A Grating-Aligned Ferroelectric Liquid Crystal Electro-Optic Shutter for Fast-Switching and Shock-Resistant Applications

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Abstract

Sub-millisecond electro-optic switching times of ferroelectric liquid crystals (FLCs) remain highly desirable for fast switching devices, such as LCoS display applications. Such materials are notoriously susceptible to damage through shock-induced flow. A simple shock-stable geometry for FLC electro-optic shutters is presented, based on homeotropic surface-relief gratings.

Author Keywords

Liquid crystals; ferroelectric; electro-optic; shutter; shock-stable; FLC; grating; alignment.

1. Introduction

Ferroelectric liquid crystals (FLCs) were a highly popular research subject for the display industry in the 1980s and 1990s, due to their sub-millisecond switching times and inherent bistability [1]. Technologies such as the Surface Stabilised FLC (SSFLC) [2] seemed suited as an alternative to nematic-based LCDs since high complexity passive displays could be made without thin-film-transistors at each pixel. Success of an FLC display requires uniform alignment of the tilted smectic layers, which must be retained for electro-optic addressing. However, such materials are susceptible to shock induced flow if not sufficiently stabilised, rendering them unsuited for large area displays. Many promising improvements have been proposed involving polymer walls and networks to strengthen such devices [3], but these can increase required operating voltages and interfere with their electro-optic response. Success has also been seen in vertical alignment geometries of FLCs [4]. Nevertheless, this sub-millisecond response time remains desirable, for instance for frame sequential colour in projector display applications. Liquid Crystal on Silicon (LCoS) spatial light modulators based on FLCs are commercially successful [5] and are less likely to be damaged by to shock than larger area devices, but new shock-insensitive modes would still be beneficial.

A simple yet novel geometry for FLC electro-optic shutters is presented, based on two surface-relief gratings to controllably align the FLC **c**-director on opposing substrates: the VGA-FLC (Vertical Grating Aligned Ferroelectric Liquid Crystal), shown schematically in Figure 1. The surface-relief gratings are treated to induce a homeotropic (vertical), alignment to the FLC layer normal, **a**, such that **a** is parallel to the substrate normal. Such alignments are shown to exhibit greater shock stability than a planar device, due to the initial alignment of the smectic layers relative to the direction of any induced liquid flow. When this geometry is pressed or shocked, flow remains in the cell plane such that most distortion to the layers is either compression or reorientation to the smectic **c**-director within the layer, shown schematically in Figure 2. The grating provides a preferred orientation for the **c**-director to which it returns following a mechanical or electrical shock through a mechanism of "self-healing", with no additional stimulus required. When combined with interdigitated electrodes (IDEs) the device is shown to switch between dark and bright states at sub-millisecond times.

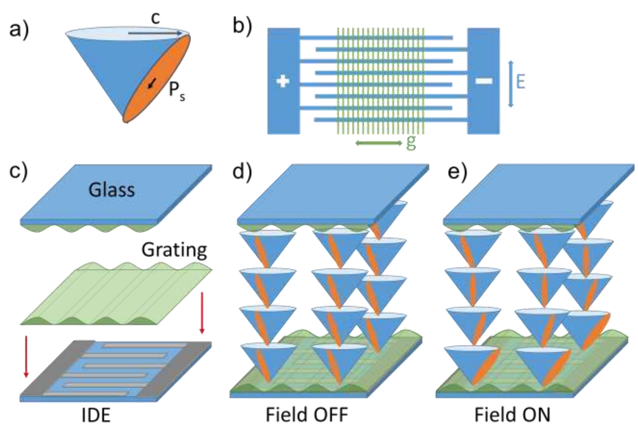

Figure 1. Schematic diagram of the VGA-FLC device geometry. a) Representation of the **c**-director, **c**, and the spontaneous polarisation, P_s, of the FLC; b) Orientation of the gratings with respect to the in-plane electrodes; c) 3D schematic of the gratings with respect to the IDE; d) Device in the OFF/dark state, with no applied electric field, where the **c**-director is homogeneously aligned through the cell; e) Device with an electric field applied to rotate the **c**-director 90° through the cell. On removal of this field, the device relaxes back to the homogeneous **c**-director alignment shown in d). Note that opposite twist will occur on opposite sides of an IDE.

