for many applications. One of the most important one is the fabrication of no-bias bend (NBB) pi cells,[15–18] which offers not only wide viewing angles without the need for multialignment domains[19] as in standard twist nematic (TN) displays that can increase the cost but also much reduced response times and hence blurring in fast-motion pictures. As is well known, usual pi cells are stable in the splay deformation [Fig. 3(a)]; a critical holding voltage is needed to transform a splay cell into a bend cell [Fig. 3(b)].[20,21] In LCD application, use is made of the increasingly reduced phase retardation in the pi cell as the bias voltage is increased, leading to different optical transmission under crossed polarizers and often also the addition of a phase compensator, which enhances the contrast of the device.[16,18] Note that the switching between the splay and bend states is generally not used due to the long relaxation time involved.[15–18] However, if the LC pretilt is large enough at the cell boundaries, the pi cell can be stable in the bend state even without a bias voltage [Fig. 3(b)].

We have successfully made NBB pi cells using this technique. The transmission-voltage characteristics of the cells were measured by the transmission of a He–Ne laser beam traversing the cell between two 45° crossed polarizers where the output from a *p-i-n* photodiode (Thorlabs, 10 ns response time) was fed to the Channel 1 input of a Hewlett Packard Infinium 54810A oscilloscope. A voltage pulse train was applied across the test cell and, at the same time, fed in parallel to the Channel 2 input of the oscilloscope. The pulse height and dc offset of the voltage train were selected to control the initial and final states of the LC cell. The pulse width and duration were chosen so that the LC cell had sufficient time to relax to the initial state during the falling edge of the pulses and the final state during the rising edge of the pulses, while a reasonably clear trace of the relaxation from the initial to the final state was displayed.

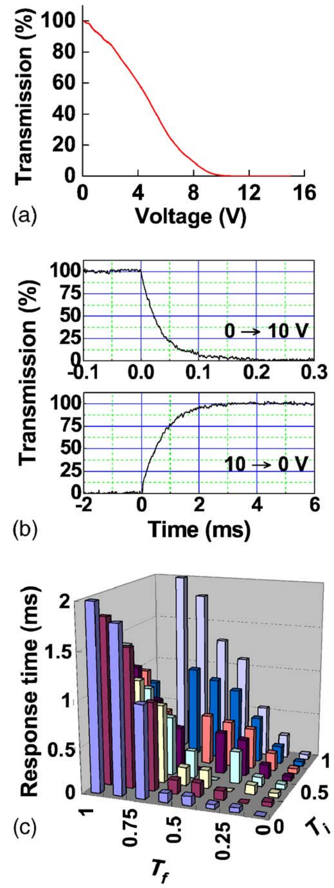

FIG. 4. (Color online) (a) The transmission-voltage characteristic of our pi cell where the cell gap is ~5 μm. The transmission data were normalized by that at zero volt (=79%). The data were taken in 0.1 V steps for $0 \leq V \leq 1$ V and 1 V steps for $V > 1$ V. (b) The oscilloscope traces of normalized transmission obtained when voltage pulse trains with pulse heights of 10 V (upper) and −10 V (lower) were applied across the cell triggering. In here, zero time is synchronized with the rising edge of the pulses. (c) Measured response times of a NBB cell made by our alignment surfaces between various initial (T_i) and final (T_f) transmission states shown in (a).

Figure 4(a) shows a representative transmission-voltage characteristic of the cells (cell gap=5 μm) for which no hysteresis was found. The fact that there is no threshold voltage noticeable from the data qualifies the cell to be a NBB pi cell. Figure 4(b) shows the oscilloscope traces of the transmission signal in switching between the brightest (0 V) and darkest (±10 V) states from which one can see that the response time (defined here as the time for the transmission signal to change by 90% of that in reaching the final state) depends strongly on the initial and final states. Figure 4(c) shows the response times between all different transmission states. As one can see, the response time generally decreases as the final transmission T_f decreases. It is due to the larger applied switching voltage, generating a larger electric torque on the LC directors. But the dependence of the response time on the initial transmission T_i is less straightforward. Specifically, it is a function of the absolute difference $|T_f - T_i|$ for a given T_f. This behavior can be understood in the following: When $|T_f - T_i|$ increases, the LC directors must rotate more to reach the final state, thus requiring more time. Nevertheless, we note that the total response time is always less than 2 ms, which is far better than the response times quoted of LCD

TV (typically 12–40 ms). It should be remarked that LCD response time is usually quoted for black-white transitions; but the frequently unquoted ones for the practically more relevant gray-gray transitions are usually much longer.[22]

Another application is bistable bend-splay LCD.[23] It is well known that bistability between the splay and bend states can be achieved if the pretilt anchoring is high enough; for conventional materials, it is from 45° to 58°.[23] We have realized such a device using the nanostructured surfaces, with demonstrated reliable bistability and good wide viewing angles. By operating in conjunction with the dual frequency driving technique,[24] we found that practical switching times can be achieved, making our device a serious contender in the field of e-book and signage applications against other bistable technologies. Details about this bistable cell will be reported in a separate publication.

IV. CONCLUSION

In summary, we have demonstrated a method of making LC alignment layers for large pretilt anchoring. Any LC pretilt from 0° to 90° can be reproducibly obtained. It relies on the formation of surface nanostructures comprising V and H alignment domains upon phase separation of a PI blend film. This method is robust, does not involve untested materials, and is compatible with existing manufacturing techniques. It should find many applications in LCD fabrication, particularly in making fast LCD for TV.

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