Substrate patterning for liquid crystal alignment by optical interference

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Inhomogeneous liquid crystal (LC) alignment surfaces comprising a succession of microdomains favoring different LC alignment directions have been demonstrated for a number of optoelectronic applications. However, the prevalent method used to fabricate these surfaces is time consuming and produce functional areas that are too small for practical use. Here, we demonstrate a simple method based on photopatterning of an azodye layer with an interference pattern produced by intercepting two coherent UV beams. This method can produce alignment patterns within seconds with a practical size of ~(0.5 cm)^2. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2209713]

There has been an enormous interest within the liquid crystal (LC) community to fabricate patterned LC alignment surfaces for their promises in numerous applications,[1] such as wide-viewing-angle display,[2,3] projection display,[4] optical grating,[1,4–9] bistable[10] and tristable[11] displays, no-bias bend-splay display,[12] and alignment surfaces with tunable LC pretilt angle,[13] etc., as well as the corresponding ordering phenomena.[14–17] This has led to a proliferation of methods for making these surfaces, including atomic force microscopic (AFM) nanolithography,[8,10–13,15–17] polarization holography,[1,9] lithographic patterning of a photosensitive layer,[2,18–21] double rubbing,[4] microrubbing,[4,5,7] laser writing,[22] use of homeotropic and homogeneous polyimide mixtures,[12] etc. Among these methods, only the first method has been demonstrated for making patterns with inhomogeneous in-planed alignment and periods of ~1 μm, which is desirable in some of the aforementioned technologies.[10–13]

In this letter, we describe a method for making micropatterned surfaces for LC alignment, in which an azodye film is exposed twice to an interference fringe pattern produced by intercepting two UV laser beams sequentially p and s polarized, with the interference pattern laterally shifted by a half period between the exposures. It produces patterns composed of alternating **x**- and **y**-alignment stripes (where **x** and **y** are the projections of the UV polarization direction **P** in the film during p and s polarization, respectively). This method is simple, fast, and allows easy control of the pattern period and LC azimuthal alignment direction.

The azodye used is the so-called SD-1 supplied by Dainippon Ink and Chemicals, Japan. The procedure of preparing the SD-1 films on indium tin oxide (ITO) glass can be found in Ref. 23. The SD-1 molecules possess an UV absorption peak at 327 nm.[23] Illumination with linearly polarized UV near this wavelength produces LC alignment perpendicular to the polarization.[24]

Figure 1 shows our setup. The He–Cd laser produces cw UV beam with wavelength $\lambda = 325$ nm and linear polarization, $\mathbf{P} \parallel \mathbf{y}$. We first rotate **P** by 90° by turning the optic axis of $\lambda/2$-plate-1 to 45° with respect to **y**. Then the beam is split into two with one afterward passing through $\lambda/2$-plate-2, which has the optic axis along **y**. Then the two (p polarized) beams are recombined to produce an interference fringe pattern to which the SD-1 film is exposed for time τ_1. Then **P** is returned to **y** by adjusting $\lambda/2$-plate-1, causing the intercepting beams to be s polarized. With $\mathbf{P} \parallel \mathbf{y}$, the beam passing through $\lambda/2$-plate-2 acquires a phase change of π with respect to the first exposure thereby the fringes are shifted laterally by a half period. The SD-1 film is then exposed to this pattern for time τ_2. The pattern period p is adjustable through the angle 2σ ($p = \lambda/2 \sin \sigma$). Lenses 1 and 2 expand the UV beam from ~1.5 to ~5 mm.

Figure 2 shows the optical images of LC cells constructed from four hence patterned SD-1 films (constituting the bottom wall; the upper wall is ITO glass coated with polyimide uniformly rubbed along **y**; the cell gap is 25 μm), placed between crossed polarizers. The LC is nematic 4′-n-pentyl-4-cyanobiphenyl (5CB). Table I lists the exposure conditions used for the $p=2$, 1.67, and 0.78 μm patterns. In Fig. 2, except for the $p=0.78$ μm cell, periodic dark and bright fringes are clearly visible, suggesting the LC alignment to be alternating between **x** and **y**. When the analyzer is rotated to the $\phi = -45°$ azimuthal direction, all four cells appear dark, confirming the bulk LC alignment to be uniform along $\phi = +45°$. The uniform appearance of the $p=0.78$ μm cell can be due to the fringes being too narrow

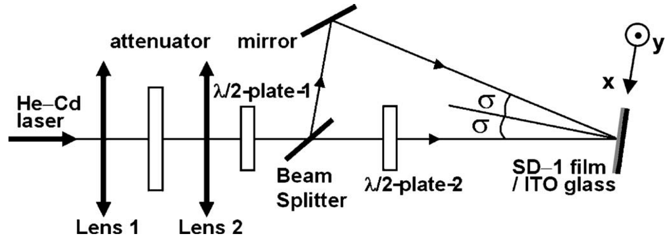

FIG. 1. Setup used to produce the inhomogeneous LC alignment pattern on the SD-1 films. The components labeled $\lambda/2$-plate-i ($i=1,2$) are half-wave plates.

