Optical patterning of multi-domain liquid-crystal displays with wide viewing angles

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The leading technology for flat, high-resolution computer and television screens is based on twisted nematic liquid-crystal displays. The successful operation of these displays requires control of molecular alignment, which is currently achieved by confining the liquid crystal between mechanically rubbed surfaces. But in addition to the practical difficulties associated with rubbing, the resulting displays suffer from restricted viewing angles arising from the uniaxial nature of the alignment process. This latter problem can in principle be circumvented if molecular alignment is varied, in a controlled manner, within individual pixels. Exposure of functionalized substrates to polarized light offers a means of achieving high-resolution patterns in the plane of the display. But to ensure that the alignment pattern imposed on the liquid crystal is free of orientation defects, the tilt angle between the long molecular axes and the substrates must be precisely controlled. Here we show how our earlier linear photoalignment strategy can be extended to obtain such control, and thereby fabricate stable, multi-domain pixel displays with markedly improved fields of view.

Underlying the electro-optical properties of all liquid-crystal displays is the requirement that, in their 'off' state (no applied electric field), the long axes of the liquid-crystal molecules—the director n—are aligned uniaxially at the two display boundaries. Moreover, to achieve stable electro-optical characteristics, the bias tilt angle θ between n and the display substrate(s) must also be well defined. Previously we have shown that anisotropic Van der Waals forces are primarily responsible for the alignment of liquid crystals on substrates treated with our linear photopolymerization (LPP) technology. In the case of poly(vinyl 4-methoxy-cinnamate) photopolymers, these forces were shown to align n perpendicular to the electric field vector E of the incident linearly polarized ultraviolet radiation which leads to anisotropic depletion of LPP prepolymer molecules and simultaneously generates uniaxially aligned photoproducts via anisotropic crosslinking.
Because of the cylinder symmetry with respect to $\mathbf{E}$ of this LPP process, the probabilities are equal for photogenerating the bias tilt angles $\theta(x) = -\theta(-x)$ on a microscopic scale, where $x,y$ are the substrate coordinates. Macroscopically this leads to zero bias tilt. Although attempts were made to break the symmetry of our LPP process by exposing LPP substrates sequentially under different directions of light incidence, the resulting angles $\theta < 0.3^\circ$ were very small and not stable for practical purposes.

From these symmetry considerations it follows that the photocrosslinking and aligning symmetries of the LPP process had to be changed. We achieved this with a modified LPP process schematically depicted in Fig. 1, such that liquid-crystal alignment occurs not perpendicular to $\mathbf{E}$ as before, but within the plane defined by $\mathbf{E}$ and $\mathbf{k}$ of the incident crosslinking ultraviolet radiation. As a consequence of the new symmetry and by changing the angle of incidence of $\mathbf{k}$, stable, photoinduced bias tilt angles $\theta$ have become possible which can be adjusted over the entire range $\theta = 0$--$90^\circ$. As an example, the top part of Fig. 1 schematically depicts two coumarin photo-prepolymer molecules which we designed to exhibit the desired LPP-aligning symmetry. Also shown in Fig. 1 (centre) are two of the four possible in-plane configurations of the anisotropically aligned coumarin photoproducts generated by the $(2 + 2)$-cycloaddition of the LPP process. Analogous to our earlier LPP model, we assume that liquid-crystal alignment $\mathbf{a}$ in the $y$-direction occurs (I) via anisotropic

FIG. 1 A pair of isotropically distributed, novel prepolymer coumarin side-chain molecules, for use in the LPP process. The directional LPP photoaction is parallel to the direction of the electric field vector $\mathbf{E}$ of the incident linearly polarized ultraviolet radiation; $R$, side-chain spacer. The photoinduced bias tilt angles $\theta(x)$ are adjustable from $\theta = 0$--$90^\circ$. The photoalignment is optically and thermally stable up to temperatures $> 200^\circ$C. The diagram at the bottom of the figure schematically depicts the photo-generation and the symmetry of our LPP process.

FIG. 2 A single pixel of a four-domain twisted nematic (TN) LCD configuration in its partly switched-on state (80% transmission between crossed polarizers). Three of the four (differently twisted) subtwist nematic helices are indicated by their respective boundary and central molecules.