The use of surface relief gratings as alignment layers for liquid crystal devices is well established, with commercial success for Zenithal Bistable Displays (ZBD) [6]. In this work, sub-micron amplitude and micron pitched surface-relief gratings are embossed onto ITO (indium-tin oxide) coated glass IDEs using a polymer film imparted with the required surface relief structure copied from a photolithographically defined master via an electro-forming step [7,8]. This geometry has led to a working prototype of a device that demonstrates both resistance to mechanical shock and sub-millisecond switching times. Improvements are suggested to further optimise the device.

With the device in the OFF state and no applied electric field, the **c**-director of the FLC is aligned perpendicular to the grating vector, **g**, at both opposing surfaces. Unwanted helical twist from one surface to the other is ensured by decreasing the chirality of the SmC*, thereby leading to a uniform surface stabilised homeotropic state. Uniform alignment occurs for the condition satisfies $P(T) > 4d$ [1] where $P(T)$ is the helical pitch of the FLC, and d the cell gap, calculated from the Gooch-Tarry equation for a TN device [9]:

$$\Delta n_{eff} d = \frac{\sqrt{3}}{2}\lambda \quad , \tag{1}$$

where Δn_{eff} is the effective birefringence of the material when tilted from the vertical through the SmC* cone angle θ_C, and λ is the wavelength of incident light. On the application of in-plane electric

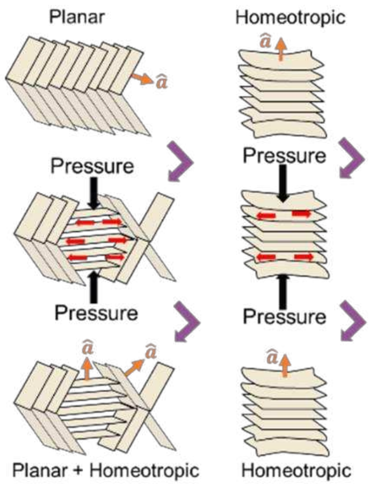

Figure 2. The mechanical response of planar and homeotropic oriented smectic layers when exposed to a mechanical shock. The layer normal, **a**, shows the layer alignment before and after a shock, with flow of the liquid crystal indicated by the red arrows. When initially in a planar orientation, flow orients the layers to **a** homeotropic alignment geometry in the effected region, which remains after force removal. In the homeotropic state the layers compress, resulting in in-plane flow of the FLC, withstanding significant damage to the smectic layers.

fields from one surface of the device, the **c**-director can be rotated by 90° through the cell to obtain a bright state, with optics analogous to those found in a twisted nematic (TN) display. This is the ON state of the device. On removal of the electric field, the **c**-director relaxes back to once again align with the grating, restoring the OFF/dark state. Alternatively, a restoring pulse can be applied to restore the OFF state to achieve similar response times to those of the ON times.

2. Grating Induced Self-Healing of the FLC c- and a- Directors

The device geometry is shown to have a resistance to shock induced flow. The homeotropic geometry itself is less sensitive to shock as applied force causes compressions rather than layer deformation, schematically shown in Figure 2. This is contrary to what happens in the planar aligned SSFLC, where pressure tends to induce zig-zag defects, and high degrees of shock lead to the induction of homeotropically aligned-layers. The sinusoidal relief grating strongly orients the **c**-director to lie in a particular direction, shown in Figure 3b and 3c. On cooling into the SmC* phase from the SmA, an undulating texture appears which eventually reorients to return to a homogeneous aligned **c**-director state given time or further cooling, shown in Figure 3a. This undulating texture is induced by the gratings and appears on cooling as each new smectic layer is formed, but with a Helfrich-Hurault type undulation [10-11]. Eventually, the layers undergo a first order alignment change and the texture changes to that of a homogenously aligned homeotropic SmC* and the undulation is relaxed. This repeats on further cooling at several temperatures that depend on cooling rate. Following a mechanical shock, a similar effect is observed whereby an undulating texture is induced, and self-heals in a similar fashion back to homeotropic **a**-director and the **c**-director aligning with the surface-relief grating, restoring the dark texture to the device. Without the surface-relief grating, such healing is not observed.

