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Creation of a Voltage Controllable Micro-Liquid Crystal Domain Using the Atomic Force Microscope Rubbing for Surface Modification

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We have studied the liquid crystal (LC) alignment on a modified homeotropic polymer surface using an atomic force microscopy (AFM) rubbing. The nano-rubbing by AFM shows well-defined LC alignment and the rubbed surface induces the LC to be planarly aligned. The hybrid aligned nematic LC cell as made shows dynamic stability while increasing voltage without causing disclination lines and asymmetric light transmittance in oblique viewing angles. The result indicates that the pretilt angle is generated from the homeotropic alignment layer to the initial scanning direction, and the device is useful as a light modulator or dynamic phase retarder in the micron or nano region. [DOI: 10.1143/JJAP.42.L607]

KEYWORDS: LC alignment, homeotropic polymer, AFM rubbing, pretilt angle

Alignment control of the liquid crystal (LC) is very important to manufacture high quality LC displays (LCDs). At present, rubbing of the polymer surface by cloth is being used for mass production of the LCDs. However, the current rubbing process is not proper for control of the LC alignment in the micron or submicron region. Recently, studies on the liquid crystal (LC) alignment in very small sized areas using atomic force microscopy (AFM) has been performed by several groups.[1–6] For the first time, Ruetschi *et al.* performed the AFM rubbing on a homogeneous alignment layer to make an LC waveguide showing that LC alignment was possible using the AFM rubbing.[1] Wen *et al.* fabricated a hybrid aligned nematic (HAN) cell by assembling two substrates: one with the AFM rubbing on a rubbed homogeneous alignment layer and one with a vertical alignment layer and they claimed that a high resolution display with grey scale is possible with the device.[4] Kim *et al.* demonstrated that in-plane instability of the LC surface alignment can be achieved by imposing a frustrated alignment on a tailored submicrometer-sized surface domain.[5] Rastegar *et al.* studied the mechanism of the LC on submicron patterned surfaces and claimed that the AFM scanned polymer surfaces do not show a pretilt angle,[6] although measured pretilt angle as a function of line density has been recently reported.[7] In addition, all previous works were related to static LC patterns, i.e. no voltage applied so that the LC cells with the AFM patterned area could do the role of only static phase retarder or light modulator.

In this study, we have performed an AFM rubbing on a homeotropic alignment layer and found that the AFM rubbing can induce the LC to be planarly aligned with some pretilt angle. And then we have fabricated a cell using two substrates with vertical alignment. The micron-patterned area shows a hybrid alignment and the light transmittance in that area is controllable by adjusting applied voltage without showing any disclination lines. Owing to voltage-dependent dynamic stability in a very small area, the device is useful as a light modulator or dynamic phase retarder in the micron or nano region. Further, the direction of the pretilt angle has been studied by investigating the light transmittance of the cell in oblique viewing directions.

To fabricate cells, a homeotropic alignment layer with side chains (RN-1517, Nissan) was coated on indium tin oxide (ITO)-coated glass substrate with a thickness of about 100 nm and cured at 220°C for one hour. The AFM rubbing was done only on one substrate using the Autoprobe large scale (LS) from Park Scientific Instruments (PSI) with diamond coated ultralevers d-type[8] cantilever of spring constant 17 N/m. The surface modification area was 5 μm × 5 μm, 10 μm × 10 μm, and 20 μm × 20 μm, of which the line density was 51.2, 25.6 and 12.8 lines/μm, respectively. The scan frequency was 1 Hz and the AFM load Force was 271.1 nN, which were in a proper range to generate a change in the LC alignment. After that, we have assembled two substrates coated with homeotropic alignment layer to give a cell gap of 4 μm, where one substrates has patterned areas by the AFM rubbing while the other substrate does not have them. The super-fluorinated LC ($\Delta\varepsilon = 7.4$, $\Delta n = 0.09$ at 589 nm) is filled at room temperature.

Figure 1 shows the texture of the cell, where the scanning direction makes an angle of 45° with one of the crossed-polarizer axes. Interestingly, the surface modified areas show a bright state irrespective of modified size, and the boundary between modified and non-modified area is quite clear. Except those areas, the cell shows a dark state since the LCs are vertically aligned in that area. In order to confirm the repeatability of the experiment, we have scanned more than

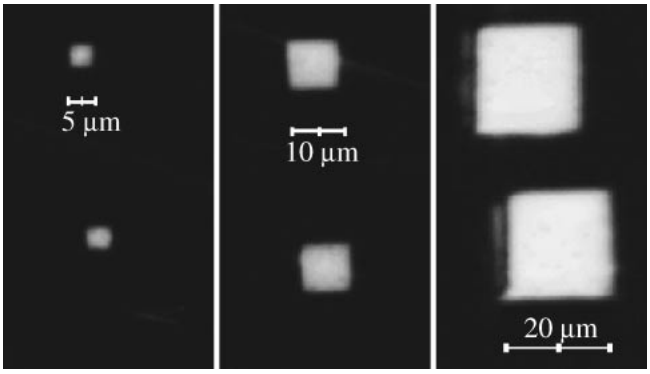

Fig. 1. Polarization optical micrograph of (a) 5 μm, (b) 10 μm, and (c) 20 μm LC squares.

