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Tunable lens by spatially varying liquid crystal pretilt angles

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We report a method of obtaining controllable spatially varying liquid crystal pretilt angles using a stacked alignment layer. The stacked alignment layer consists of nano-domains of horizontal and vertical alignment materials. The pretilt angle is controlled by varying the domain ratio of the two layers. By using photoalignment material as the top layer, the pretilt angle can be controlled by varying the UV light dosage. A spatially variable UV light beam can be used to control the pretilt angle spatially. An electrically tunable-focus liquid crystal lens is obtained using this method. © *2011 American Institute of Physics*. [doi:10.1063/1.3567937]

I. INTRODUCTION

Study of heterogeneous surface for liquid crystal (LC) alignment has witnessed a rapid growth in recent years[1–15] because such alignment arrangement is capable of generating variable high pretilt angles. The value of the pretilt angle in a liquid crystal cell is important in determining the characteristics of the display. Various applications are possible if such variable pretilt angles are available, such as bistable displays devices[16] and no-bias bend fast switching mode LCD.[14] Previously we have proposed a nano-structured surface by mixing horizontal and vertical alignment polyimide to obtain high pretilt angle.[12] In this paper, we demonstrate a new nanostructure using stacked alignment layers that is capable of generating arbitrary pretilt angles by controlling the ratio of horizontal and vertical alignment domain size. In particular, a photoalignment material is used as the top layer. In this configuration, the domain ratio can be controlled by varying the UV dosage. Thus a spatially varying UV light beam can be used to generate a spatially varying pretilt angle profile. In particular, we applied this technique to the fabrication of a tunable lens. A tunable liquid crystal lens has been investigated, and several configurations have been proposed, such as using nonuniform cell gap[17,18] or structured electrode.[19–25] We shall show that by using the variable pretilt approach, a large size lens with reasonable F numbers can be fabricated.

II. STACKED ALIGNMENT LAYERS (SALs)

The experiment process for preparing the SAL is shown in Fig. 1. In the first step, vertical alignment polyimide JALS2021 from JSR Corporation was spin-coated on ITO glass substrate. It was then cured and rubbed in the usual manner. In the second step, a horizontal alignment polymer ROP-103 from Rolic Ltd. was spin-coated on top of the polyimide layer. A UV light source was then used to polymerize this layer. Finally, a solvent, such as cyclohexanone was used to rinse the unexposed top ROP-103 material. This final step results in a top alignment layer that was discontinuous. This discontinuous layer, in combination with the continuous bottom layer, constitutes the nano-structure alignment layer.

The discontinuity of the top alignment is affected by both the concentration of the ROP-103 and the UV dosage. When the ROP-103 concentration is low, there may not be enough material to cover the whole surface, which will lead to the formation of a discontinuous layer. The UV dosage determines the level of polymerization. If the UV light intensity is low or the exposure time is also low, the ROP-103 layer may not be fully polymerized. Then in the rinse step, the unpolymerized material will be rinsed away and a discontinuous layer is formed. The model shown in Fig. 2 is used to study the pretilt angle relation with the stacked alignment layers. The structure in the model represents one unit cell in the discontinuous SAL. λ is the domain size of a unit cell that consists of the area of horizontal alignment λ_H and the area of vertical alignment λ_V.

The average pretilt angle, according to Ref. 11 is related to the ratio between domain size λ and extrapolation length of domain i which is defined as:

$$\ell_{ei} \equiv K_{11}/W_{\theta i} \quad (1)$$

where i denotes horizontal or vertical alignment domain, K_{11} is the LC splay elastic constant, $W_{\theta i}$ is the polar anchoring strength of domain i. For E7 that was used here, K_{11} is about 11 pN. The polar anchoring energy strength can be measured by a high voltage method.[26] The polar anchoring energy strength of the bottom vertical alignment polyimide layer is about 5×10^{-4} Jm^{-2}, and the top horizontal alignment polymer layer is about 1×10^{-3} Jm^{-2}. So the extrapolation length is about 16 nm. If the domain size λ is much smaller than the extrapolation length, the LC configuration could be considered as uniform, and the average pretilt angle will have nonlinear relationship with domain ratio $p = \lambda_H/(\lambda_V + \lambda_H)$:[11]

