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Static alignment states in a bistable azimuthal nematic device with blazed grating sidewalls.

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Abstract

Bistable azimuthal alignment has been produced in channels of homogeneous nematic liquid crystal with periodic grating sidewalls. The grating morphologies included a symmetric triangular profile (blaze/pitch (b/p) = 0), an asymmetric highly blazed sawtooth profile (b/p = 0.5), and profiles with different amounts of blaze asymmetry between these two extremes. The observed optical textures and the trend in the relative frequency of occurrence of the two stable states as a function of the asymmetry were in agreement with the predictions of n-director based Frank-Oseen nematic continuum theory. A sidewall grating morphology with an intermediate degree of blaze asymmetry, b/p = 0.3, gave the highest optical contrast between the bistable states.

Keywords

Nematic liquid crystals, bistable states, polarisation, birefringence

PACS keywords

42. Optics; 42.25.Ja Polarization; 42.25.Lc Birefringence; 42.70.Df Liquid crystals; 42.79.Kr Display devices, liquid-crystal devices; 77. Dielectrics etc; 77.84.Nh Liquids, emulsions, and suspensions; liquid crystals

1. Introduction

Conventional liquid crystal displays require continual electrical addressing to maintain even static images. Bistable nematic and cholesteric displays have the ability to retain a static image in the absence of any applied electrical power, and therefore have potential applications where low update rate is required for example in e-paper, e-billboards and for smart labels and smart cards in the retail arena [1] [2] [3] [4] [5].

In a nematic liquid crystal layer, azimuthal bistability (or multistability) refers to the situation where two (or more) distinct stable alignment states of the nematic n-director occur in the plane of the nematic layer, for example at different average angles of rotation in the layer. For the different states to remain stable under ambient conditions, i.e. with no applied electric field, there must be an energy barrier that prevents one of the states spontaneously transforming to the other state or vice versa. Methods of producing azimuthal bistability or multistability include: patterning the substrates that contain the nematic layer with a micro-scale surface bi-grating or with nano-scale gratings [6] [7]; arrays of posts within the layer or spanning the width of the layer [2] [8] [9]; and lateral confinement by dividing the layer into square well regions [8] [10] [11] [12] or channels [13] [14].

In a practical display device there must be a mechanism for switching between the bistable states in response to the electric fields produced by applying voltages to row or column electrodes. Switching between stable states in bistable nematic devices using the coupling to the flexoelectric polarisation has been investigated theoretically in the literature [15] [16] [17] [18]. In a previous experimental study of nematic channels by the current authors the switching between the bistable states was achieved using dual frequency addressing of a highly dispersive nematic liquid crystal [14].

The current authors have previously demonstrated stable azimuthal alignment states in the plane of a homogeneous layer of nematic liquid crystal that have been created by the action of one or more grating sidewalls. As long as the distance between the sidewalls (i.e. the width of the channels) is several times greater than the thickness of the layer then the occurrence and nature of these azimuthal alignment states are determined almost entirely by the morphology of sidewalls of the channels and not by the alignment properties of the upper and lower confining plates [13]. The nematic ndirector then remains in the plane of the layer and there is no observed out-of-plane tilt. Previously a periodic grating channel sidewall morphology has been investigated for which the profile of the grating is triangular and symmetrical within each period [13] [14]. In channels bounded by two symmetrical periodic grating sidewalls (either in phase or out of phase) two alignment states have been observed. These states did not form the basis for a practical display device because there was little optical contrast between the two bistable states when viewed in transmission (or in reflection) with polarised incident light and a crossed analyser. The motivation for current work was to investigate the director configurations when an asymmetry is introduced into the cell geometry, to consider the possible destabilising effect of this asymmetry, and to produce bistable states for which the average optical transmitted (or reflected) intensities are as distinct as possible. A practical display device that switches between these states would then be capable of displaying black and white images at high contrast. To achieve this aim a blaze asymmetry has been introduced within each period sidewall grating profiles.

