Micropatterned Alignment of Liquid Crystals

液晶のマイクロパターン・アライメント

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Abstract

Micropatterned alignment is a novel method for aligning liquid crystals (LC). The alignment technique generates different surface alignment orientations on a micron length-scale. This provides unique control of the LC orientation both near the alignment surface and in the bulk of the LC layer. Using micropatterned alignment, a number of new devices have already been realised. These devices include cells of arbitrary pretilt, graded refractive index (GRIN) micro-lenses and a bistable LC mode. Applications of these devices are numerous and include 2D-3D switching displays with better light efficiency, low power products for mobile use and liquid crystal displays (LCD) with novel electro-optical properties. Micropatterned alignment is still in its infancy, but as the field matures, more novel devices and applications will result that could potentially revolutionise switching speed, power consumption and functionality of LCDs.

マイクロパターン・アライメントは液晶の配向を行う新しい方法である。本配向技術によりミクロンオーダーで表面の配向方向を変えることができる。また配向表面近くだけでなく，液晶層内部の配向も制御することが可能となる。既にマイクロパターン・アライメントを応用することにより様々な新しいデバイスが実現されている。例えば任意のプレチルトを持ったセル，GRINマイクロレンズ，双安定液晶モードなどが挙げられる。具体的な応用としては高輝度2D/3D切替ディスプレイ，携帯機器用低消費電力液晶パネル，電子光学的に新しい特性を持った液晶ディスプレイ等数多い。マイクロパターン・アライメント技術はまだ研究段階にあるが実用化されれば数多くのデバイスや応用が生まれ，LCDのスイッチングスピード，消費電力，機能などに革命を起こすであろうと期待されている。

Introduction

Micropatterned LC alignment is an area of research that has recently attracted attention. Micropatterned alignment involves locally patterning the alignment properties of a surface in order to generate a desired LC orientation within the bulk of the LC layer. The patterning is performed such that patches that induce different alignment directions (different θ and ϕ, see **Fig. 1**) at the surface cooperate to induce a single resultant alignment direction in the bulk of the LC layer. Uniform LC alignment via non-uniform surface alignment is a somewhat counterintuitive approach to the conventional LC alignment rationale. In order to achieve uniform LC alignment from non-uniform alignment patches, it is imperative that the size of the alignment patches have at least one dimension that is smaller that the thickness of the liquid crystal layer.

A variety of experimental techniques have been employed in order to fabricate micropatterned surfaces for LC alignment [1][2][3][4]. However, the majority of these micropatterning techniques cannot be implemented for mass manufacture of LCDs. Photoalignment is the only technique that is currently available for relatively fast fabrication of uniform, large area micropatterned surfaces. It has been argued that photoalignment can be used for mass LCD manufacture and proponents often cite this non-

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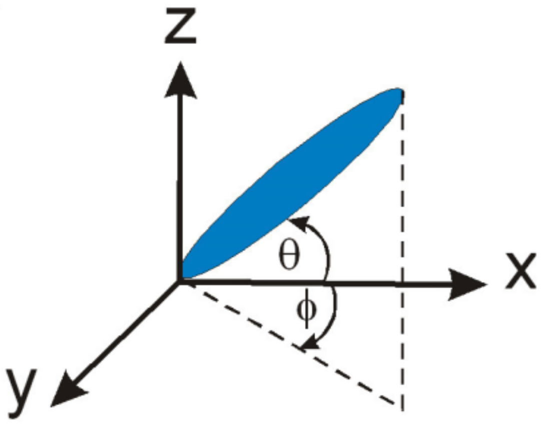

Fig. 1 LC alignment requires control over the azimuthal angle (ϕ) and the zenithal angle (θ) that the LC molecule makes with a surface (x-y plane).

contact alignment method as having advantages over the conventional rubbed-polyimide alignment method [5]. For this reason, all the micropatterning structures described herein are fabricated using photoalignment.

1. Micropatterned pretilt control

To illustrate an application of micropatterning, let us consider the angle, θ , that an LC molecule adopts at a surface – θ is known as the *pretilt angle*. When θ =90˚, rod shaped LC molecules adopt alignment that is perpendicular to the local surface and when θ =0˚ the LC molecules adopt alignment that is parallel to the local surface. Conventionally rubbed polyimide cannot easily achieve large area, high quality intermediate pretilt in the range 10˚< θ <80˚. This issue was addressed by Ong et al [1] and more recently by Yeung et al [3] who employed surfaces composed of patches that induce homeotropic (vertical) alignment that are surrounded in a matrix inducing planar alignment. By varying the area ratios of the surface alignment patches, pretilt from 0˚ to 90˚ was achieved. This method of pretilt control via patterned surfaces is shown schematically in **Fig. 2**. The exact nature of the bulk alignment orientation is primarily governed by the area ratios of the different surface alignment patches. Theoretically, the bulk LC orientation is also a function of the polar anchoring energies of the different surface alignment patches and a function of the anisotropic elastic constants of the LC material itself. In practice however, the influence of anchoring energy and anisotropic elastic constants on the bulk alignment orientation are of secondary importance to controlling the area ratios of the different alignment patches.

