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Four-domain twisted vertically aligned liquid crystal pixels using microrubbing

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Microrubbing (μ -rubbing) technique is used to create four-domain twisted vertically aligned liquid crystal pixels for wide viewing angle displays. A metallic sphere of 1 mm diameter is used to locally rub a homeotropic polyimide surface to create a four-domain pixel. We use μ -rubbing to accurately control the surface pretilt angle of the liquid crystal from the normal, which directs the liquid crystal molecules to respective direction on applying a voltage. We report on twisted vertically aligned configurations with symmetric isointensity curves, high contrast, and attractive electro-optic performance. The optical simulations of the liquid crystal director orientation, viewing angle characteristics and switching behavior of the four-domain are also presented.

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Patterning surfaces to align liquid crystals has important implications in many industries, including applications for displays,¹ telecommunication devices,² and security elements.³ There are several approaches in which one can prepare patterned surfaces for liquid crystal alignment, including photolithographic techniques,⁴ photoalignment using lithographic masks⁵ or holographic methods,⁶ selected deposition of SiO₂,⁷ nano-scratching of polyimide,^{8,9} laser manipulation of azo-dye doped polyimides,¹⁰ etc. The most ubiquitous application of patterned alignment is found in the liquid crystal display (LCD) industry, where patterning is performed on the subpixel level in order to average out the strong optical anisotropy introduced by the liquid crystal orientation.^{11,12}

With the commercial arrival of liquid crystal television on the near horizon, there is a compelling need for subpixel patterning techniques that can be performed on large area displays in a simple and inexpensive way. Currently used techniques to fabricate wide viewing angle vertical alignment displays¹³ include four-domain alignment based on ridges applied underneath the alignment layer,¹⁴ fringe field structure,¹⁵ vacuum deposition techniques,¹⁶ photolithographic techniques, etc. These techniques are process intensive and are therefore more expensive to implement on large area displays. In this contribution we demonstrate how a microrubbing (μ -rubbing) technique can be used in conjugation with homeotropic polyimide alignment layers to create high contrast and symmetric viewing twisted vertically aligned display.

The experimental setup used for the μ -rubbing process is depicted in Fig. 1(a). A metallic sphere of 1 mm diameter under a 150 g load comes in physical contact with a polyimide alignment layer (150 nm thickness), which supports homeotropic boundary conditions. The polyimide is rubbed

with the metallic sphere as the substrate is moved by a translation stage at a velocity of 10 mm/min. This creates a $\sim 45 \mu\text{m}$ line, of which the exact width depends on the load applied, the thickness of the polyimide layer and the diameter of the metallic sphere. The sphere is then translated by $45 \mu\text{m}$, and then the substrate is counter rubbed creating an adjacent line with an opposing rubbing direction. This is repeated several times on each substrate.

Glass fiber spacers ($5 \mu\text{m}$) are then deposited on the substrates, and the substrates are subsequently secured together with UV curable glue at the edges. The rub directions on the top and bottom surfaces are oriented in orthogonal directions. With this particular polyimide, the μ -rubbing creates a small but well-defined unidirectional tilt angle away from the substrate normal $\bar{N}$ as illustrated in Fig. 1(a). We anticipate that the μ -rubbing introduces a small tilt of the aliphatic chains that are present in the polyimide for promoting homeotropic anchoring in the unrubbed normal state. The single line width is found to be $45 \mu\text{m}$ with a depth range of $5\text{--}15 \text{ nm}$. The average surface roughness of the μ -rubbed area is found to be $8 \pm 2 \text{ nm}$ as determined by atomic force microscopy.

The liquid crystal material which possesses a negative dielectric anisotropy ($\Delta\epsilon = -3.1$) was filled in the cell by capillary action at 100°C . The crystal rotation method¹⁷ was used for the surface pretilt angle measurement, antiparallel cell with $18 \mu\text{m}$ cell gap were constructed by recording parallel with same rubbing directions touching each other, and the pretilt is measured to be 1° off the surface normal $\bar{N}$.

Figure 1(b) illustrates the schematic of the four-domain in the OFF (zero-voltage) and ON (high voltage) states. In the zero-voltage state a homeotropic state is obtained with a small but well-defined unidirectional tilt angle. When a high voltage is applied the molecules align perpendicular to the electric field direction since the material possesses a $-\Delta\epsilon$. Since the pretilt angle of the four regions of a pixel is uniquely defined by the μ -rubbing process, the four mid-

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FIG. 1. (a) Illustration of the μ -rubbing apparatus and the direction of LC molecules orientation. (b) The vertically aligned twist mode is schematically illustrated in the OFF and ON state.

plane tilt angles are pointing in different directions. In the OFF state the sample is perfectly black since the domain boundaries are not visible in this state.