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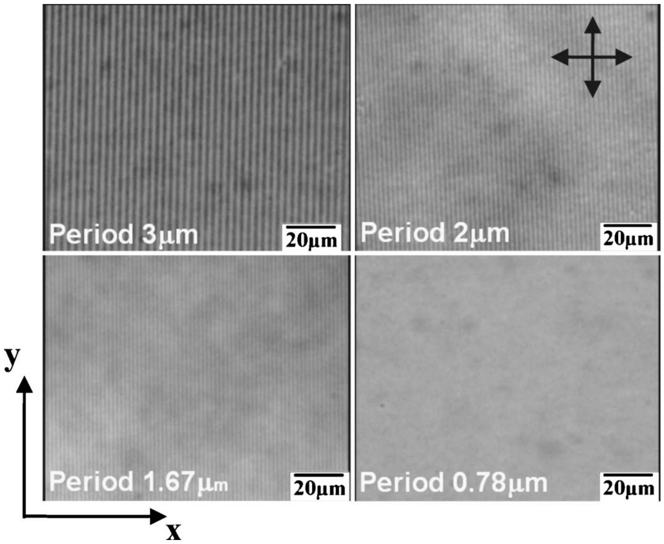

FIG. 2. Optical images of four representative LC cells constructed from SD-1 films patterned with different periods as shown. The double-sided arrows indicate the polarizer and analyzer directions used in taking the pictures.

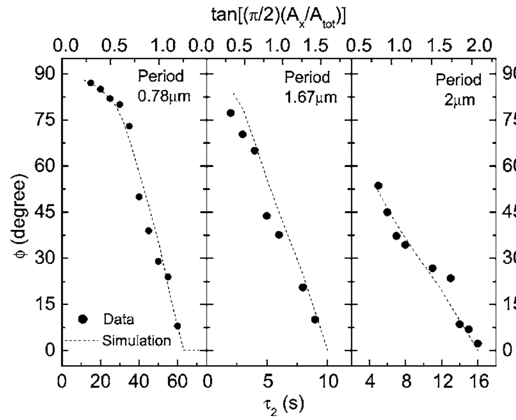

FIG. 3. ϕ vs τ_2 for the $p=2$, 1.6, and 0.78 μm patterns (solid circles, lower axis). The dashed lines are simulations of ϕ plotted against $\tan(\pi A_x/2A_{\text{tot}})$ (upper axis).

to be resolved optically or the LC director field essentially uniform along $\phi=+45°$.[15]

We measure the effective azimuthal surface energy $W_{\phi,\text{eff}}$ for *bulk* LC alignment along $\phi=+45°$ of the $p=2$, 1.67, and 0.78 μm patterns as detailed in Ref. 25. For comparison, we measure the azimuthal surface energy W_ϕ of similarly exposed SD-1 films, but the UV polarization was held $\|\mathbf{y}$ in both exposures. The results show that $W_{\phi\text{eff}}/W_\phi$ is between 0.05 and 0.2 (Table I), which is consistent with the former result obtained from checkerboard-textured surfaces.[15]

Figure 3 displays plots of the average LC azimuthal alignment ϕ vs τ_2 (solid circles) for the $p=0.78$, 1.67, and 2 μm patterns subject to the otherwise same exposure conditions given in Table I. As seen, ϕ (measured from **x**) decreases monotonically from 90° to 0° as τ_2 increases. It means that the ratio of the summed area of the **x** alignment domain A_x to the total area of the film A_{tot} progressively increased from 0 to 1. According to a previous result,[24] the orientation of the azodye molecules in a freshly prepared SD-1 film is random. The first exposure produces azodye alignment along **y** with varying degrees [i.e., $\langle P_2(\theta)\rangle$ is varying; here, $\langle\cdots\rangle$ denotes ensemble averaging, $P(\theta)=(1/2)\times(3\cos^2\theta-1)$, and θ is the orientation of the azodye molecule with respect to **P**] according to the intensity profile of the fringes. The second exposure causes progressive rotation of the azodye molecules away from the alignment along **y**. According to the diffusion model,[24] for azodye films with preexisting alignment, interactions among the azodye molecules cause an additional term, $a\langle P_2(\theta)\rangle P_2(\theta-\theta_0)$, to the effective potential governing the azodye alignment (where a is a constant and θ_0 is the direction of the existing alignment). For $\theta_0=90°$, i.e., the preexisting alignment is $\perp\mathbf{P}$, the incident UV must possess an intensity larger than a threshold $\propto 3a\langle P_2(\theta)\rangle/k_BT$ before the original azodye alignment can be altered.

We examine the validity of this prediction. The SD-1 film is exposed to uniform UV irradiation twice with the same sequence of polarization as before. The first and second exposure times are fixed at 24 and 6 s, respectively. The second exposure intensity I_2 is kept at 2.82 mW/cm^2 and the first exposure intensity I_1 varied. The result, plotted as ϕ vs I_1, is displayed in Fig. 4 by the solid squares. As seen, the second exposure begins to overwrite the alignment effect of the first exposure when I_1 falls below 2.2 mW/cm^2. But a similar experiment with I_2 increased to 6.18 mW/cm^2 (open circles) shows that overwriting occurs even for much larger I_1.