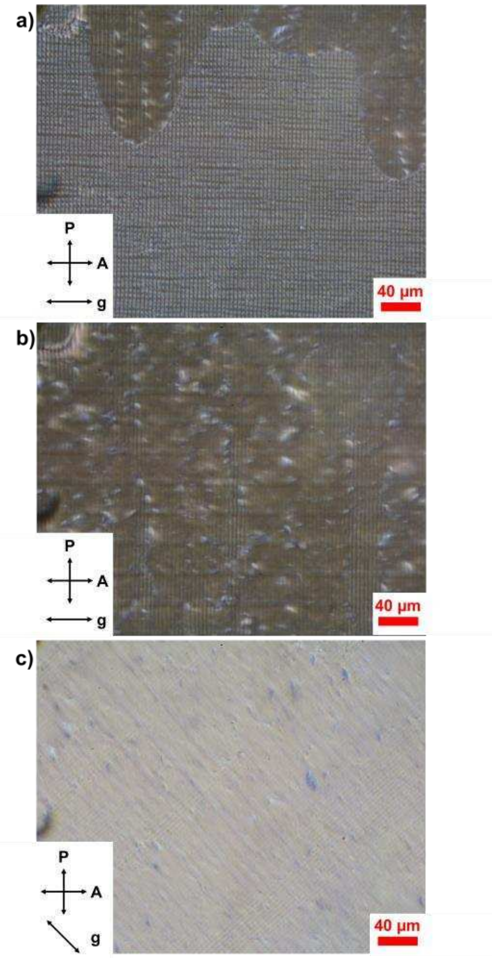

Figure 3. a) A carpet-like texture of the FLC held at 55℃, showing the changes in texture on either side of a moving disclination line as new smectic layers form resulting in a more uniform texture. The direction of flow is from top to bottom. A similar effect is seen when the device is susceptible to a shock. b) With time, the undulations completely disappear, until the device is further cooled or shocked. The texture is not black due to slightly misaligned gratings, and a high light intensity to clearly show the undulating texture. c) a 45° rotation of the device to show **c**-director alignment is maintained.

Care must be taken if optimising the surface relief-gratings in order to not compromise their induced shock-stability, as changes to the grating profile might change its effectiveness at restoring the smectic **c**-director. In addition, the homeotropic alignment applied to these gratings can be explored, as the induced surface anchoring will play a large role for device shock-stability. The effects of changing the properties of the gratings will be discussed in a future publication.

3. Electro-Optic Response

Devices were tested for their electro-optic responses using crossed polarising optical microscopy (POM) to study the alignment of the FLC both with and without electric fields, and determine optical response times. The FLC used throughout the study was SCE13* tuned to give an appropriate pitch using its racemic mixture (SCE13R). This material exhibits a SmC* phase from <-20°C to 60.8°C. Figures 4 shows the optical textures of the aligned cell, and

Figure 5 the electro-optic response times of the device on electrical addressing. Response times for the grating aligned device are found to be sub-millisecond at 50°C, where $\tau_{(ON)} = 0.37 \pm 0.03$ ms, and $\tau_{(OFF)} = 0.23 \pm 0.02$ ms, for a device with a cell gap d = 12 µm, electrode spacing l = 22 µm, grating amplitude and pitch of 0.2 µm and 4 µm respectively, and spontaneous polarisation $P_s = 4$ $nCcm^{-2}$. Response times for various temperatures and applied voltages are shown in Figure 5.