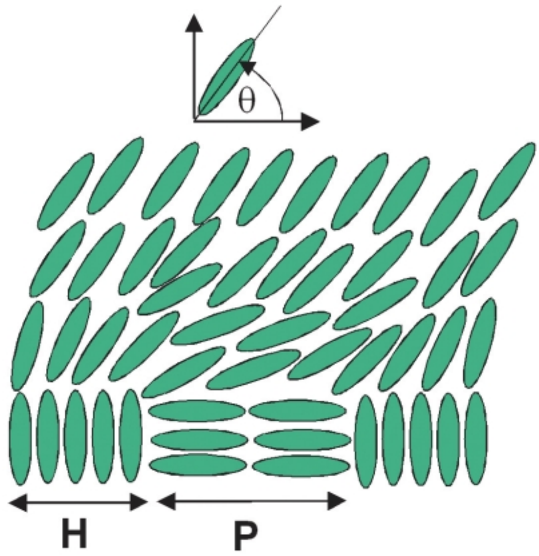

Fig. 2 A micropatterned surface composed of planar (P) alignment patches and homeotropic (H) alignment patches. The H and P patches cooperate to induce an average pretilt θ in the bulk of the LC.

1•1 Pretilt control experiments

Pretilt control was achieved at SLE via micropatterned photoalignment [6]. A polyimide alignment material RN-1338 (Nissan Chemical Industries Ltd.) was spin coated onto ITO coated glass plates and cured under a nitrogen atmosphere at 180°C. The alignment material RN-1338 promoted homeotropic alignment of nematic LCs 5CB and E7. However, after irradiation from sufficient fluence of linearly polarised deep UV radiation (~1 Jcm^{-2} @ ~250 nm) the alignment material RN-1338 undergoes photodissociation (bond-breaking) and planar alignment of the LC molecules results. Deep UV exposures were carried out with a 1000-Watt Mercury/Xenon high-pressure arc lamp. In order to pattern the surface alignment directions, a chrome mask was brought into contact with the RN-1338 coated substrate and the air between the two interfaces was evacuated to ensure good resolution of the lithographic features. The chrome areas of the mask prevent UV illumination of the underlying substrate and consequently preserve the intrinsic homeotropic alignment property of RN-1338. However, the polyimide situated under the no-chrome regions undergoes photodissociation and planar liquid crystal alignment results with an azimuth angle that is normal to the UV incident polarisation axis. The mask was composed of one-dimensional stripes of chrome and no-chrome with different regions on the mask having different area ratios of chrome to no-chrome. Depending upon the mask region, both the chrome and no-chrome stripe widths varied from 1 to 3 microns. The period of the patterning pitch was between 2 and 4 microns, depending upon mask region. Two RN-1338 polymer coated substrates were exposed to UV, glued together to form a cell with a 25 µm gap and subsequently filled with LC. The LC pretilt was measured conoscopically and found to vary from ~30˚ to ~70˚, depending upon on the area ratio of the homeotropic to planar patterning. These results are presented in **Fig. 3**.

Further investigations revealed that similar pretilt control results from two-dimensional (chequerboard) patterning of homeotropic and planar patches. It was also found that the patterning could be either uniform or random in nature without affecting the overall bulk pretilt.

2. Micropatterned GRIN lenses

Pretilt control is extremely important because it governs the optics and the switching characteristics of an LCD. However, pretilt control is only one small application of micropatterning. The following section describes the application of micropatterning to realise novel LC lenses.

Let us consider a situation where a surface is micropatterned with patches that induce both planar and homeotropic alignment. The previous section showed that the area ratio of the two different alignment patches control the bulk pretilt in the LC layer. It follows that if the ratio of planar inducing areas to homeotropic inducing areas is spatially varied, then the bulk pretilt will also vary spatially. By controlling the spatial functional form of the bulk pretilt, it has been possible to fabricate a novel optical structure: a micropatterned graded refractive index (GRIN) lens.