Figures 2 show the optical microscopy pictures and corresponding iso-intensity curves of the twisted vertically aligned cell, measured under different voltages, for the specific polarization and rub directions depicted in Fig. 1(b). The symmetric nature of the iso-intensity curve is visible in the ON state clearly showing the attractiveness of this configuration for wide viewing angle applications. The optical simulation of the viewing angle characteristics of the four-domain twisted vertically aligned cell is calculated using extended Jones matrix method.¹⁸ The experimental results are comparable with the simulation results as shown in Fig. 2

The subpixel size is approximately $45 \times 45 \mu\text{m}^2$ and the domain boundaries are black. In this pixel, two right-handed and two left-handed subpixels exist. A common problem of all vertically aligned displays, independent of mode, is that there is significant light leakage in the zero voltage state at larger angles due to the polarizers.¹⁹ Our pixels are no exception to this limitation as can be seen in Fig. 2 (top image). However, a simple *c*-plate compensation can be used to

FIG. 2. (Color online) Polarizing microscope photographs and the corresponding iso-intensity curves of the twisted vertically aligned four-domain cell under different voltages created by μ -rubbing. The optical simulations of the viewing angle characteristics at the same voltages are also shown.

minimize the light leakage and improve the viewing volume in the zero voltage state.²⁰

Figure 3 shows the experimental and simulated transmission-voltage (T - V) curve of twisted vertically aligned four-domain pixel. A traditional T - V curve is obtained with no on-axis light leakage in the OFF state, there-

FIG. 3. Experimental and calculated transmission-voltage curve for the twisted vertically aligned four-domain cell. The dynamic response time is also shown in the inset.

FIG. 4. (Color online) Results of 2DIMMOS calculations for the director orientation of the twisted vertically aligned cell at 0, 3.5, and 5 V. Calculated transmittance vs position on the same section is also plotted above.

fore resulting in an extremely high ON/OFF contrast ratio of 580:1 for normal viewing. The slight discrepancies in the simulation may be due to small deviations in the elastic constants (k) and dielectric constant ($\Delta\epsilon$), but also due to a weaker anchoring than assumed in the calculation. The inset in Fig. 3 shows the dynamic response times (measured between 10% and 90% transmission) for the twisted vertically aligned mode. In this case the OFF time (relaxation) is essentially constant as expected, and the ON time scales roughly with the inverse of voltage as expected from the theory.²¹

Figure 4 shows the two-dimensional (2D) director patterns (vertical cross sections) simulated with the 2dimMOS program.^{22,23} This figure depicts the vertical cross sections of the cell having two subpixels. The gray rods represent the directors, where the light end indicates a forward direction and the dark ends indicate a backward direction with respect to the plane of drawing. In this calculation we selected a cross section of a pair of μ -rubbed patterns on the top substrate and a single μ -rubbed pattern on the bottom substrate, which are orthogonal to each other. The left half of the top substrate is having a pretilt of 89° (μ -rubbed area) with an azimuthal angle of 90° and the right half is having the same pretilt with an azimuthal angle of 270° . The bottom substrate also possesses the same pretilt with an azimuthal angle of 180° . From the simulations study we observe the orientation of directors in applied field and the formation of disclination lines. In Fig. 4 the directors in the two domains are inclined

in opposite directions. In an applied field this results in the formation of disclination line in which the director rotates over 180° , giving rise to dark regions in the transmission as shown on the top part of the figure, which are comparable with our experimental observations in Fig. 2.

In conclusion we propose a μ -rubbing process for the construction of a multidomain twisted vertically aligned display. This configuration shows a highly symmetrical viewing volume and extremely high contrast. Optical simulations indicate that the viewing angle and switching behavior are almost identical to that of the experimental results. We believe that our technique will be useful for the industrial manufacturing of full color display based on twisted vertically aligned mode. In practical display manufacturing process many-ball systems (comblake) can be utilized. This technique is simple and economical as compared to lithographic techniques currently used for multidomain vertical alignment. We also believe that our μ -rubbing process can be potentially scaled up and used in the production of large area displays in future.

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