2. Device details

The geometry used in the investigations is shown in figure 1. A nematic liquid crystal layer of thickness $w = 22 \ \mu m$ was confined in the *x-y* plane by two glass substrates. The inside surfaces of the substrates were coated with a 0.2 μm thick layer of SU8 photoresist which imparted degenerate planar alignment to the nematic liquid crystal (MicroChem Corp., MA, USA). The SU8 layer is indicated by the cross-hatch shading in figure 1(b). SU8 photoresist sidewalls further confined the nematic liquid crystal into channels running along the *x*-direction. The channel width was $d = 100 \ \mu m$, where *d* is defined in figures 1(a) and 1(b). The photolithography and process details for fabricating the device were the same as described in previous publications [12]. The ends of the channels were open and the commercial nematic liquid crystal E7 (Merck KGaA, Darmstadt, Germany) was filled into the channels by capillary action with both the material and the device at 80 °C, above the isotropic-nematic phase transition temperature of 68 °C. After filling the device was cooled slowly at 0.5 °C per minute to room temperature.

The ratio of the channel width to the layer thickness, w/d, was in the regime where the layer thickness was small enough relative to the channel width so that the nematic ndirector remained in the *x-y* plane. At the same time the channel width was small enough relative to the layer thickness so that the interaction with the sidewalls determined the nature of the alignment states within the channel. This interaction overcomes the natural tendency of the nematic to form a Schlieren texture at the SU8/glass substrates that would normally occur because of the planar degenerate alignment at the SU8 surfaces [11] [19].

The sidewalls were periodic gratings constructed from linear sections between the apex peaks and the troughs, as shown by the profile of the grating in the *x*-*y* plane in figure 1(a). The peak to trough amplitude of the grating was $a = 20 \,\mu\text{m}$ and the grating pitch was $p = 80 \,\mu\text{m}$. Grating profiles with different blaze asymmetries were used in the investigation. The profiles of the gratings on either side of the channel are inverted relative to each other, i.e. if the channel width was reduced towards zero the two gratings would "fit together". Different degrees of asymmetry were introduced by creating channels in which the troughs had been laterally shifted in one direction towards the peaks by the distance *b*. When $b = 0 \,\mu\text{m} (b/p = 0.0)$ each period of the sidewall gratings has a symmetrical triangular profile. The maximum amount of asymmetry in the investigation was with $b = 40 \,\mu\text{m} (b/p = 0.5)$ which gives a highly blazed sawtooth profile.

3. Modelling the bistable alignment states

The n-director based Frank-Oseen nematic continuum theory [20] [21] has been used to predict the nematic alignment states for the geometry depicted in figure 1. Experimental observations indicate that the n-director remains in the *x*-*y* plane of the device [11] [14] and so the assumption is made that the n-director only varies in the lateral two dimensions and can be written in the form $\mathbf{n} = (\cos\theta, \sin\theta, 0)$ where $\theta(x, y)$ is the angle between the n-director and the x-direction defined in figure 1. On the SU8 boundaries there is degenerate planar anchoring of the n-director. In order for the easy direction to be parallel to the surface the surface free energy is written in the form $W_{\text{surf}} = W \sin^2(\theta - \alpha(x))$ where W is the anchoring strength and $\alpha(x)$ is local the angle of the grating surface with the x-axis [22] [23]. The governing equations were solved using a finite element package [24] to determine the resulting director profile for a given geometry. An isotropic elastic constant was used in the simulations, $K = 1.75 \times 10^{-11}$ N, and relatively strong surface anchoring, $W = 2 \times 10^{-5}$ N m⁻¹.