Fig. 4 is an illustration of a splay-bend micropatterned GRIN lens structure. Micropatterned GRIN lenses with a twist deformation are also possible. The micropatterned alignment patches are suitably proportioned to induce a macroscopic bulk orientation that gives the cell its lensing properties. The lens focuses light that is polarised in the plane of the splay-bend deformation whereas light of the orthogonal polarisation is not focused. Light polarised in the plane of the deformation experiences an effective refractive index (n_{eff}) that varies from n_o at the edge of the lens to n_e at the centre. For positive LC materials (i.e. $n_e > n_o$) the micropatterned GRIN lens focuses light in the manner depicted in **Fig. 4** and is equivalent to a conventional planar-convex glass lens.

The ability of a lens to bring light to a tight focus across the field effectively defines the imaging ability of the lens. For GRIN lenses, the variation of n_{eff} as a function of distance across the lens dictates the imaging ability. Since the functional form of n_{eff} is dictated by the details of the

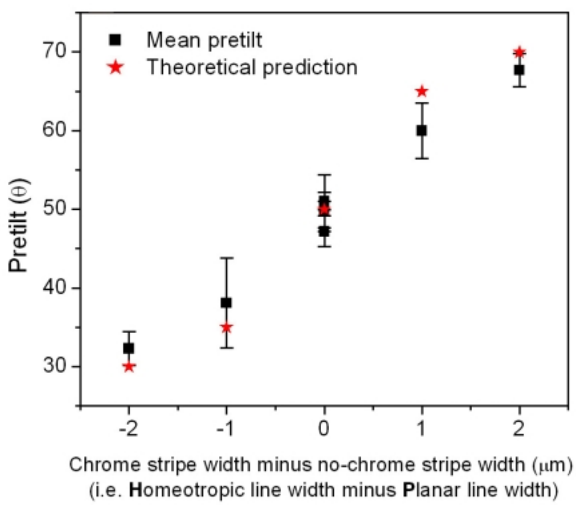

Fig. 3 Illustrates pretilt variation as a function of the alignment stripe width. When homeotropic and planar line widths are equal (**H-P**=0), pretilt is ~45°. When **H-P**<0, bulk pretilt is decreased while **H-P**>0 yields higher pretilts.

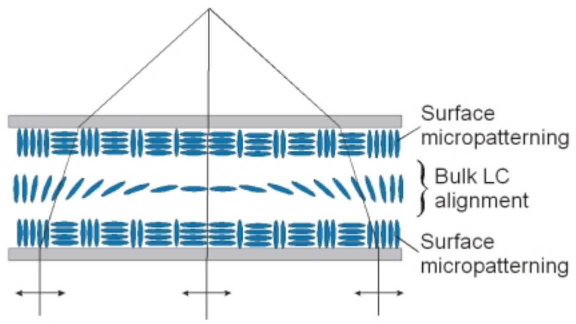

Fig. 4 Micropatterned alignment patches are suitably proportioned to induce a macroscopic bulk alignment that varies from ~90° at the edge of the lens to ~0° at the center of the lens. The lens only focuses light that is polarised in the plane of the LC deformation.

micropatterning, a micropatterned lens can be conceived that has an optimum variation in n_{eff}. The vast majority of LC lenses suffer from aberrations that degrade imaging because the functional form of n_{eff} (or the functional form of the refracting interfaces) is not optimum. Micropatterned LC GRIN lenses potentially have superior imaging properties to all other LC lenses partly because they are easier to optimise for a given imaging application. The optimisation is relatively trivial because the functional form of n_{eff} can be easily manipulated via the micropatterned surface.

2•1 Micropatterned GRIN lens experiments

Images taken under a polarising microscope of a novel micropatterned 2D GRIN lens with a twist deformation are shown in **Fig. 5**. When the microscope is focused on the substrate surface, the micropatterning structure is revealed (**Fig. 5a**). By moving the microscope stage down, the foci of the micropatterned GRIN lenses are then imaged by the microscope (**Fig. 5b**). The focal length of this lens was found to be ~1.5 mm in air. The focal length is a function of the cell thickness (25 μm) and the birefringence of the LC material (δ n=0.19). An increase in either the cell thickness or the birefringence yields a lens with a shorter focal length.

As depicted in **Fig. 5**, the micropatterned GRIN lenses focus light with no applied voltage. The focal length of the lenses can be continually varied between the design focal length and infinity by application of a suitable voltage. **Fig. 6** shows the effect of an increasing applied voltage on the foci of the lenses shown in **Fig. 5**. For all images, the separation of the GRIN lenses from the microscope objective lens remains constant. It is evident that the application of ~10 V yields a focal length that is effectively at infinity.

