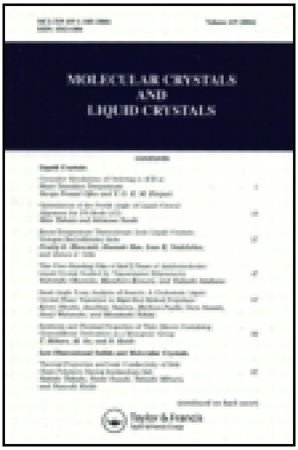

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Asymmetric Switching in FLC Microdisplays

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Microdisplays employing ferroelectric liquid crystals operate at the low voltages available on integrated circuit backplanes. At these low drive voltages the behavior of the 0.7 μm liquid crystal films are significantly influenced by surface interactions and the presence of a chevron in the smectic layers. Notable among the observed effects are asymmetries in the rise and fall optical responses. We present data illustrating and quantifying the principal asymmetries, and we conjecture that they are directly related to the asymmetric polar surface interaction together with a chevron plane which is not at the mid-plane of the liquid crystal film.

Keywords: chevron; display; ferroelectric liquid crystal; surface interaction; switching asymmetry

INTRODUCTION

Ferroelectric liquid crystal (FLC) switching, as used in microdisplays, such as the one shown in Figure 1, occurs as a consequence of a change in the polarity of the electric field applied to an FLC cell. The microdisplay FLC always experiences an applied electric field having one of two polarities. On switching, the reversed field interacts with the FLC spontaneous polarization, causing the polarization to reverse direction, too, and this change carries with it the FLC optic axis, which is nominally parallel to the FLC's director. The director is carried around the smectic cone, changing direction between two field-selectable optic axis states, $\mathbf{n}^+$ and $\mathbf{n}^-$, both having the optic axis in the plane of the FLC cell. When such a cell is properly disposed between crossed

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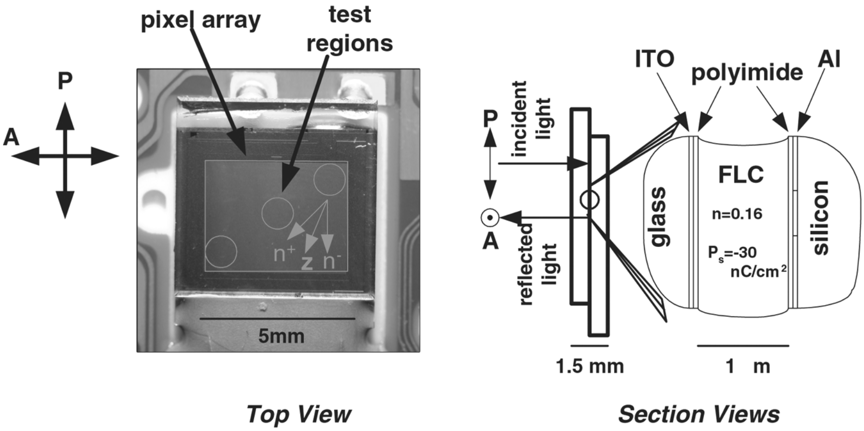

FIGURE 1 The top view is a photograph of a test cell which is mounted on a flexible circuit. The overlaid symbols show the direction of the normal to the smectic layers (**z**) and the optic axis orientations ($\mathbf{n}^+$) and ($\mathbf{n}^-$) of the two equilibrium states while the circles show the size and position of the regions in which measurements were made. The section views show the crossection of the cell at two different magnifications as well as showing cell construction and the values of birefringence (Δn) and spontaneous polarization (P_s). The disposition of the polarizer (**P**) and analyzer (**A**) in the illumination are also indicated.

polarizer (**P**) and analyzer (**A**), as shown, the $\mathbf{n}^+$ state rotates the plane of polarization of the incident light so that light passes through the analyzer to produce a bright- or on-state. In the $\mathbf{n}^-$ state, the optic axis is parallel to the polarizer, the light is not rotated, and it is blocked by the analyzer producing a dark- or off-state. The optical response refers to the time-dependent amount of light passing through the analyzer during the transition between states.