A potential disadvantage of using nematic continuum theory is that it does not allow the correct representation of nematic defects [22]. However, the present authors have previously found that modelling these types of geometries using n-director based theory and using the rigorous Q-Tensor theory give very similar results, even when dynamic reorientation occurs, provided that the defects remain close to the edges of the channels [14]. Figure 2 shows theoretical 2-dimensional n-director alignment configurations for two grating sidewall profiles, the symmetrical triangular profile with b/p = 0.0 in (a) and (c), and the blazed sawtooth asymmetrical profile with b/p = 0.5 in (b) and (d). In these figures the solid lines indicate the n-director orientation at different *x*-*y* positions in the channels. The director angle at the sidewalls is constrained by the strong anchoring to orient at the tangent to the grating surface. There are two distinct types of alignment configuration near to the grating boundaries of the channel that can be identified within the individual V-shaped grooves of the sidewalls.

The alignment state shown in figures 2(a) and 2(b) will be referred to as the "horizontal" alignment configuration. The near-sidewall alignment for both of the director configurations is characterised by the nematic n-director smoothly following the contours of the grating. The variation in the orientation angle of the n-director θ (with respect to the *x*-direction) reduces exponentially with distance in the *y*-direction [25] from being at the tangent at the sidewall to being substantially parallel to the channel direction in the centre of the channel. Very similar mid-channel near-horizontal alignment is predicted for both the symmetric zero blaze grating (b/p = 0.0) and for the high blaze asymmetric grating (b/p = 0.5) in figures 2(a) and 2(b) respectively.

The alignment state shown in figures 2(c) and 2(d) will be referred to as the "tilted" alignment configuration. The near-sidewall alignment for both of the director configurations is characterised by the nematic n-director pointing towards the vertex points near to the apexes of the peaks and in the troughs of the grooves leading to a high n-director orientation angle θ near to the surfaces. This near-grating alignment configuration was first investigated theoretically using Schwartz-Christoffel conformal mapping transformations for symmetric grating profiles in reference [26] and blazed grating profiles in reference [27]. For the symmetric zero blaze grating (b/p = 0.0) in figure 2(c) this type of near-surface alignment leads to a substantially vertical orientation of the n-director in the centre of the channel. For the high blaze asymmetric grating (b/p = 0.5) in figure 2(d) both of the grating surfaces promote a tilted n-director orientation with the tilt in the same direction and this leads to a substantially uniform tilted orientation in the centre of the channel. The symmetry here is critical, if the grating profiles were mirror images reflected about the centre of the channel [27] then they would promote tilted alignment in opposite directions, $+\theta$ from one side and $-\theta$ from the other side, leading to zero tilt horizontal alignment in the centre of the channel.

Figure 2 shows two stable states for each of the symmetric grating and the highly blazed grating sidewall geometries. For the symmetric grating there is a horizontal state (a) and a vertical state (c). The difference in average tilt angles for these two states is 90°, where the word "average" is used to refer to the n-director orientation for a significant proportion of the area of the channel. If these two states were viewed between crossed polarisors then they would give very similar optical transmission intensities. The theoretical maximum optical contrast that can be achieved between two azimuthal alignment states is when the two states differ in their net in-plane n-director orientation angle by 45°. The blazed grating geometry in figures 2(b) and 2(d) is much closer to this, with $\theta \approx 0^\circ$ in the centre of the channel for the horizontal state (b) and $\theta \approx 38^\circ$ in the centre of the channel for the tilted state is therefore likely to be between b/p = 0.0 and b/p = 0.5, but closer to the latter value.

4. Optical textures of static bistable alignment states

Experimental optical textures for horizontal and for tilted alignment states are shown in figure 3 and figure 4 respectively. These are bistable textures: in general both of the alignment textures can be observed in the same single channel separated by transition regions of elastic distortion. Temperature cycling the device up to above the nematicisotropic transition temperature of 68 °C and then back down to room temperature randomised the positions of the stable states. There were, however, small areas where one of the stable states remained pinned on a surface imperfection.