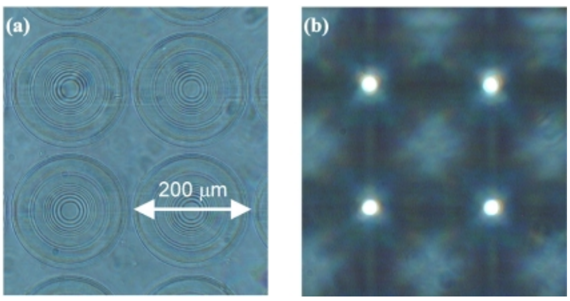

Fig. 5 Image of a) GRIN lens surface micropatterning and b) the resulting GRIN lens foci.

2•2 The future of switchable lenses for display applications

A variety of different switchable LC lenses have been conceived and fabricated over the years but none have yet been implemented into a mass manufactured product [7][8][9][10]. This is largely due to the fact that the cost of LC lens manufacture has been prohibitively high and the resulting LC lens quality too low for a product to offer commercial advantage. Compared with other LC lens fabrication procedures, micropatterned GRIN lens fabrication is relatively simple and consequently mass manufacturing is potentially cheap. This fact coupled with relatively easy optimisation of GRIN lens performance makes micropatterned GRIN lenses competitive in the field of switchable imaging devices.

A switchable 2D-3D display is an application that has been identified as ideally suited to low cost, high quality switchable LC lenses. In the 2D mode, the lenses are effectively switched-off and perform no imaging function. When the lenses are activated, pixels of the underlying base panel are imaged in the far field. For Sharp 3D displays, the left and right eye observes alternating pixel columns. Switchable lenses for a switchable 2D-3D display offer advantage over the parallax barrier method because the 3D image can be made twice as bright.

3. Azimuthal bistability and in-plane switching

Micropatterned alignment can also be used to make bi- or multi-stable LCDs. These displays remain in a particular switched state even after the switching voltage is turned off. Therefore micropatterned bistable LCDs require very little power to display a fixed image, making them suitable for ebooks and similar storage display applications.

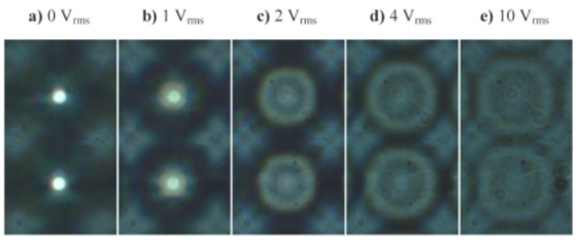

Fig. 6 Images of GRIN lens foci at 0V, 1V, 2V, 4V, and 10V. As the voltage is indreased, the LC molecules realign causing the focal length to increase.

Bistable alignment can occur where the interaction between the liquid crystal and the alignment layer encourages two different liquid crystal orientations. Kim et al [11] have demonstrated that by patterning the alignment layer into small domains with azimuthal (in-plane) surface alignment directions at 90° degrees to each other two stable orientations of a liquid crystal layer are obtained. **Fig. 7** shows how the bistable liquid crystal orientations are the averages of the two surface alignment directions.

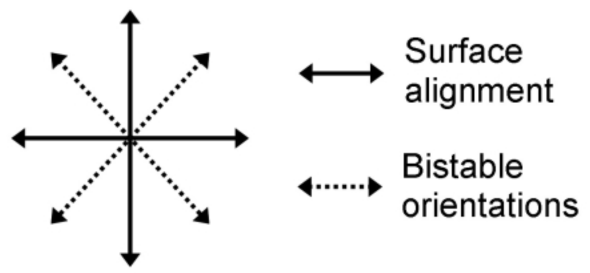

Fig. 7 Effect of azimuthally micropatterned alignment on average liquid crystal orientation.

3•1 Bistable device construction

RN1349 alignment layer was used to produce a micropatterned surface with two azimuthal alignments. This material gives zero pretilt alignment. The patterning consisted of two polarised UV exposures, first a uniform exposure of 35 mJ/cm^2 and second a patterned exposure of 120 mJ/cm^2 with polarisation perpendicular to the first. The resulting alignment pattern consisted of lines of 1 μm width.

Devices were assembled with one glass substrate having micropatterned alignment and a counter substrate having conventional rubbed alignment. The geometry of the alignment directions is shown in **Fig. 8**. When filled with liquid crystal this device had two stable orientations of the liquid crystal layer, both twisted by 45° between the substrates, but with opposite senses of twist. Switching between the two bistable liquid crystal orientations was achieved with in-plane electric fields from two orthogonal pairs of electrodes.