Due to the symmetry of the surface-relief grating, there are two possible directions for the **c**-director to orient, resulting in the defect lines seen in the dark texture of Figure 4a. These cause a loss in optical contrast being bright, and can't be removed by applying electric fields, or by controlling the rate of cooling into the SmC* phase, or a combination of both. Their removal might be achieved by capillary filling of the FLC in the SmC* phase, such that the grating orients the **c**-director with the direction of flow. Alternatively, a set of IDEs on the opposing substrate can be used in conjunction with the first set to ensure the **c**-director orients in the same direction between IDEs, forcing defects to lie just above the electrodes. These two domains appear optically identical when electrically addressed through crossed polarisers despite twisting through 90° in different directions, and so should not affect the measured electro-optic response times of the device. This same effect is also observed on either side of an IDE, as the direction of the field determines which way the **c**-director will rotate to latch its P_s to the field. This can be shown using a full wave plate at 45° to the crossed polarisers, where additive and subtractive retardation result in two separate birefringence colours based on the direction of **c**-director twist. Figure 4c shows these opposite twists in an electric field over an IDE and defect line.

4. Device Optimisation

At 30°C, the rotational viscosity, γ_φ, of the FLC material increases, which causes the ON times to increase by a factor of four, and off times by more, causing an increase into millisecond response times. It is predicted that these response times can be significantly reduced to below 1 ms at 20°C to 30°C for such a geometry following some device optimisation. As both ON and OFF times are electrically addressed, we roughly expect [12]:

$$\tau_{(ON)} = \tau_{(OFF)} \sim \frac{\gamma_\varphi}{P_s E} \quad , \qquad (2)$$

where ON and OFF times are expected to be almost equal, although the complex geometry induced by the grating will likely influence this. Therefore, optimising the pitch and amplitude of the surface-relief gratings should lead to faster response times. Reducing the IDE spacing will further increase the response times of the FLC, as higher fields can be applied at the same sample voltages ($E \propto V.d/l$ for IDEs), where the applied voltage is usually the limiting factor in electrical addressing. Importantly, using a FLC optimised for the device, with higher P_s, SmC cone angle, θ_C, and birefringence, Δn, will also allow significant improvements to the response times. Currently the P_s of the FLC used is only 4 $nCcm^{-2}$, while materials with $P_s > 50$ $nCcm^{-2}$ would increase response times proportionately, provided the high pitch is maintained to give the uniform surface stabilized homeotropic state. A higher birefringence or cone angle would allow the cell gap of the device to be reduced, while continuing to satisfy the Gooch-Tarry equation for white light transmission. With such modifications, it is realistic to achieve response times in the order of 10's of microseconds. By just considering the $P_s = 35$ $nCcm^{-2}$ for SCE13* at 30°C, the current geometry should easily achieve $\tau_{(ON)} \sim 0.7$ ms and $\tau_{(OFF)} \sim 0.4$ ms at applied pulses of ±15V.

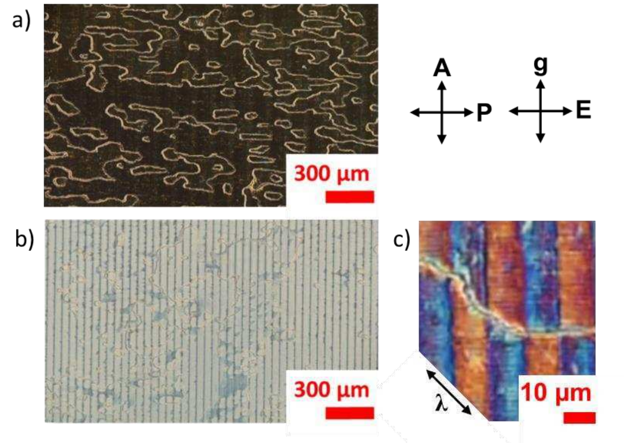

Figure 4. The texture of the SmC* in a) the OFF, and b) the ON state; c) the two opposite twists of the SmC* **c**-director in the presence of an electric field across an IDE and over a defect line.

