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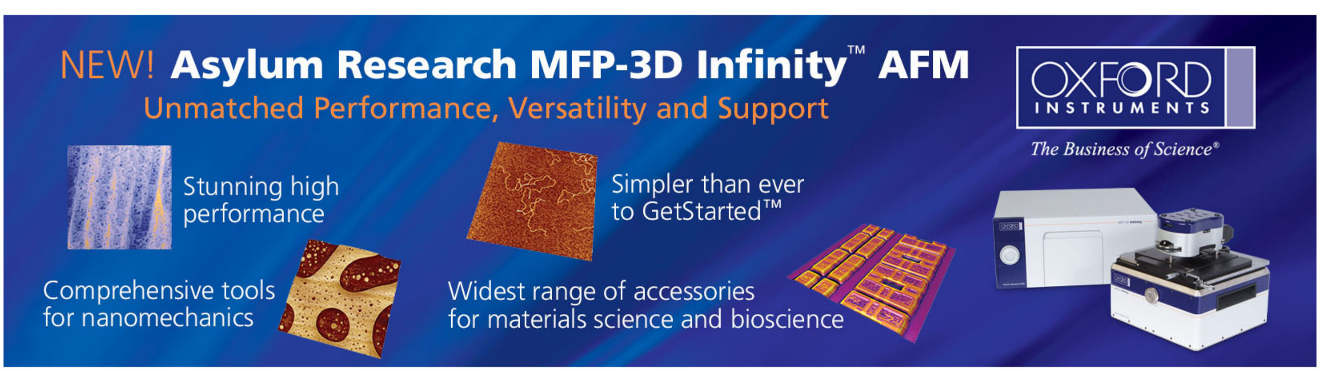

Investigation of the transient symmetric *H* state in a pi cell

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The so-called symmetric H (H_s) state has been reported to have submillisecond response times, which results from the symmetric profile of the liquid crystal director; however, no direct evidence has been obtained to show the profile symmetry. The difficulty in proving this symmetric structure by direct observation results from the short lifetime of H_s state (typically around a few tens of milliseconds). In the work reported here, the authors utilize a burst driving method along with stroboscopic illumination from blue and red light emitting diodes to capture conoscopic images for the H_s director profile; these showed good agreement with their modeling. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2772670]

The use of a liquid crystal (LC) pi cell,[1] also known as the optically compensated bend (OCB) mode, is noted for its fast switching rate owing to its immunity from the backflow effect. Generally, it is operated in the bend state (V state), which is capable of taking less than 4 ms to complete the switching process.[1–5] However, because of the topological difference between the ground splay state and V state, a nucleation transition has to be completed to operate the pi cell in the V state. This transition can be initiated by applying a critical voltage in advance to prime the cell from the splay state to the V state, and the voltage should be held to sustain the device in V state. To prevent the unwanted recovery from the V state to the splay state, a number of techniques have been reported to reliably prime the pi cell.[6–9]

In contrast, the symmetric H (H_s) state is a transient state obtained by a sudden application of voltage to the ground splay device. Owing to its topological similarity with the splay state, the operation in the H_s state needs no priming, i.e., it is continuous with the ground state. Moreover, the H_s state has been reported to have the merit of very fast switching, on a scale of 1 ms.[10]

In previous work, it was suggested that under field application, the H_s state has an internal director structure in which the director in the center of the device remains parallel to the surfaces. This "decouples" the two halves of the pi cell; thus the cell is effectively divided into two half-thickness Fréedericksz devices, from which the fast switching behavior results.[10–12] The switching rate enhancement, ignoring the flow effect of the pi cell, can be explained by

$$\tau \propto \frac{d^2\gamma}{K_{11}\pi^2}, \tag{1}$$

where τ represents the relaxation time of the pi cell, d the cell gap, γ the viscosity, and K_{11} the splay elastic constant. Thus, the smaller the effective thickness of the switching layer, the faster the device. Some modeling and experimental results have shown that the switching rate of the H_s state is faster than that of other states in a pi cell by a factor of 4, which supports the existence of the central nonswitching region which decouples the LC director in the two halves of the cell.[10–12] This central region and decoupled switching should lead to the H_s state having a symmetric director profile; however, no direct evidence has been presented to demonstrate the profile symmetry. The difficulty in proving this symmetric structure by direct observation was due to the short lifetime of H_s state (typically around a few tens of milliseconds, although it can be present for hundreds of milliseconds in certain circumstances). In this letter we report work where we utilized a burst driving method along with stroboscopic light emitting diode (LED) illumination to capture the conoscopic images for symmetric LC director profile of the H_s state.