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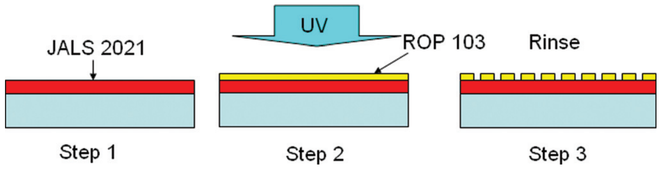

FIG. 1. (Color online) Experiment process for preparing SAL.

$$\theta_{AV} = \theta_V + \frac{1}{2}\tan^{-1}\left[\frac{(1-p)W_H \sin 2(\theta_V - \theta_H)}{(p-1)W_H \cos 2(\theta_V - \theta_H) - pW_V}\right]. \quad (2)$$

In the opposite limit, if the domain size λ is much larger than the extrapolation length, the average pretilt angle will have a linear relation with the domain ratio:[11]

$$\theta_{AV} = p\theta_H + (1-p)\theta_V. \quad (3)$$

At the interface, the LC alignment will just copy the inhomogeneity of the surface pattern, which, however, will become uniform within one domain size period from the surface. That is, when $z > \lambda$, the LC configuration will be uniform and the pretilt angle will be θ_{AV}. So to better control the pretilt angle by varying the domain ratio, the linear relation is better than the nonlinear relation because the linear case has larger processing window. However, the domain size should not be too large otherwise the inhomogeneity will be too large and uniform alignment will not occur.

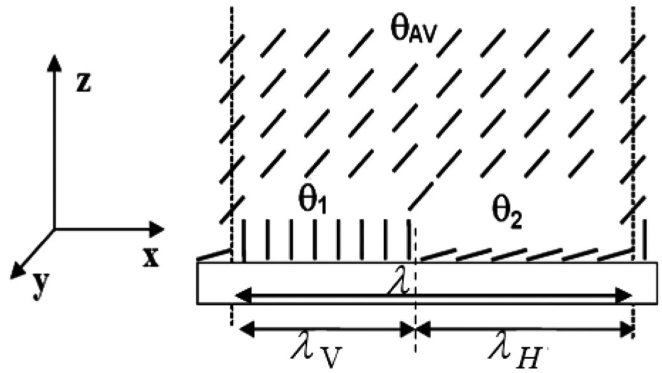

FIG. 2. Model for studying the LC pretilt angle relation with the stacked alignment layers.

We studied the alignment surface for different concentrations of ROP-103. Figure 3 shows pictures of the stacked