The textures in figures 3 and 4 were recorded in transmission using a polarising optical microscope with a magnification of 500×. Each row shows the optical texture for a sidewall grating with a different degree of asymmetry starting from the left with a symmetrical triangular profile b/p = 0.0, and then increasing the asymmetry b/p = 0.1, b/p = 0.2, b/p = 0.3, b/p = 0.4, to the most asymmetrical sawtooth profile b/p = 0.5 on the right hand side. Each column shows the optical texture for five different orientations of the crossed polarisers: $-45^{\circ}/+45^{\circ}$, $-22.5^{\circ}/+67.5^{\circ}$, $0^{\circ}/90^{\circ}$, $+22.5^{\circ}/-67.5^{\circ}$, and $+45^{\circ}/-45^{\circ}$ where the first angle refers to the input polarisor orientation and the second angle to the crossed analyser orientation. The device remained static whilst the polarisors were rotated. As would be expected there is negligible difference in the optical texture recorded at $-45^{\circ}/+45^{\circ}$ and the texture recorded at $+45^{\circ}/-45^{\circ}$ for a given 2-dimensional director configuration.

For all of the grating profiles shown in figure 3 the darkest texture with the minimum overall transmitted intensity occurs when the crossed polarisors are oriented at $0^{\circ}/90^{\circ}$. The lightest texture having the maximum overall transmitted intensity occurs with the crossed polarisors at $-45^{\circ}/+45^{\circ}$. This observation is consistent with the n-director orientation being horizontal for a significant proportion of the area of the device for all degrees of blaze asymmetry at the sidewall surfaces, as shown in figure 2(a) and 2(b). With the polarisors at $0^{\circ}/90^{\circ}$ light regions occur in the grooves of the sidewalls due to the tangential n-director orientation in the immediate vicinity of the walls and the associated elastic distortion of the n-director in these regions. When the polarisors are rotated these distortion regions give dark brushes which separate to one of the sides of the troughs, which side depends on the direction of rotation of the polarisors.

The optical textures in figure 4 correspond to the tilted alignment states shown in figures 2(c) and 2(d). For the most symmetrical grating profile, b/p = 0.0, in figure 4 the darkest texture is for polarisors at 0°/90°. For the symmetrical grating the ndirector alignment is close to vertical for a significant proportion of the channel which leads to an optical texture that is not so dissimilar from the corresponding horizontal state in figure 3. Classification of a particular experimental optical texture as a horizontal or a tilted alignment state was assisted by looking at neighbouring alignment states along the same channel and the elastic distortion regions between them at different polarisor orientations. In a device for which b/p = 0.0 switching between the horizontal and vertical states would lead to little change in the average transmitted intensity. As the asymmetry is increased in figure 4 the darkest optical textures no longer occur for polarisors at 0°/90°. For blaze asymmetry values of b/p = 0.3, b/p = 0.4 and b/p = 0.5 the darkest textures occur for polarisor orientations of $+22.5^{\circ}/-67.5^{\circ}$ or $+45^{\circ}/-45^{\circ}$. This is indicative of the n-director orientation becoming tilted away from vertical for a significant proportion of the area of the device.

Theoretical optical textures for horizontal and for tilted alignment states are shown in figure 5 and figure 6 respectively. These textures were obtained using the expression $T = \sin^2[2\theta(x, y)]$ from the 2 dimensional n-director configurations n(x, y) calculated with Frank-Oseen nematic continuum theory. There is good agreement between the appearances of the theoretical optical textures and of the corresponding experimental textures for different values of the blaze asymmetry, as well as confirmation that each of the two states is stable for these values of blaze. For the horizontal states in figures 3 and 5 the darkest textures, looking in the centre of the channel, occur when the

crossed polarisors are oriented at 0°/90° for all values of b/p. For the tilted states the textures for which the central area of the channel appears darkest in figure 6 occur for: 0°/90° when b/p = 0.0; -22.5°/+67.5° when b/p = 0.1 and b/p = 0.2; +45°/-45° when b/p = 0.3; and +22.5°/-67.5° when b/p = 0.4 and b/p = 0.5.