3•2 Bistable switching

Bistable switching between the two liquid crystal orientations is shown in **Fig. 9**. The device was positioned between two polarisers so that one orientation appeared light and the other dark. The switching threshold was measured as the voltage at which one of the bistable orientations completely bridged the gap between the electrodes. Once an area of the device was switched to a particular state it remained in that state for more than 24 hours, even with no applied voltage.

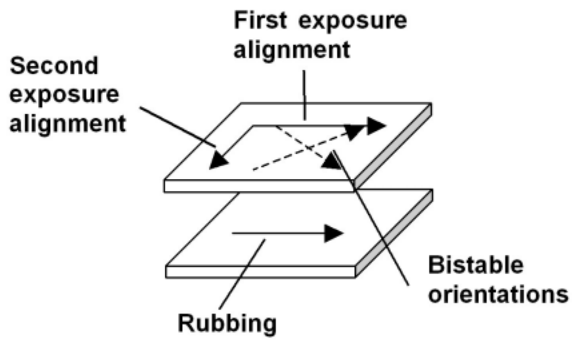

Fig. 8 Bistable device construction.

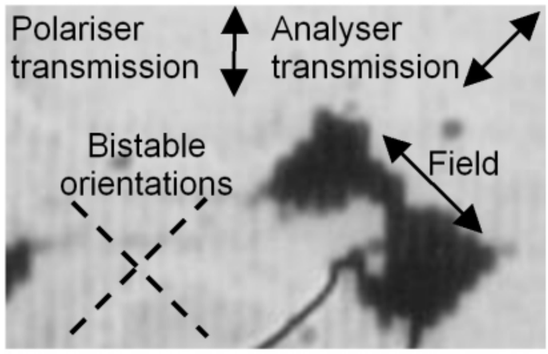

Fig. 9 Bistable switching of the liquid crystal orientation by an in-plane field.

The measured switching threshold voltages for two different liquid crystals are given in **Table 1**, also given is the ratio for the switching voltages. Kim et al. derive the following equation for the threshold switching voltage, E_{th}.

$$E_{th} = \frac{W_0}{2\sqrt{K_{22}\Delta\varepsilon}} \quad (1)$$

Where Wo is the surface anchoring energy, K_{22} the twist elastic constant and $\Delta\varepsilon$ the dielectric anisotropy. The anchoring energy, W_0 is not well defined for micropatterned alignment. However it should be approximately constant for all the cells measured. Equation 1 predicts that the threshold voltages for the two liquid crystals used should be inversely proportional to the square root of their dielectric anisotropy and twist elastic constant. The results in **Table 1** confirm this prediction.

Table 1 Mean switching voltage (standard deviation in brackets).

Liquid Crystal	Threshold Voltage (V)	$1/(K_{22}\Delta\varepsilon)$
E7	113(4)	1.04
ZLI4792	172(17)	1.60
Ratio	1.5	1.5

4. Complete control of LC alignment through micropatterning

Sections 1 and 2 demonstrate that micropatterned alignment can provide complete control over zenithal alignment while section 4 demonstrated control over azimuthal alignment. It follows that suitable micropatterning can *simultaneously control both* azimuthal and zenithal orientation of LC alignment. In order to control the orientation of LC molecules in 3-dimensional space, the micropatterned alignment requires 3 non-parallel, non-co-planar surface alignment directions.

If an alignment layer has one intrinsic alignment orientation, a single patterning step that re-orientates part of the surface to adopt a new alignment orientation provides complete control of the LC alignment in a single plane. An additional patterning step that provides a third LC surface orientation thus enables complete, 3-dimensional control over the LC alignment. To date, there have been no reported LC devices that utilise 3 surface micropatterned orientations. As the field of micropatterning matures, novel devices that employ 3 non-parallel, non-coplanar micropatterned directions are sure to result.

Conclusions

Micropatterned alignment is an area of academic interest owing to the realisation of new physics and commercial interest owing to the emergence of novel optical devices. The basic feasibility of micropatterned alignment has been demonstrated experimentally via lithographic photoalignment. A novel micropatterned GRIN lens has been invented that has advantage over existing switchable LC lenses since the new lenses are relatively simple to optimise and fabricate. Azimuthal bistability and in-plane switching has been demonstrated for micropatterned devices. While the switching voltages are too high for commercial products, these switching voltages can be reduced with further development.

Immediate applications of micropatterned alignment include: novel switchable retarders, GRIN lenses for switchable imaging applications (such as 3D), bistable/multistable LCD modes for low power applications and LCDs with novel electro-optical properties. As research into micropatterned alignment continues, many new LC devices will result. If future micropatterned devices can be mass manufactured with low cost, high quality and yield products that offer commercial advantage, then a revolution in LCD alignment technology will occur.

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