Initially a typical pi cell (with 2.6 um cell gap, filled with LC material E7, and using parallel rubbed polyimide as the alignment layers) was positioned at 45° between crossed polarizers and the transmission measured during signal application. With an impulse voltage signal of 5 V_{rms}, the intensity variation during the state transitions from ground splay state to H_s and into the asymmetric H (H_a) states was observed by a photodetector, as shown in Fig. 1. The H_s state was observed to have a lifetime dependence on the applied voltage. As the applied voltage is increased, generally the lifetime of H_s state (seen in the duration of the H_s plateau in Fig. 1) will be longer. However, at higher voltages the V state rapidly nucleates and transition into the OCB mode occurs.

To observe conoscopic images of each state, the device was driven by a burst wave form for H_s state formation and a continuous wave form for H_a state formation. As shown in Fig. 2, the burst driving wave form was composed of two parts: an operating time (period A) and a delay time (period B). The operating time was determined by the need to switch the device into the H_s state but avoid break down into the H_a

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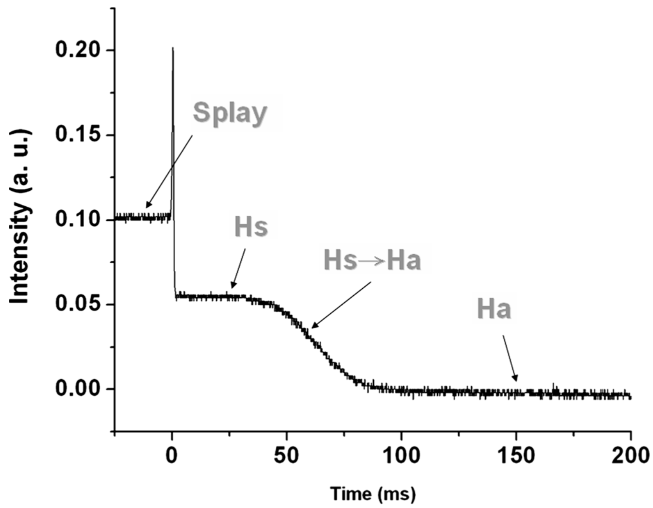

FIG. 1. Basic device behavior under field application (observed by a photodetector). Initially the device is in the ground splay state. When the field is applied (at around $t=0$ ms), a rapid transition into the H_s state takes place. Later this state breaks down into the H_a state(s).

state(s) (or transition into the V state). The delay time allowed recovery of the ground splay state. In this case, the operating time was set as 10 ms and the delay time as 90 ms; meanwhile, the stroboscopic LED illumination was set to delay from the start of the switching signal by 5 ms (to allow formation of the H_s state), then to illuminate for 5 ms and be off for 90 ms (to synchronize with the device switching signal). This synchronized driving scheme ensured that only the H_s state was captured by the conoscope. To further check the results, the conoscopic images were obtained using two different wavelengths of light source; using a blue LED ($\lambda=436-486$ nm) and a red LED ($\lambda=622-654$ nm) for illumination.

Based on the Frank-Oseen continuum theory,[13,14] using an energy density as defined in Eq. (2) (where the symbols have their usual meanings), the equilibrium director profiles in the liquid crystal device can be calculated,

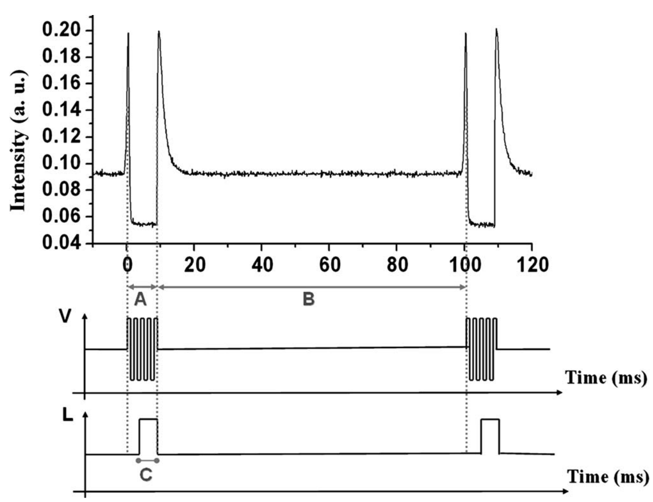

FIG. 2. Burst driving wave form for the device and illuminating LED. Period A represents the operating time (during which the device is switched into the H_s state), period B is the delay time between bursts (allowing relaxation back to the ground splay state), and period C is the illumination time, during which conoscopic images are obtained.