Asymmetry in FLC switching refers here to differences which are observed in the optical responses of a FLC cell when it turns on compared to when it turns off. Optical responses are illustrated in Figure 2. Four curves are shown in the figure: two curves are responses measured in a cell like the one shown in Figure 1; the other two curves are the optical response of a simple model based on an ordinary differential equation where the parameters have been adjusted to yield generic responses that illustrate our expectations for simple, symmetric switching. The responses are normalized, and those which change from 0 to 1 are called rising, while those which change from 1 to 0 are termed falling. In all cases, the driving electric field was switched at time $t = 0$.

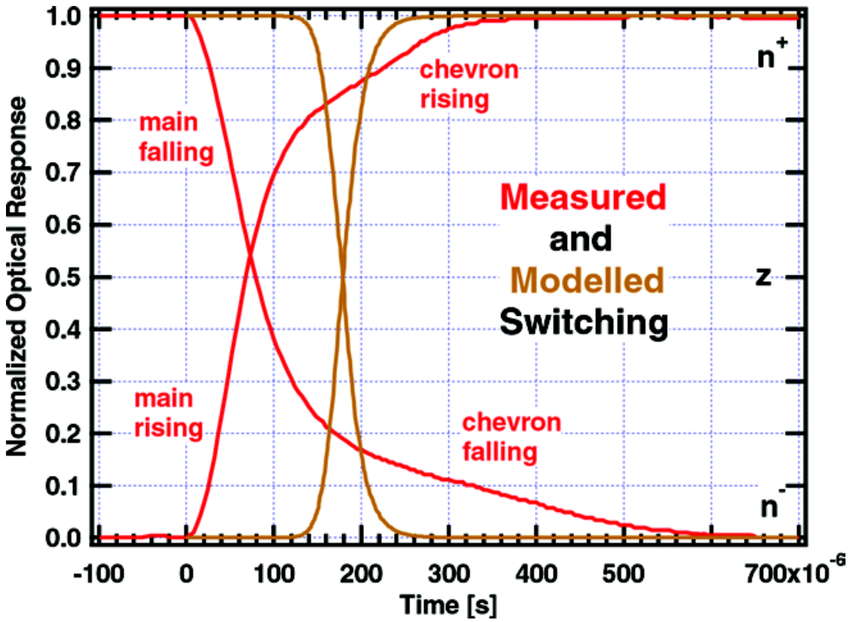

FIGURE 2 Optical response curves are shown for a simple model and for typical measured responses, together with labels defining nomenclature.

The measured optical responses differ from the model in three main respects. First, the observed responses start changing more rapidly following a change of the applied electric field than does the simple model. Second, the observed responses exhibit a pronounced change of slope when they reach about 80% of their total change. Third, the measured responses for both rising and falling transitions have markedly different slopes for the remainder of the switching beyond the 80% level, and this constitutes an asymmetry. Detailed data acquired from many devices show other differences like this third one, and some of these will be described below. Taken together, these differences establish that switching in the two directions proceeds very differently. We refer to these differences collectively as asymmetry.

The first two main differences have straightforward explanations. That the measured curves start changing more rapidly than for the simple model is a consequence of a distorted director field. FLC microdisplays operate at low CMOS voltages, so the torque exerted by the electric field on the FLC polarization is comparable to the interaction forces at the surfaces and at the chevron, with the consequence that the electric field cannot force a uniform orientation of the polarization and thus of the director. This means that the polarization is not everywhere perfectly aligned with the electric field prior to switching, so following switching, part of the FLC immediately experiences a finite electric torque to get it started switching, and it begins to do so. The simple model, having small surface interaction and no chevron, is dominated by the electric force. It is nearly in a state of unstable equilibrium at the instant of switching, so the initial torque is small, and the director motion starts slowly.

That the observed response curves exhibit a change of slope is due to the presence of a chevron in the FLC smectic layer structure. Handschy [1] first described a switching mechanism which proceeds via domain wall propagation, and ascribed it to surface domains. Following the discovery of chevrons by Rieker, *et al*. [2], the domains were shown instead to be associated with switching of the chevron interface. Xue [3] studied the propagation speed of the domain walls which turned out to be different in different directions and showed it to be associated with the latter stages of the switching process. The domain walls are visually observed after the change in slope. Moreover, the change in slope disappears when a cell is driven with a high voltage to produce the stripe or quasi-bookshelf texture which is free of the usual chevrons. Thus we interpret the slower rate of change of the optical response as primarily due to the time-dependent density of nucleation sites of the chevron domains together with the propagation speed of the domains. The simple model, on the other hand, does not treat the chevron structure.