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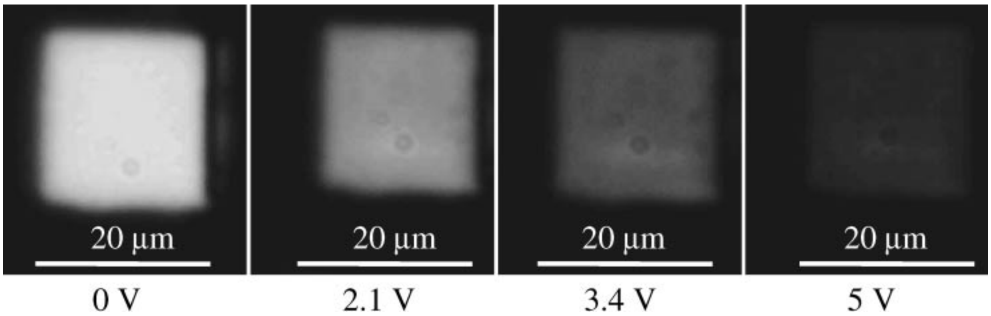

Fig. 2. Polarization optical micrograph of 20 μm LC squares, showing a change in light transmittance with increasing voltage without causing disclination lines.

one area but the results are the same. From the results, we can understand that the AFM rubbing clearly changes the surface status of the homeotropic alignment layer and even the very small size of an area is definable by the AFM rubbing. For the all LC squares, we have applied voltage to see what occurs in that area. As shown in Fig. 2, the brightness of the 20 μm squares decreases with increasing voltage since the vertical electric field causes the LCs to be vertically aligned. In addition, the LCs outside the squares will be vertically aligned more perfectly due to positive dielectric anisotropy of the LCs. Interestingly, while changing voltage up and down; we do not see any hysteresis and any disclination lines inside the squares. This indicates that an LC device made in this way can do the role of light modulator or dynamic phase retarder in a very small area with blocked light in all other areas. Further, the result implies that the surface modification of vertical alignment causes some arbitrary tilt angle so that when a voltage is applied, the LC orients parallel to a vertical field in one direction. This characteristic allows making a very high-resolution LC display with a highly controllable grey scale.

Previous work reported that the AFM rubbing does not create a pretilt angle since the rubbing direction is both left and right.[6)] If this is true, the LC squares should show some disclination lines that result from collision of the LCs due to tilting up in left and right direction at the same time. However this is not true for the vertical alignment layer. Now, to verify the LC alignment in the square area, we have rotated the cell by an angle of 45°, that is, the rubbing direction is coincident with one of polarizer axes. Surprisingly, the cells with 10 μm and 20 μm LC squares show a clear dark state except minor light leakage near the domain boundary due to not precise enough boundary during the AFM rubbing, as shown in Fig. 3. The cell with the 5 μm LC squares show the same results. Since the dark state means that the optic axis of the LC is coincident with one of the crossed polarizer axes, this result informs us that the modified area has a hybrid LC alignment as shown in Fig. 4, that is, the AFM rubbing on vertical alignment layer causes the LC to be in planar alignment with some tilt angle. Now the final question, in which direction the pretilt angle is generated, arises. If the LC square has a hybrid alignment with the optic axis making 45° with the crossed polarizers, the cell should show asymmetric light transmittance along the scanned direction when changing viewing direction from front to left or right since the retardation value of the cell changes as the viewing direction changes. Here, the right direction is the same direction at which the AFM tip starts to scan at first; in general the AFM tip scans to right at first and then stepping down to nanometer scale depending on line density, scans to left to change a polymer surface, repeatedly. Figure 5 shows a change in light transmittance depending on viewing directions. At a left and right oblique

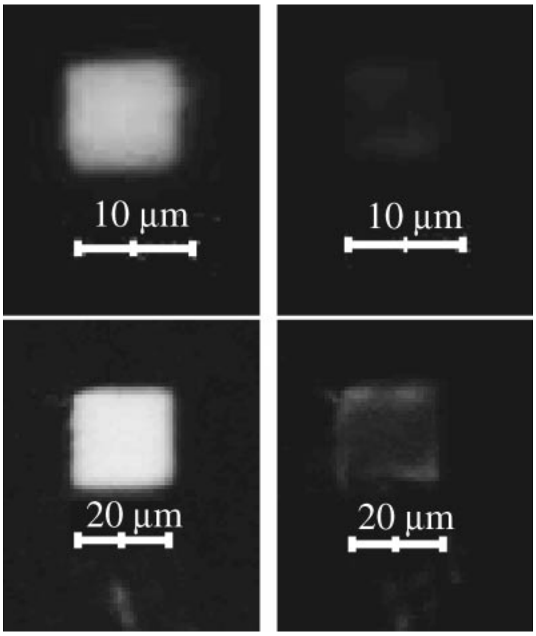

Fig. 3. Polarization optical micrograph of 10 μm and 20 μm LC squares with rubbing direction coincident with one of the crossed polarizers.