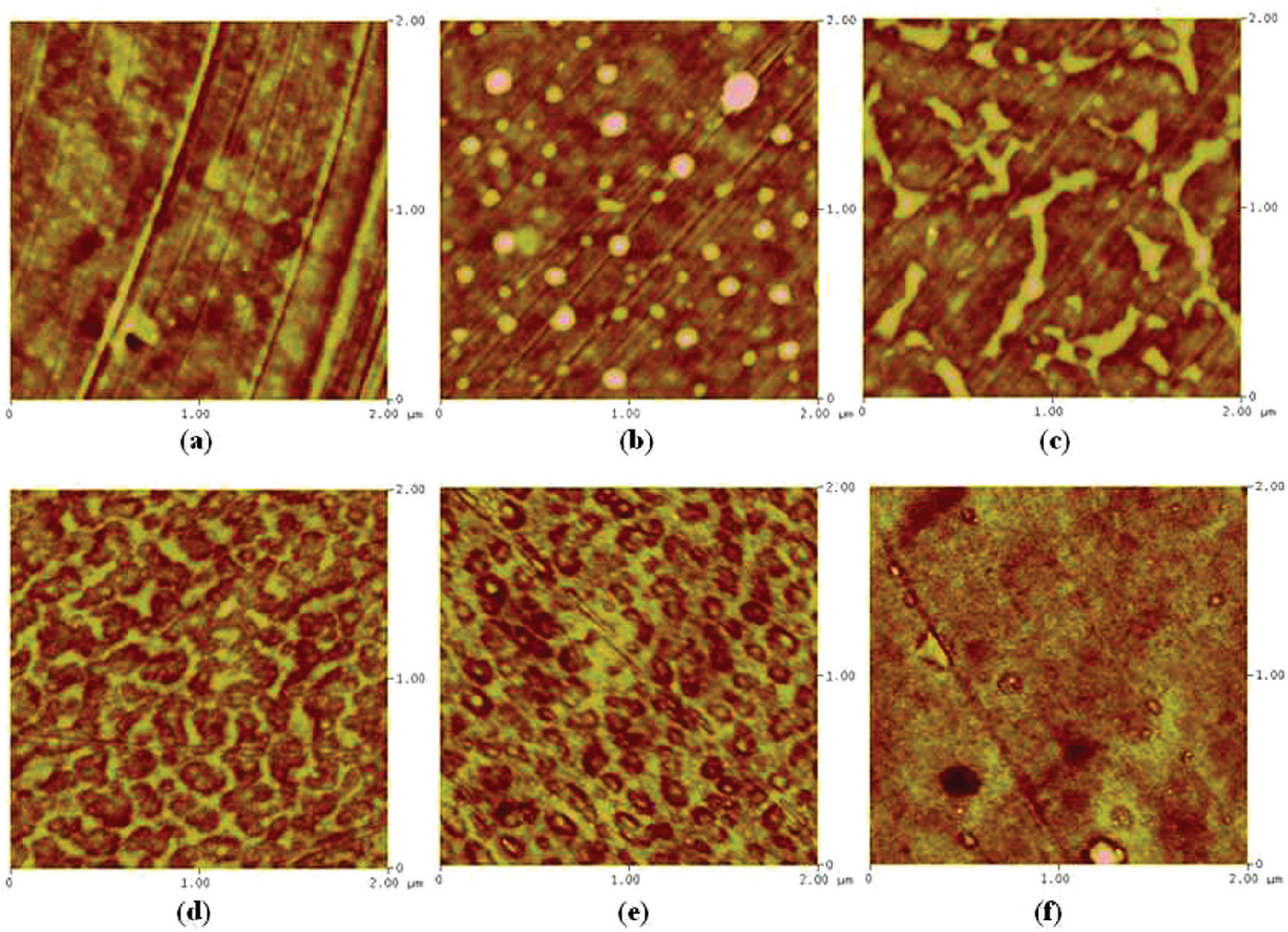

FIG. 3. (Color online) (a) Vertical alignment surface without ROP-103; (b) SAL surface with 2% ROP-103; (c) SAL surface with 4% ROP-103; (d) SAL surface with 6% ROP-103; (e) SAL surface with 8% ROP-103; (f) SAL surface with 10% ROP-103.

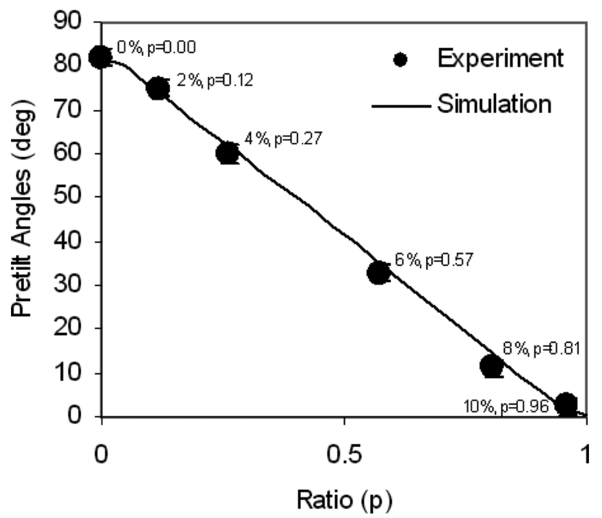

FIG. 4. Relation between domain ratio and average pretilt angle.

alignment layers using an atomic force microscopy (AFM). From the AFM pictures, it can be calculated that the average domain size is about 0.4 to 0.58 μm. This is a proper value for both a linear average pretilt angle condition and a uniform alignment.

To verify the linear relation between the domain ratio and average pretilt angle as indicated in Eq. (3), the domain ratio is calculated using the AFM picture, and the pretilt angle for anti-parallel cell with the same alignment structure in both substrates is measured using the crystal rotation method.[27] It can be seen that the experimental result fit very well with simulation (Fig. 4). The pretilt angle of the SAL linearly depends on the domain ratio. Any pretilt angle between planar and vertical alignment can be obtained by changing the domain ratio.