What has not been previously noted is the third difference, the asymmetry, mentioned above. We will explain below that this has a plausible explanation. First, we describe the details of our measurements and our data analyses.

EXPERIMENT

Figure 1 shows a top view and a section of one of the test cells which were measured. The cell consists of an array of $12 \times 16\,\mu m$ aluminum pixel electrode/mirrors which are fabricated on a silicon wafer and a glass window which carries an ITO electrode. The silicon has no underlying circuitry as would a complete microdisplay. Both the silicon and the glass are spin-coated with a thin layer of polyimide and rubbed unidirectionally to promote FLC alignment. The window is attached to the silicon substrate by a thin, invisible line of glue around the pixel array. Silica balls having $1\,\mu m$ diameter are dispersed in the glue to set the cell's gap thickness. The rubbing directions on the two substrates are made parallel. The cell has been filled in vacuum through a gap in the upper right corner of the glue line with the FLC mixture designated DT11601. Following filling, the temperature was lowered and the pressure was raised, both slowly, to reach ambient conditions. The gap in the glue line was then sealed. The cell is mounted on a flexible circuit, and electrical connection to the outside is via wirebonds which are below the cell, covered by an elastomeric encapsulant. Electrical connection to the ITO electrode on the window is provided by Indium solder and conductive epoxy. All 10 cells discussed here were made simultaneously on the same silicon wafer and were filled together after the wafer was separated into individual cells thus assuring that the cells received identical treatment at every step.

The FLC birefringence averages $\Delta n = 0.16$ in the visible, so the cell is one quarter-wave thick near 575 nm. The FLC spontaneous polarization is $P_s = -30\,nC/cm^2$. The arrows and letters overlaid on the photograph show the directions of the normal to the smectic layers (**z**), which direction is also nominally parallel to the rubbing direction, and the two equilibrium orientations of the FLC film's effective optic axis when driven by voltages which are positive ($\mathbf{n}^+$) and negative ($\mathbf{n}^-$) relative to the ITO window electrode. At ambient conditions, the FLC in the cell is a SmC_2^* monodomain with the chevrons convex in the rubbing direction.

To make measurements, cells were mounted inside a temperature controlled hot stage on the rotating stage of a polarizing microscope. The temperature was controlled to 25 ± 0.1°C, and the pixel electrodes were driven with a 180 ± 1 Hz square wave with an amplitude 1.65 ± 0.02 V relative to the ITO on the glass window. The incident light was linearly polarized white light from an incandescent bulb driven by a stabilized DC voltage. The cell's optical response was detected by an amplified photodiode located at the microscope's trinocular port, and the output was displayed on a digital oscilloscope which captured both the response and the drive signal. Ten cells were each tested and then tested a second time. All the measurements reported here were made in the center test area of the cells.

Microdisplays are usually aligned between the polarizer and analyzer with, for example, $\mathbf{n}^-$ parallel to the polarizer. This gives the best contrast, but it also means that the optical response is less sensitive to changes in optical axis for $\mathbf{n}^-$ as compared to changes in $\mathbf{n}^+$ (unless the optic axis rotates through exactly 22.5° which is not the case here). To avoid this measurement asymmetry, we measured the directions of $\mathbf{n}^+$ and $\mathbf{n}^-$ and then set the stage to orient the bisector of these two directions at 22.5° from the polarizer. This orientation assures symmetric measurement sensitivity about the $R = 0.5$ level.

Figure 3 illustrates the method employed here of making quantitative analyses of the measured optical response curves. The method is called the piecewise linear fit (PWLin). The basic approach is to fit straight lines to the main switching part and to the chevron switching part of the optical response. The main switching line is constrained to pass through the point on the curve which has the maximum derivative of optical response and it has the maximum derivative as its slope. The chevron switching line is a least squares fit to the data lying within the chevron segment of the optical response. Two switching times, the main switching time τ and the chevron switching time τ_c were defined as the reciprocals of the slopes of the respective lines. The delay time t_d is defined as the time between the switching of the drive at $t = 0$ and the intersection of the main line with the initial response level. The time of the maximum derivative $t_{max,d}$ and the response level $R_{max,d}$ at that time were also recorded. The intersection point of the two line segments defines the "corner" which occurs at (t_c, R_c). The parameter t_c is not independent, since it can be calculated from t_d and τ, so it is not considered in what follows. The fitting which yielded all these parameters was carried out by a computer program