Figure 7(a) shows the integrated elastic energies contained in the theoretically calculated 2 dimensional n-director configurations for the tilted alignment states (solid line) and the horizontal alignment states (dashed line) as a function of the amount of blaze, b/p. Nematic continuum theory was used in the calculations and, since the energy of nematic defect cores [22] is undefined in this theory, the subsequent energy integrations use a grid which excludes a small region around the defects. The horizontal state is predicted to contain the lowest elastic energy for sidewall gratings that are symmetrical and those that have a blaze asymmetry up to b/p = 0.43. There is a cross over at this asymmetry value and above b/p = 0.43 the tilted state is predicted to contain the lowest elastic energy.

Figure 7(b) shows the frequencies of occurrence of the tilted (solid line) and horizontal (dashed line) states as a function of the amount of blaze, which was varied in the devices in the range b/p = 0 to 0.5 in steps of size b/p = 0.05. The frequency of occurrence at each value of blaze asymmetry was made by counting the number of periods of the sidewall channels that enclosed the vertical state, the number of periods that enclosed the tilted state, and then expressing each number as a percentage fraction of the total number of periods counted. For each value of the blaze asymmetry observations were made on up to 8 adjacent channels in the same device. Three measurements of the frequency of occurrence data are shown which are indicated (in the order in which the measurements were made) by circles, squares, and diamond symbols. Between each set of measurements the device underwent a thermal cycle up to the isotropic phase of the nematic liquid crystal.

In experimental devices the horizontal state was found to occur more frequently for the most symmetrical sidewall profiles for low values of the blaze asymmetry. At high values, i.e. for the most blazed asymmetrical profiles, the tilted state was found to occur more frequently. The crossover between these two regimes for the three sets of measurement data shown in figure 7(b) lies in the range between b/p = 0.27 and b/p = 0.32. This trend is in agreement with the theoretical simulations since the horizontal state occurs more frequently at lower blaze asymmetry values where it is predicted to have lower energy, and the tilted state occurs more frequently for higher blaze asymmetry values where it is predicted to have lower energy. The crossover value predicted by the theoretical simulations, at b/p = 0.43, is somewhat higher than the experimentally observed value.

5. Transmitted intensities of bistable alignment states

Figures 8(a) and 9(a) show the theoretical average transmitted intensities between crossed polarisors of the horizontal and the tilted alignment states respectively (figures 5 and 6). The intensities were calculated from the theoretical n-director alignment configuration at each blaze asymmetry value by averaging the value of $T = \sin^2[2\theta(x, y)]$ over an area that covered one period of the sidewall grating in the *x*-direction and across the channel from trough to trough of opposing grating sidewalls in the *y*-direction. The transmission through any regions covered by the sidewall grating was assumed to be zero.

Experimental transmission measurements were made using a SPOT photometer (Minolta LS-110) for which the light collection area was circular with a diameter that was approximately the width of one grating period relative to the magnified image of the device produced by the polarising microscope. The experimental transmitted intensity values in figures 8(b) and 9(b) were calculated using the expression $T = (I_T - I_{cross})/(I_{para} - I_{cross})$ where I_T was the measured transmitted intensity through the experimental device between crossed polarisors, $I_{cross} = 0.3 \pm 0.1$ Cd m⁻² was the transmitted intensity of an unfilled device placed between crossed polarisors with broad band white light illumination.

For the horizontal stable alignment state the minimum transmitted intensity occurs for all values of the blaze asymmetry when the crossed polarisers are oriented at $0^{\circ}/90^{\circ}$, as shown in figure 8. There is good agreement between the theoretical curves in figure 8(a) and the results from observations in experimental devices in figure 8(b). This is consistent with the nematic n-director remaining oriented parallel to the channel and the *x*-axis for the majority of the area of the channel for all values of the blaze asymmetry.