Because ROP-103 is a linearly photo-polymerizable polymer (LPP), different UV light dosage will lead to different level of polymerization. If the UV light intensity or exposure time is not enough, the ROP-103 layer may be just partially polymerized. The unpolymerized ROP-103 material will be rinsed away. Thus different domain ratios can be obtained, resulting in different pretilt angles.

In our experiment, ROP-103 concentration 10% was used. After spin-coating, the ROP-103 was exposed to UV light for different durations. The UV lamp used here is 200 mJ/cm^2 with center wavelength of 300 nm. Two substrates with the same treatments were assembled in anti-parallel rubbing direction so that a homogeneous alignment cell is formed. The pretilt angles were then measured. The pretilt angles as a function of exposure time are plotted in Fig. 5. It can be seen that it is possible to control the pretilt angle by varying the exposure time.

III. FABRICATION OF LENS USING A UV LASER

Obviously another way to vary the UV light dosage is by varying the light intensity with the same exposure time. A different light intensity will lead to different polymerization speeds. Thus it is possible to get spatially variable pretilt angles by exposure to a spatially variable UV intensity profile. A UV laser with a Gaussian profile can therefore be used to induce spatially variable pretilt angles.

The process for preparing the substrates is almost the same as the previous stacked alignment layers case. The only difference is that a UV laser is used instead of a uniform incoherent lamp. After the SAL process, a discontinuous ROP-103 layer is formed. In the center of the laser spot, the pretilt angle is the smallest due to the highest polymerization level of ROP-103. Then the top and bottom substrates were placed in an anti-parallel rubbing direction with the vertical alignment layer and then filled with liquid crystal (E7). The upper substrate of the LC cell was a single vertical alignment layer that gave high pretilt angles. The bottom substrate was a SAL. This resulted in a hybrid aligned nematic (HAN) cell structure.

To test the optical properties of this HAN cell, the sample was put between two crossed polarizers. The rubbing direction of the bottom substrate is at 45° to both polarizers. Green light at 530 nm was incident from one side of the polarizer and passed through the LC cell and was imaged by a microscope camera. A 1 kHz ac voltage source was used to drive the LC cell. The transmittance of the LC cell is given by

$$T = \sin^2\left(\frac{\pi d \Delta n}{\lambda}\right). \tag{4}$$

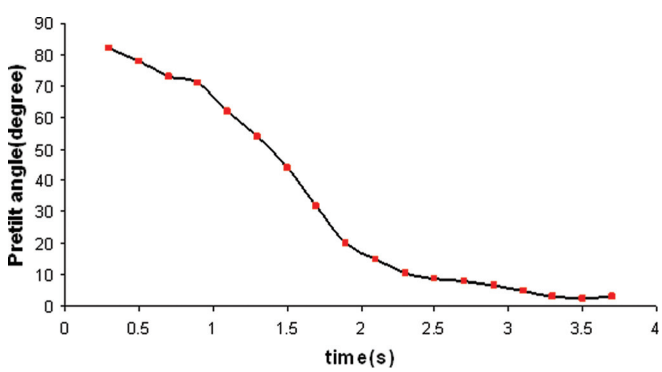

FIG. 5. (Color online) Pretilt angles as a function of exposure time.

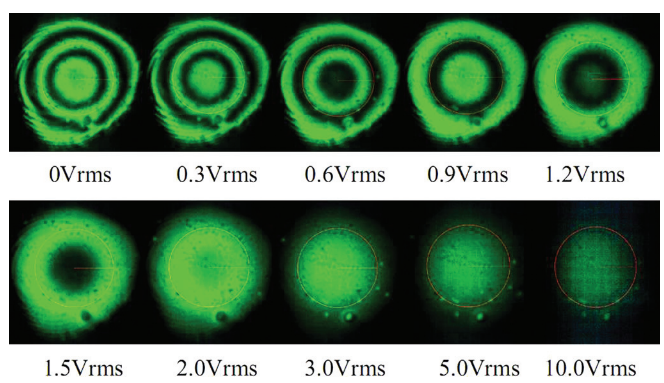

FIG. 6. (Color online) LC lens under different voltages.