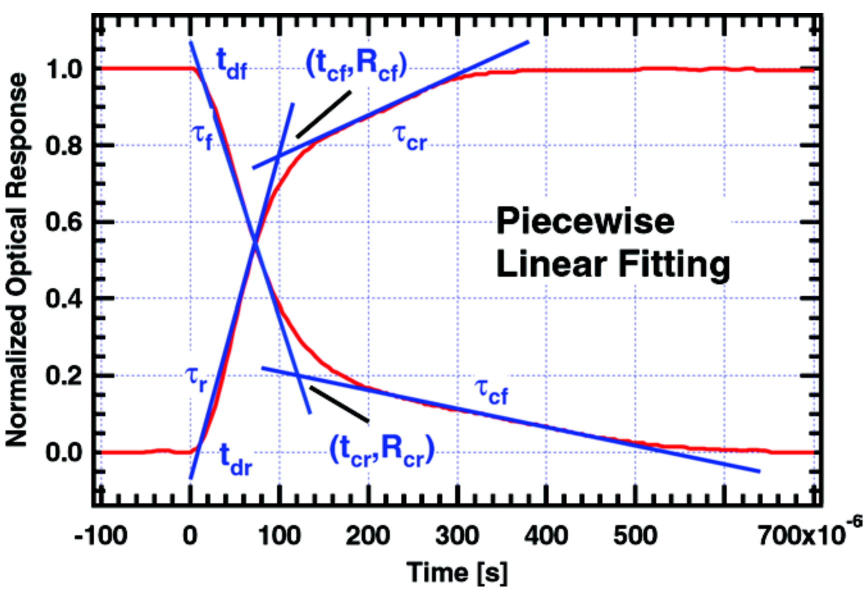

FIGURE 3 The measured switching curves are approximated by piecewise linear fits (PWLin) to the main switching and the chevron switching, using the fitting parameters shown.

embodying appropriate algorithms. In this figure and in the subsequent figures showing the results, all the parameters carry an additional subscript r or f designating their association with the rising or falling waveforms, respectively.

MEASUREMENT RESULTS

As our main goal is to investigate the difference between the rising and falling optical responses, we present our data as a plot for each of the PWLin parameters. Each plot shows the value of a parameter for the falling transition against the value of the corresponding rising transition. The two axes of each graph span the same range of values, and a dashed line is included to delineate the symmetry locus.

Figure 4 displays the results for the delay time t_d. It is short for both transitions, suggesting considerable amount of distortion in the equilibrium director fields. The falling transition, at about 21 μs, averages about 10% longer than the rising transition. Together these facts

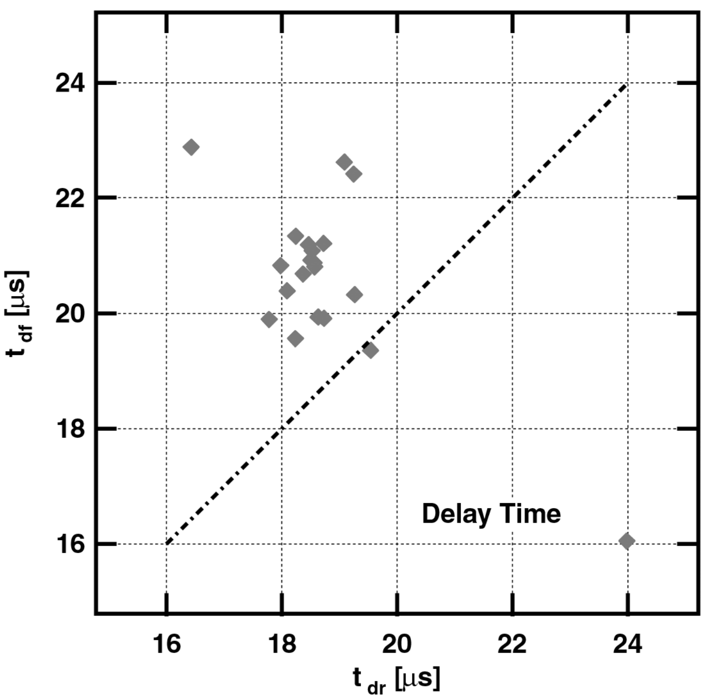

FIGURE 4 The delay time t_d of the falling transition near 21 μs averages about 10% longer than that of the rising transition.

suggest that the shorter rising delay may be due to a greater amount of distortion in the $\mathbf{n}^{-}$ than in the $\mathbf{n}^{+}$ state.