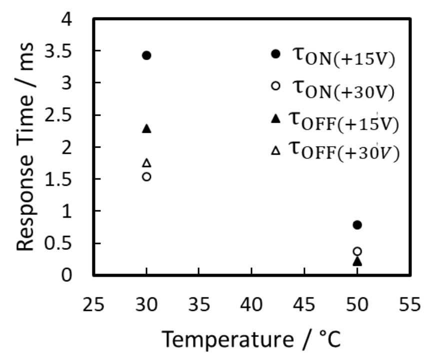

Figure 5. a) Response times for a VGA FLC device with d = 12 µm, $P_{s(30°C)} = 7$ $nCcm^{-2}$, on the application of 15V and 30V driving pulses, at 30℃ and 50℃, where the error bars are the size of the data points. Sub-millisecond response times are obtained for the device at 50℃.

5. Conclusions

A novel FLC device has been reported using a shock resistant homeotropic geometry in combination with surface-relief gratings, and addressed with in-plane electric fields. Desirable FLC alignment in the device is shown, with desirable electro-optic responses on the application and removal of electric fields, where sub-microsecond response times are obtained: $\tau_{(ON)} = 0.37 \pm 0.03$ ms, and $\tau_{(OFF)} = 0.23 \pm 0.02$ ms at 50°C These are expected to be reduced further on device optimisation, by balancing the influence of the peak to peak amplitude and pitch of the gratings on the smectic layers, whilst maintaining shock stability. In addition, using a sufficiently high spontaneous polarisation FLC will further reduce these times. The removal of line defects inherent to the geometry is also expected to increase the optical contrast of the device and improve response times. Shock-stability is shown in the device, with a self-healing mechanism occurring in the form of a dissipating undulating smectic texture, assisted by the surface-relief grating to controllably realign the **c**-director.

6. Impact

A prototype device is proposed for the alignment and shock stability of a ferroelectric liquid crystal for high speed electro-optic applications, utilising a simple geometry and fabrication techniques that can easily be adapted into existing fabrication processes. On optimisation, such a device will have great potential for use in LCoS spatial light modulators, for use in high-speed adaptive optics, head-mounted displays for virtual/augmented reality and telecommunications.

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8. References

[1] J. C. Jones, "On the biaxiality of smectic C and ferroelectric liquid crystals", Liquid Crystals, **42(5–6)**, 732–759 (2015).

[2] N. A. Clark, S. T. Lagerwall, "Submicrosecond bistable electro-optic switching in liquid crystals," Applied Physics Letters, **36(11)**, 899–901 (1980).

[3] H. Furue et al., "Mesogenic polymer stabilized ferroelectric liquid crystal display exhibiting monostability with high contrast ratio and grayscale capability", Japanese Journal of Applied Physics, **36**, L1517-1519 (1997).

[4] D. Kim et al., "Mechanical stability of a flexible ferroelectric liquid crystal display with a periodic array of columnar spacers", Applied Physics Letters, **87,** 051917 (2005).

[5] L. Banks et al., "73.4: Real-time diffractive video projector employing ferroelectric LCOS SLM," SID Symposium Digest Technical Paper, **37(1)**, 2018-2021 (2006).

[6] G. P. Bryan-Brown, C. V. Brown, and J. C. Jones, "Bistable Nematic Liquid Crystal Device," US6249332 (1995).

[7] J. C. Jones, "The Zenithal Bistable Display: from concept to consumer," Journal of the Society for Information Display, **16(1)**, 143–154 (2008).

[8] M. Wahle et al., "Embossing reactive mesogens: a facile approach to polarization-independent liquid crystal devices", Advanced Optical Materials, **7(2)**, 1801261 (2019).

[9] C. H. Gooch and H. A. Tarry, The optical properties of twisted nematic liquid crystal structures with twist angles ≤90 degrees, Journal of Physics D: Applied Physics, **8(13)**, 1575-1584 (1975).

[10] W. Helfrich, "Deformation of cholesteric liquid crystals with low threshold voltage", Applied Physics Letters, **17(12)**, 531-532 (1970).

[11] J. Hurault, "Static distortions of a cholesteric planar structure induced by magnetic or ac electric fields", The Journal of Chemical Physics, **59(4)**, 2068-2075 (1973).

[12] V. G. Chigrinov and A. Srivastava, "Ferroelectric liquid crystal cells for advanced applications in displays and photonics," Molecular Crystals Liquid Crystals, **595(1)**, 39–49 (2014).