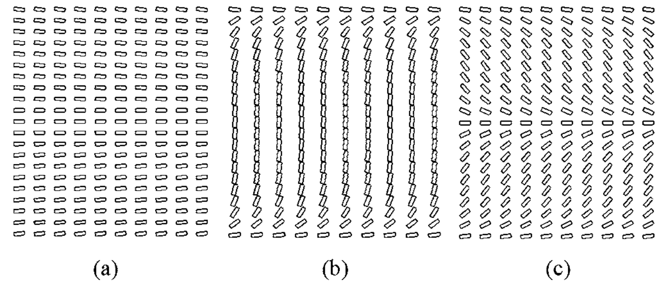

FIG. 3. Director configurations of (a) splay, (b) H_a, and (c) H_s states determined by using a simple finite-difference relaxation routine to minimize the bulk energy.

$$F = \frac{1}{2}\{K_{11}(\nabla \cdot \mathbf{n})^2 + K_{22}[\mathbf{n} \cdot (\nabla \times \mathbf{n}) - q_o]^2 + K_{33}[\mathbf{n} \times (\nabla \times \mathbf{n})]^2\} - \frac{1}{2}(\mathbf{D} \cdot \mathbf{E}). \qquad (2)$$

Using typical liquid crystal material parameters (those for E7) and initializing from a ground splay state with a slight asymmetry (to allow eventual formation of the H_a state), we can obtain the director profiles of each state as shown in Fig. 3. After calculating the director profiles, an extended Jones matrix technique[15] can be used to determine the conoscopic images of each state for wavelengths corresponding to using blue and red LEDs as the light sources (examples of which are shown in Fig. 4).

The conoscopic measurement results within a viewing cone of around 30° show directly the symmetry of ground splay and transient H_s states, and also the asymmetry of the H_a state. In addition, the modeling based on the theory outlined above was used to determine conoscopic images within the viewing cone of around 30° (for the light field distribution of the LC director profiles illustrated in Fig. 3). The experimental and theoretical results are shown in Fig. 4; the measured conoscopic images (a)–(f) are in good agreement with the modeling results (g)–(l) (at least for the restricted viewing cone of around 30°—it is difficult to obtain good agreement over very wide viewing cone angles due to the illumination system used). The asymmetry in the H_s state is evident in both the experimental results [Fig. 4 images (c) and (d)] and the modeled images [Figs. 4(i) and 4(j)]. The symmetry of the ground splay state is as expected [Fig. 4 images (a), (b), (g), and (h)]. More important for this work is the symmetry evident in Fig. 4 images (e) and (f) (experi-

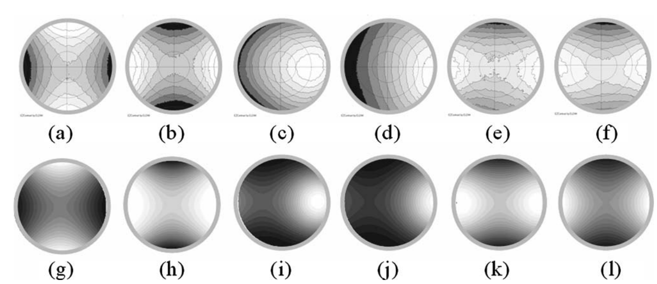

FIG. 4. Measured conoscopic images of the device: (a) and (b) in splay state, (c) and (d) in H_a state, and (e) and (f) in H_s state. Simulated results: (g) and (h) in splay state, (i) and (j) in H_a state, and (k) and (l) in H_s state. The cases of (a), (c), (e), (g), (i), and (k) are illuminated/modeled with a blue LED, while the cases of (b), (d), (f), (h), (j), and (l) are illuminated/modeled with a red LED. (Each set of data has been normalized to optimize the image and exploit the image's full dynamic range.)

mental) and (k) and (l) (theoretical). The good agreement between these is evident that the director profile of the H_s state is indeed as expected, with decoupling of the director in the two halves of the cell. Moreover, according to our modeling, if the center point (zero tilt) of the director structure is off center by 5% of the thickness of the device, then the conoscopic image is off axis by 15°. Thus, we can be confident that the method used here is very sensitive to asymmetry in the structure.

We have confirmed the existence of the symmetric profile of the liquid crystal director in the H_s state by stroboscopic conoscopic imaging. Along with the modeling, the transient nonswitching of the director in the center of the device and the consequent decoupling of the directors in the two halves of the device have been verified to occur. These decoupled directors divide the device into two half-thickness Fréedericksz layers which result in the fast-switching behavior.

Although the H_s state has merits of fast switching and no need for priming, extending the lifetime of the transient H_s state is imperative for commercial applications. By using a repeated burst driven pi cell along with the stroboscopic LED illumination, we can observe every section of state transition by varying the position of illumination period on the time axis (as shown in Fig. 2). These state transition sections can also be modeled, which may help to come up with a method for extending the lifetime of the H_s state.

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