Figure 5 shows the the results for the main switching time. The falling transition averages about 135 μs or about 30% slower than the rising transition. This suggests that the cell resistes being driven in the $\mathbf{n}^{-}$ more than into the $\mathbf{n}^{-}$ state.

Figure 6 plots the time of occurrence $t_{max,d}$ of the maximum slope of the main switching. Clearly, these values show that the time resolution is limited by time quantization. Despite this, the values are clearly small, indicating that the maximum switching rate occurs quite early in both transitions and that the falling transition probably comes up to speed a little later than the rising transition.

Figure 7 illustrates that the level of optical response $R_{max,d}$ at the maximum slope occurs at about 0.21 for both transitions, and there appears to be no asymmetry in this value. This is much smaller than the value around 0.5 for the simple model which occurs when the

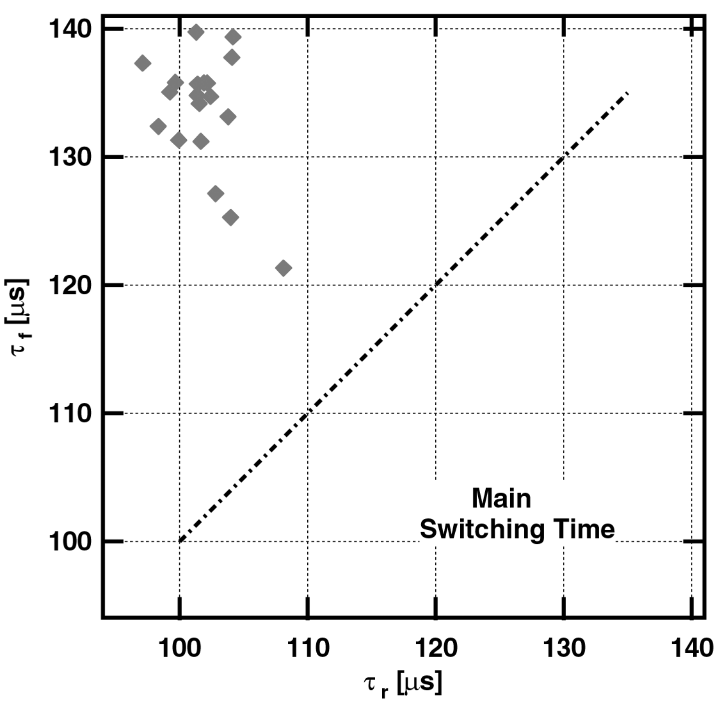

FIGURE 5 The main switching time τ for the falling transition averages about 135 μs or 30% slower than the rising transition.

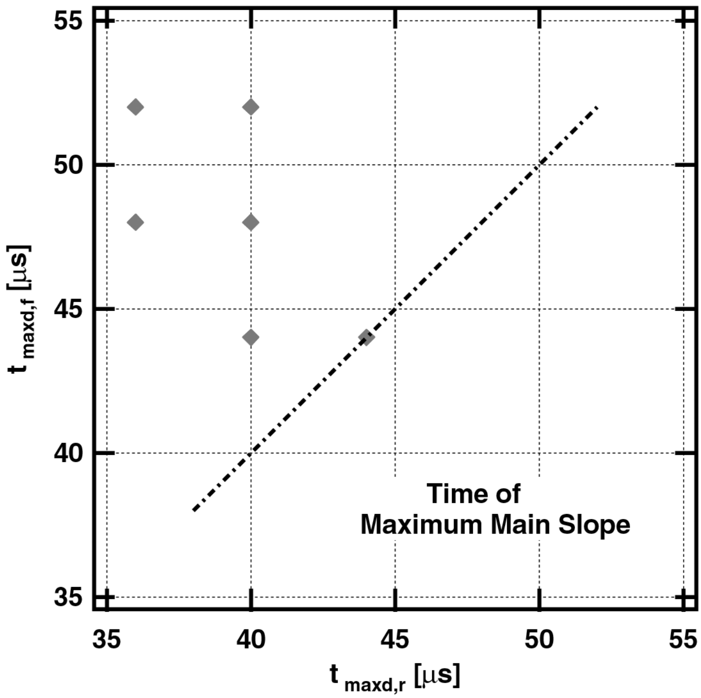

FIGURE 6 The measured time of occurrence $t_{max,d}$ of the maximum slope of the main switching is hampered by coarse time resolution which leads to obvious quantization limitations.

polarization is perpendicular to the electric field and thus experiences the maximum electrical switching torque.