The theoretical and experimental optical transmission results for the tilted stable alignment state are shown in figures 9(a) and 9(b) respectively. The minimum of the theoretical curves shifts in figure 9(a) monotonically in the direction of negative input polarisor angles as a function of the amount of blaze asymmetry. The minimum transmitted intensity occurs at -5° for b/p = 0, -20° for b/p = 0.1, -41° for b/p = 0.2,

45° (or -45°) for b/p = 0.3, 33° (or -57°) for b/p = 0.4, and 23° (or -67°) for b/p = 0.5. This observation is consistent with the nematic n-director in the majority of the area of the channel tilting to higher values relative to the *x*-axis as the amount of blaze asymmetry is increased. The "ideal" tilt angle of 45° occurs for a blaze asymmetry of b/p = 0.3.

The minima in the experimental optical transmission curves in figure 9(b) shows the same trend of shifting in the direction of negative input polarisor angles as a function of the amount of blaze asymmetry. The minimum transmitted intensity occurs at -0° for b/p = 0, -25° for b/p = 0.1, 25° (or -65°) for b/p = 0.2, 25° (or -65°) for b/p = 0.3, 30° (or -60°) for b/p = 0.4, and 25° (or -65°) for b/p = 0.5. The dependence on the amount of blaze asymmetry is not monotonic in an experimental device. In theoretical simulations small changes in grating shape can be made and the resolution of the mesh in the partial differentiation solver can be refined so that the results vary smoothly as a function of these small changes. A real experimental system does not necessarily always settle into the global minimum energy configuration. In the current device there are neighbouring bistable states along the same channel, inevitable small imperfections in the SU8 layers on the bounding plates (although the wall features themselves were sharply defined), and there is also some anchoring, albeit weak, on the upper and lower substrates that confine the layer into the *x-y* plane.

The largest difference between optical transmission of the horizontal and tilted states occurs for b/p = 0.3 for the theoretical n-director configurations and for blaze asymmetry values between b/p = 0.2 and b/p = 0.4 in the experimental devices. For crossed polarisors oriented at 0°/90° and b/p = 0.3 the theoretical optical transmission is 0.076 for the horizontal state, 0.713 for the tilted state, and the ratio of these two values is 9.4. The experimental optical transmission for this polarisor orientation and grating asymmetry value is 0.27 ± 0.05 Cd m⁻² for the horizontal state, 0.66 ± 0.05 Cd m⁻² for the tilted state, and the ratio of these two values are the optical transmission values with the value for a blank device between crossed polarisors subtracted.

6. Conclusion and discussion

The theoretical maximum optical contrast that can be achieved between two azimuthal alignment states is when the two states differ in their net in-plane n-director orientation angle by 45°. Theoretical simulations and experiment measurements on devices that use sidewall-dictated alignment in nematic channels have shown that

bistability remains when an asymmetric, through a blazed grating, is introduced and that maximal contrast can be achieved using blazed grating sidewalls with a blaze asymmetry value of b/p = 0.3. In order to produce the tilted state the profiles of the gratings on either side of the channel must be inverted relative to each other.

In a practical device it would be possible to further increase the optical transmission contrast between the bistable horizontal and the tilted alignment states by reducing the amplitude and pitch of the grating as much as possible. This would have two beneficial effects. Firstly this would increase fill factor which is the area of the device that is covered by the electro-optical nematic layer as a fraction of the total area of the device which includes both the sidewalls plus the nematic layer. Secondly, a smaller amplitude sidewall grating would still dictate the stable nematic n-director orientation angles in the channel but the regions of distortion near to the grating peaks and troughs (which reduce contrast) would occupy a relatively smaller proportion of the active area of the device.

A further potential benefit of blaze asymmetry in the sidewall grating profiles is that the time for switching between the bistable states could be reduced. In a previous study of nematic channels, that was referred to in the introduction [14], there was one symmetric grating sidewall and one straight sidewall and switching between the bistable states was achieved using dual frequency addressing of a highly dispersive nematic liquid crystal. The switching mechanism involved the creation and collapsing of filament-like director reorientation (tilt-wall) loops with the associated motion and annihilation of surface defects along and close to the edge at the sawtooth sidewall. This process would potentially be quicker along the shorter edges of a blazed grating, and using this effect in combination with reduced amplitude and reduced pitch gratings could improve switching speeds still further. An investigation of the effect of sidewalls with blaze asymmetry on switching mechanisms will be presented in a future publication.