This result implies that the ultimate growth of the **x** alignment domains shown in Fig. 3 cannot occur by a simple rotation of the azodye molecules from **y** to **x** energized by the second exposure. We propose that it occurs by a systematic progression of the domain walls where $\langle P_2(\theta)\rangle=0$ so that no threshold intensity is required for overwriting. Consider the conservation of energy when a domain wall moves to expand the **x** domains at the expense of the **y** domains,

TABLE I. UV exposure conditions and azimuthal surface energies.

	First UV exposure (↕)		Second UV exposure (↔)		Azimuthal surface energy (10^{-5} J/m^2)	
Period (μm)	Average UV intensity (mW/cm^2)	τ_1 (s)	Average UV intensity (mW/cm^2)	τ_2 (s)	Inhomogeneous alignment ($W_{\phi,\text{eff}}$)	Uniform alignment (W_ϕ)
2	1.94	24	2.95	6	0.25±0.05	1.95±0.4
1.67	2.02	16	2.99	5	0.15±0.05	1.64±0.4
0.78	0.45	110	0.46	43	0.08±0.05	1.43±0.4

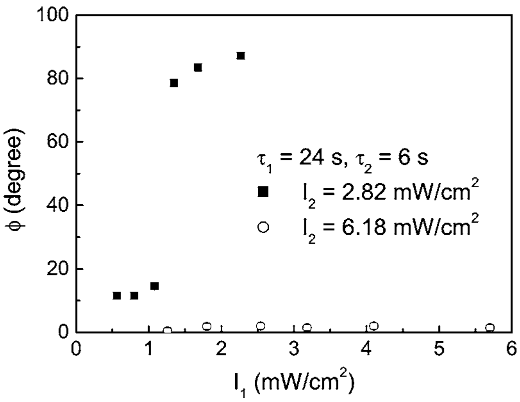

FIG. 4. Average LC azimuthal alignment found on SD-1 films exposed to a uniform UV laser beam polarized along **x** for 24 s with different intensities I_1 (plotted as the abscissa) followed by a second uniform exposure with UV polarization changed to **y** for 6 s and a fixed intensity of I_2, set to 2.82 and 6.18 mW/cm^2 for the two measurement series shown.

$$(\chi_{\parallel}-\chi_{\perp})\frac{E(x)^2}{2}\frac{d|x|}{dt}hw=-\frac{dU(\theta)}{d\theta}\frac{d\theta}{dt}, \qquad (1)$$

where $\chi_{\parallel}$ and $\chi_{\perp}$ are the electric susceptibilities of the SD-1 layer $\parallel$ and $\perp$, respectively, to the electric field $E(x)$ of the UV light, x is the coordinate of the domain wall, t is the time, h and w are, respectively, the thickness and width (along **y**) of the SD-1 layer, and $U(\theta)=(1/2)I_2(x)\alpha hw\tau\cos^2\theta$ is the potential energy governing the azodye alignment.[24] [Here, α (cm^{-1}) is the absorption coefficient of the SD-1 layer and τ is the relaxation time for the rotation of the azodye molecules.] The absolute sign in Eq. (1) ensures that the **x** domains always expand at the expense of the **y** domains to lower the energy. By adopting $E(x)^2\propto I_2(x)$ and $d\theta/dt\propto I_2(x)$,[24] Eq. (1) leads to $d|\mathbf{x}|/dt\propto I_2(x)\propto\cos^2(\pi x/p)$. Integrating once gives $\pi|\mathbf{x}|/p\propto\tan^{-1}t$. Since the **x** domains expand through simultaneous advancement of the left and right walls, $A_x/A_{\rm tot}=2|x|/p$ and $t\propto\tan(\pi A_x/2A_{\rm tot})$.

We simulate the variation of ϕ with $\tan(\pi A_x/2A_{\rm tot})$ by using the model of Ref. 15 and assuming the values of W_ϕ in Table I. The results are displayed by dashed lines in Fig. 3. Clearly, the simulations provide a good description of the data. The model also implies that the time scale for complete overwrite of the first alignment effect varies linearly with p and $(d\theta/dt)^{-1}$ ($\propto I_2^{-1}$ from above). From Table I, the ratio p/I_2 for p=2: 1.67: 0.78 μm patterns is 0.40: 0.33: 1, which agrees reasonably well with the ratio for the observed τ_2 for complete overwrite, i.e., 0.27: 0.15: 1 (Fig. 3). The systematically shorter measured time than predicted may come from the assumption that $d\theta/dt\propto I_2(x)$, which is due to calculations assuming the incident UV to be uniform.[24] This overlooks torques that can arise from elastic recoil from the inhomogeneous azodye field and cause the discrepancy.

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