Figure 8 shows the level of the optical response R_c at the PWLin corner. This point locates the transition between main switching and chevron switching, and it exhibits a small, but significant, asymmetry with the falling corner occurring slightly later than the rising corner.

Figure 9 shows that the chevron switching time for the falling transition is about $2.5\times$ slower than for the rising transition. This is the largest asymmetry which has been found. Clearly, the dynamics of chevron switching are very sensitive to the underlying causes of the switching differences.

The piecewise linear analyses clearly show that the two switching transitions are different and give rise to asymmetries. The asymmetry is most pronounced for the rate of switching during the chevron portion of the transitions. All the evidence is consistent with an interpretation which assumes more elastic distortion the $\mathbf{n}^-$ than in the $\mathbf{n}^+$ state.

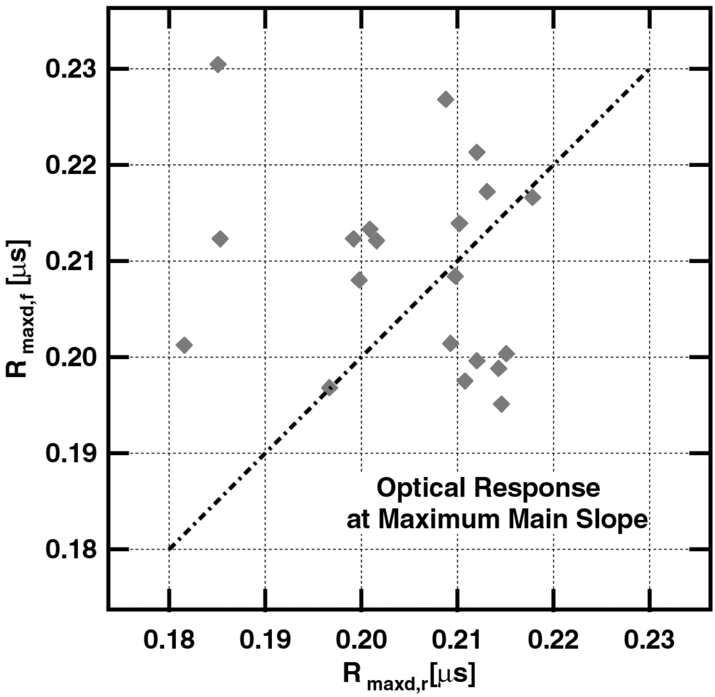

FIGURE 7 The level of the optical response $R_{max,d}$ at the maximum slope of the main switching does not exhibit any pronounced difference between rising and falling transitions.

DISCUSSION

The root cause of the observed asymmetry is conjectured to reside jointly in two circumstances. The first is that, in addition to the pretilt and azimuth anchoring surface interactions, there is a polar surface interaction between the FLC and the alignment layer. The second is that the chevron plane is not located at the mid-plane of the FLC film but is, instead, offset toward one surface.

The polar surface interaction is clearly an asymmetry, but it is not alone capable of producing the observed optical asymmetry as the following argument shows. The sign of the polar interaction is the same for the FLC at both polyimide surfaces. Hence in one equilibrium driven state, one portion of the chevron would have the preferred polar orientation at its surface and the other would not. In the other equilibrium driven state the two chevron portions would exchange orientations at the surface. For a chevron occupying the FLC film's mid-plane, the