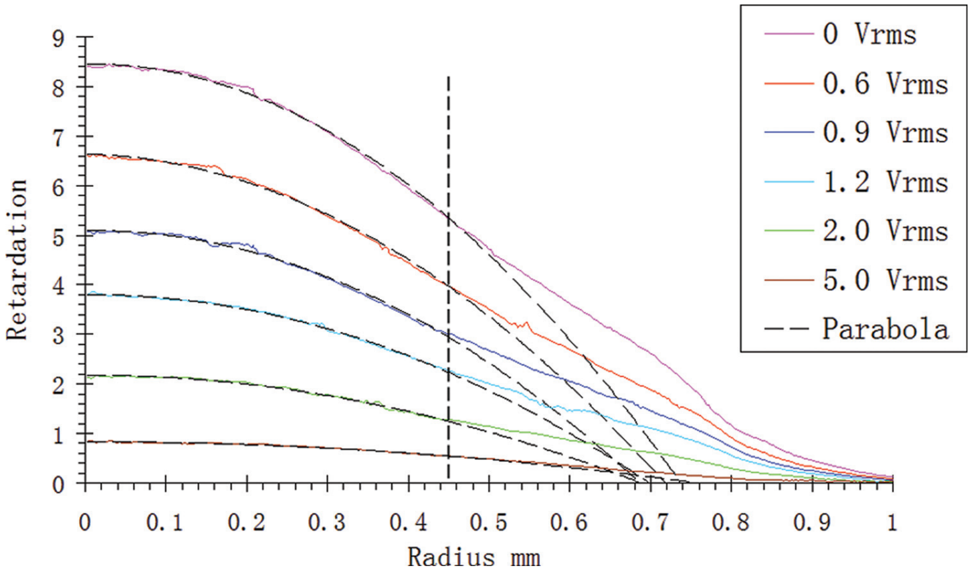

FIG. 7. (Color online) Retardation profile in different voltages.

Figure 6 shows photographs of the cell at different voltages. The brightness of the photo represents the transmittance, which can be used to calculate the phase retardation profile.

The retardation profile calculated in different voltages is shown in Fig. 7. The x-axis parameter radius represents distance to the center point. The y-axis parameter retardation is $\delta = \pi d\Delta n/\lambda$. Because a parabola retardation profile is ideal for making a lens, parabolic approximation was made (dashed line in Fig. 7) for every retardation profile. It can be seen that in the radius range of 0.45 mm, the retardation profile fits very well with the parabola curve in all voltages. So within this area, the cell truly acts as perfect lens, and the 0.45 mm radius circle was drawn as a red circle in Fig. 6.

The focal length of the lens at different voltages can be obtained by using the function:[23]

$$f = \frac{r^2}{2d\Delta n} \tag{5}$$

Where r is the radius of the LC lens, d is the LC cell thickness, Δn is the effective refraction index difference between the lens center and edge of the lens. The results are shown in Fig. 8. It can be seen that when there is no voltage applied, the focal length is 19 cm. The focal length is tunable from 19 cm to infinite by applying a voltage to the lens.

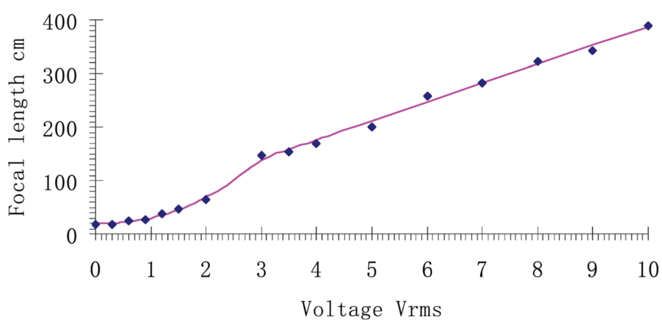

FIG. 8. (Color online) Relation between voltage and focal length.

IV. CONCLUSION

We have demonstrated an alignment surface (SAL) that is capable of patterning arbitrary pretilt angles spatially for a liquid crystal layer. It is achieved by stacking two alignment materials where the top layer is a photoalignment material. Thus the spatial profile of the pretilt angle can be controlled by the spatial profile of the UV source. A variable-focus liquid crystal lens was achieved by SAL. The SAL layer is quite powerful in generating any spatial pretilt angle variation. Many applications can be realized using such spatially variable pretilt angles. For example, a beam steering device can be made.

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