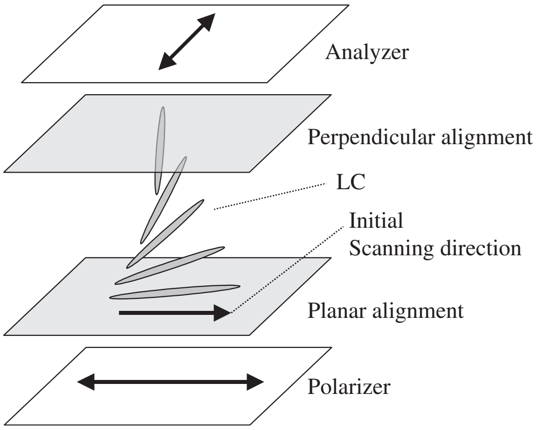

Fig. 4. The configuration of the LC molecules in the LC square.

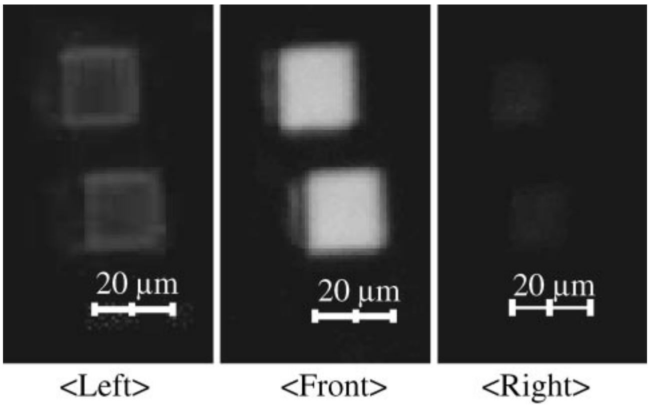

Fig. 5. Polarization optical micrograph of 20 μm LC square showing light transmittance at front, and left and right oblique directions.

direction with a polar angle of 30°, the color changes to yellow and dark, respectively. This indicates that the LC director is tilted in one direction and further, dark color indicates that in that direction, the retardation is highly reduced compared to that at normal direction since the ordinary and extraordinary light propagates through the short axis of the LC molecules whereas yellow color indicates that the cell retardation value is larger than that at normal direction. Therefore, the optical micrograph in Fig. 5 clearly confirms that the LC has a hybrid alignment and in addition, the pretilt on the bottom substrate is generated to the right direction that is coincident with the initial scanning direction. In order to confirm that the pretilt angle is always generated to the initial scanning direction, we have performed an initial scanning to downward direction. As expected, the modified area clearly shows asymmetric light transmittance in vertical direction, that is, the transmittance decreases and increases at downward and upward oblique viewing angles than those at normal direction. This clearly indicates that the pretilt angle is generated to downward direction. Finally, we have changed a line density to observe how the transmittance in scanned areas changes. Figure 6 shows a decreased transmittance with decreasing a line density at different sizes of patterned areas. This exhibits that the effective retardation value of a cell at normal direction is reduced as a line density decreases, indicating that the pretilt angle is changed with a variation of the line density. Although we did not measure the pretilt angle, quantitatively since they are only micron-size, the textures observed in Fig. 6 clearly indicates a change of the pretilt angle as a function of a line density.

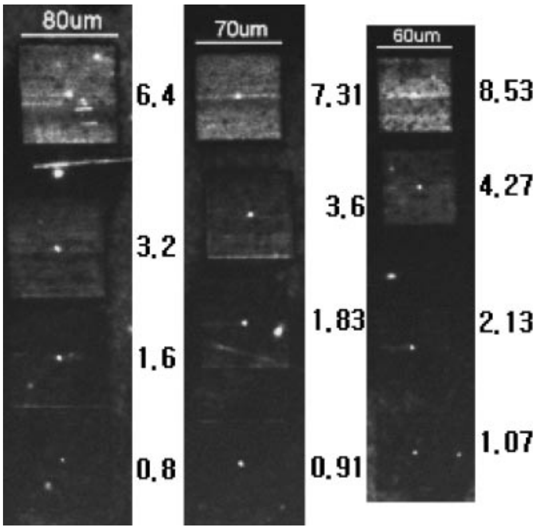

Fig. 6. Polarization optical micrograph of (a) 80 μm, (b) 70 μm, and (c) 60 μm LC squares with decreasing line density from top to bottom where the number indicates a line density.

In summary, we have found that a change in the LC pretilt angle of the homeotropic alignment layer is possible by the AFM rubbing, while the degree of the pretilt angle depends on scanning conditions. Further, we have fabricated hybrid-aligned nematic LC cells in micron size and found that the pretilt angle is generated in the direction coincident with the initial scanning direction. For the first time, we have developed a LC device that can switch as a dynamic light modulator in a few micro regions since it shows dynamic stability against applied voltage without causing any disclination lines. This allows making a high-resolution display with a voltage-controllable grey scale.

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8) Diamond coated ultralevers d-type is a registered trademark of PSI.