FIG. 3 Top, transmission--voltage characteristics at vertical white-light incidence of a photoaligned, single-domain twisted nematic (TN) display (dashed line) and a four-domain TN display with 100-μm subpixel size (solid line). Both LPP-aligned displays exhibit $\theta(\text{LPP}) = 1.3^\circ$ bias tilt. For comparison (dotted line) we show characteristics of the polyimide (PI)-brushed display with $\theta(\text{PI}) = 1.5^\circ$ bias tilt; PI SE610 from Nissan Chemical. The three displays are operated in their first minimum, and use TFT mixture 84/57 from ROJIC Ltd. Bottom, transmission--voltage characteristics of a single-domain photoaligned supertwisted nematic (STN) display (solid line) and of a conventionally, PI-brushed STN display (dashed line), both with contrast ratios $> 25$. The respective slope steepnesses are $V_{90}/V_{50} = 1.043$ (LPP) and 1.046 (PI); where 90 and 50 correspond to the respective display transmission in per cent. The respective bias tilt angles are $\theta(\text{LPP}) = 7.5^\circ$ and $\theta(\text{PI}) = 7.0^\circ$; twist angle $\phi = 240^\circ$; STN mixture 7728 from ROJIC Ltd; PI SE610 from Nissan Chemical.
Van der Waals interactions of the rigid cores of the anisotropically crosslinked photoproducts, (2) via anisotropic steric interactions with their partly aligned (in the y-direction) hydrocarbon polymer chains and (3) via anisotropically depleted prepolymer molecules (not shown in Fig. 1). All the photoaligned displays below are based on the new LPP symmetry shown in Fig. 1. The LPP photoprocessing steps have been described elsewhere\(^{10,12}\).

Figure 2 depicts schematically, a partially switched single pixel of a four-domain twisted nematic (TN) display configuration. As in the photoaligning patterning process described recently\(^{10}\), we used a single photomask to generate the LPP-aligning patterns of Fig. 2. The two different bias tilt directions \(\Theta\) on each substrate determine the appropriate twist sense of the four subtwisted nematic liquid-crystal displays (LCDs). Different bias tilt angles were achieved by changing the direction of the wavevector \(\mathbf{k}\) (Fig. 1). On a macroscopic scale, the optical anisotropies of the differently aligned central directors \(\mathbf{n}\) of the four sub-helices compensate each other (Fig. 2). Therefore, the angular dependence of four-domain displays is strongly reduced compared with single-domain displays. In Fig. 2 this is indicated by the emphasised central molecules of the four differently aligned, single-domain sub-helices.

We show in Fig. 3, top panel, the vertical transmission–voltage characteristics of two LPP-photoaligned TN displays. For comparison, a polyimide (PI)-brushed, conventional single-domain TN display is included. One of the photo-aligned displays is single-domain, the other is a photopatterned four-domain display according to Fig. 2. From Fig. 3 and the large contrast ratios \(> 150\) of all three displays, it follows that the static transmission–voltage characteristics at vertical light incidence of photoaligned single- and multi-domain displays are identical to those of conventional, brushed displays. This also holds for the dynamics of the three displays.

The large bias tilt angles, which are prerequisites for realizing stable highly twisted configurations exhibiting very steep transmission–voltage characteristics, could up to now only be achieved with brushed substrates. The only partially photoaligned super-twisted nematic (STN) display which we have recently described was made by combining a (low-tilt) photoaligned substrate with a high-tilt brushed substrate\(^{10,12}\). As a consequence it was difficult to reach the steep transmission–voltage characteristics required for realizing multiplexed high-information-content STN displays. Figure 3, lower panel, shows the stable, hysteresis-free transmission–voltage characteristics of the first, fully photoaligned STN display at vertical white-light incidence. For comparison an identically configurated display with brushed PI-substrates is shown. The equally steep slopes of the two graphs in Fig. 3 and the comparably large bias tilt angles demonstrate that photo-
aligned, highly multiplexable and high-contrast supertwisted displays have become feasible.

Figure 4 demonstrates the remarkably improved field of view of a photo-aligned four-domain TN displays (top) compared with the strongly angle-dependent brightness of a conventionally brushed, single-domain display (bottom). The angular dependence of the brightness of the two partially switched-on displays in Fig. 4 was measured in all four quadrants between vertical light incidence and 60° off-axis. The grey levels at vertical light incidence are identical for both displays, and correspond to 50% transmission in Fig. 3. Figure 4 shows that, instead of remaining constant, the brightness of the conventional display changes by nine grey levels (out of ten) within its first and third quadrant, whereas the brightness of the photoaligned four-domain display changes by only three grey levels within any of its four quadrants.

The remarkably improved viewing performance of photoaligned multi-domain displays is further illustrated by the photographs in Fig. 5 which show the angular dependence of the grey level of a large single pixel at 70% vertical transmission of an LPP-aligned four-domain display (top) and of a PI-aligned single-domain display (bottom). The centre pictures were taken at vertical light incidence, the others at 40° in the four quadrants. The comparison is self-explanatory. Also shown in Fig. 5 (ringed) is an enlarged view of a four-domain display pixel viewed at 40° in the first quadrant. This shows the four photopatterned and differently aligned TN-subpixels whose macroscopically averaged transmission accounts for the improved angular view of the photoaligned four-domain display.

We have shown that high-resolution (<5 μm) liquid-crystal aligning patterns with defined and broadly adjustable bias tilt angles have become feasible with our linear photoalignment technology. For this reason, and because of its stability with respect to light and heat, photoalignment renders mechanical alignment with its detrimental generation of dust particles and electrostatic charges obsolete. LPP photoalignment of monomeric and polymeric liquid crystals not only improves the performance of existing displays, such as their viewing properties, but also opens up interesting new display configurations and non-display-related optically anisotropic devices, such as optically patternable interference filters, polarizers and optical retarders.