References

- [1] I. Dozov, M. Nobili, G. Durand, Appl. Phys. Lett. 70, 1179 (1997)
- [2] S. Kitson and A. Geisow, *Appl. Phys. Lett.* **80**(19), 3635 (2002)
- [3] G.P. Bryan-Brown, C.V. Brown and J.C. Jones, UK Patent GB2318422, 16 Oct 1995
- [4] C.V. Brown, M.J. Towler, V.C. Hui and G.P. Bryan-Brown, *Liq. Cryst.* 27, 233 (2000)
- [5] D-K Yang, J West, L-C Chien, and JW Doane, J. Appl. Phys. 76, 20 (1994)
- [6] J-H. Kim, M. Yoneya and H. Yokoyama, *Nature* **420**, 159 (2002)
- [7] G. P. Bryan-Brown, M.J. Towler, M.S. Bancroft, D.G. McDonnell, UK patent GB2286467, 8 Feb 1995
- [8] R.N. Thurston, J. Cheng and G.D. Boyd, *IEEE Trans. Elec. Dev.* ED27(11), 2069 (1980)
- [9] A. Majumdar, C.J.P. Newton, J.M. Robbins and M. Zyskin, *Phys. Rev. E.* 75, 051703 (2007)
- [10] N.J. Mottram, A. Ramage, G. Kelly and A.J. Davidson, UK patent GB20040026582, 8th June 2006
- [11] C. Tsakonas, A. Davidson, C.V. Brown and N. J. Mottram, *Appl. Phys. Lett.* **90**, 111913 (2007)
- [12] G.G. Wells and C.V. Brown, Appl. Phys. Lett. 91, 223506 (2007)
- [13] S. Ladak, A. Davidson, C.V. Brown and N.J. Mottram, J. Phys. D: Appl. Phys. 42, pp 85114-85121 (2009)
- [14] A.J. Davidson, C.V. Brown, N.J. Mottram, S. Ladak, and C.R. Evans, *Phys. Rev. E.* 81(5), 051712 (2010)
- [15] A.J. Davidson and N.J. Mottram. Phys. Rev. E. 65(5), 51710, (2002)
- [16] L.A. Parry-Jones and S.J. Elston. J. Appl. Phys. 97(9), 93515, (2005)
- [17] C. Denniston and J.M. Yeomans. Phys. Rev. Lett. 87, 275505, (2001)
- [18] T.J. Spencer and C.M. Care. *Phys. Rev. E*. 74(6), 61708, (2006)
- [19] S. Chandrasekhar, "Liquid Crystals", 2nd Ed. Cambridge University Press (1992) ISBN 052142741X
- [20] F.C. Frank, Disc. Faraday. Soc. 25, 19 (1958)
- [21] C.W. Oseen, Trans. Faraday. Soc. 29, 883 (1933)
- [22] P.G. de Gennes and J. Prost, "The Physics of Liquid Crystals", 2nd Ed. Oxford University Press Clarendon Press (1995) ISBN 0198517858
- [23] A. Rapini and M. Papoular, J. Physique Colloq. 30, C4-54 (1969)
- [24] COMSOL Multiphysics version 3.5a. COMSOL AB, Burlington MA, U.S.A. www.comsol.com, 2007.

- [25] D.W. Berreman, Phys. Rev. Lett. 28, 1683 (1972)
- [26] G. Barbero, Lett. al. Nuovo Cimento 29(17), 553 (1980)
- [27] G. Barbero, Lett. al. Nuovo Cimento 32(2), 60 (1981)

Figure captions

- Figure 1 The device geometry. (a) Shows a plan view of the structure and (b) shows a side view.
- Figure 2 Theoretical 2-dimensional director alignment configurations for: (a) and (b) the horizontal alignment state; (c) and (d) the tilted alignment state. The alignment configurations are shown for two grating sidewall profiles, symmetrical b/p = 0.0 in (a) and (c), and sawtooth (most asymmetrical) b/p = 0.5 in (b) and (d).
- Figure 3 Experimental optical textures for horizontal alignment states between crossed polarisers. Each column shows the optical texture for a sidewall grating with a different degree of asymmetry. Textures are shown for sidewalls where b/p = 0.0 (symmetrical), 0.1, 0.2, 0.3, 0.4, 0.5 (sawtooth profile, most asymmetrical). The rows show each of textures viewed at a different orientation of the crossed polarisers: -45°, -22.5°, 0°, 22.5°, and 45° (as shown to the left of the figure).
- Figure 4 Experimental optical textures for tilted alignment states between crossed polarisers. Each column shows the optical texture for a sidewall grating with a different degree of asymmetry. Textures are shown for sidewalls where b/p = 0.0 (symmetrical), 0.1, 0.2, 0.3, 0.4, 0.5 (sawtooth profile, most asymmetrical). The rows show each of textures viewed at a different orientation of the crossed polarisers: -45°, -22.5°, 0°, 22.5°, and 45° (as shown to the left of the figure).
- Figure 5 Theoretical optical textures for horizontal alignment states between crossed polarisers. Each column shows the optical texture for a sidewall grating with a different degree of asymmetry. Textures are shown for sidewalls where b/p = 0.0 (symmetrical), 0.1, 0.2, 0.3, 0.4, 0.5 (sawtooth profile, most asymmetrical). The rows show each of textures predicted for a different orientation of the crossed polarisers: -45°, -22.5°, 0°, 22.5°, and 45° (as shown to the left of the figure).
- Figure 6 Theoretical optical textures for tilted alignment states between crossed polarisers. Each column shows the optical texture for a sidewall grating with a different degree of asymmetry. Textures are shown for sidewalls

where b/p = 0.0 (symmetrical), 0.1, 0.2, 0.3, 0.4, 0.5 (sawtooth profile, most asymmetrical). The rows show each of textures predicted for at a different orientation of the crossed polarisers: -45°, -22.5°, 0°, 22.5°, and 45° (as shown to the left of the figure).

- Figure 7 (a) Elastic energies of the tilted (solid line) and horizontal (dashed line) alignment states as a function of the amount of blaze, b/p. (b) The frequencies of occurrence of the vertical (solid line) and horizontal (dashed line) states as a function of the amount of blaze, b/p. Three measurements of the frequency of occurrence data are shown (indicated by circles, squares, and diamond symbols) and the device was thermally annealed between each set of measurements.
- Figure 8 The transmitted intensity of horizontal alignment states as a function of polarisor angle. Data are shown for sidewalls where b/p = 0.0 (squares), 0.1 (circles), 0.2 (up triangle), 0.3 (down triangle), 0.4 (diamond), and 0.5 (crosses). The plots in figure (a) were generated from the theoretical textures shown in figure 5. The plots in figure (b) were measured using a photodiode on an experimental device exhibiting the textures shown in figure 2.
- Figure 9 The transmitted intensity of tilted alignment states as a function of polarisor angle. Data are shown for sidewalls where b/p = 0.0 (squares), 0.1 (circles), 0.2 (up triangle), 0.3 (down triangle), 0.4 (diamond), and 0.5 (crosses). The plots in figure (a) were generated from the theoretical textures shown in figure 6. The plots in figure (b) were measured using a photodiode on an experimental device exhibiting the textures shown in figure 3.



Figure 1 (CREvans D363272PAP40015 figure01.eps)



Figure 2 (CREvans D363272PAP40015 figure02.eps)











Figure 7 (CREvans D363272PAP40015 figure07.eps)



Figure 8 (CREvans D363272PAP40015 figure08.eps)



Figure 9 (CREvans D363272PAP40015 figure09.eps)