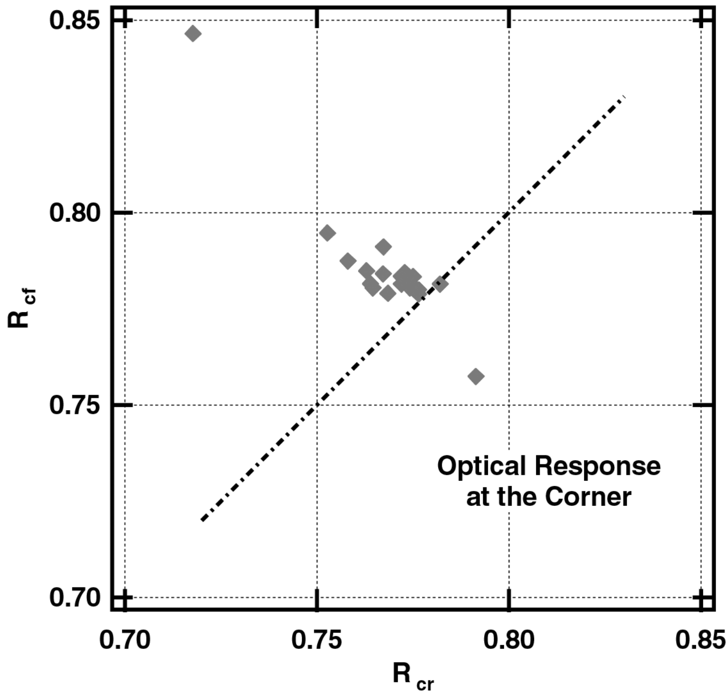

FIGURE 8 The level of the optical response R_c at the PWLin corner exhibits a small, but significant, asymmetry in which the corner occurs slightly later in the falling transition than in the rising transition.

situation at the chevron would also be exchanged but otherwise the same in both equilibrium states. On switching the overall optical path would be identical for both transitions as one of the chevron portions passes through each of two sequences of director fields. Thus no asymmetry in the optical response could arise.

This interchangability of the two chevron portions during opposite switching transitions would be eliminated if the chevron plane were asymmetrically located in the FLC film. In such cases, the distortion of the director field is expected to be different for the two chevron portions for any given field direction. On reversing the field, the distortions would again be different, but not just by a simple exchange. That is because, with fixed director orientation at the surfaces and at the chevron, the amount of distortion depends on the distance between the chevron and the surface. Since the distances are different, the distortion must be different for the two chevron portions. Thus

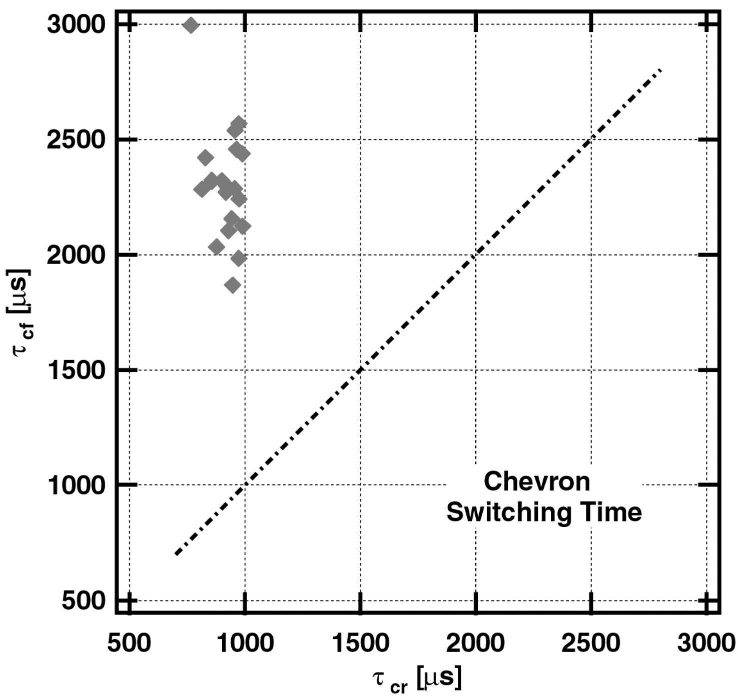

FIGURE 9 The chevron switching time τ_c of the falling transition is about $2.5\times$ greater than that of the rising transition. This is the largest asymmetry which has been found.

with both a polar interaction and an asymmetric chevron plane, the optical response can be asymmetric for the two transitions.

There is a phenomenon called color bands which provides some evidence for the asymmetric chevron plane. Color bands can be observed in some FLC cells when the cell is driven to its off-state. The color bands appear as pale, unsaturated color stripes which are nominally parallel to the smectic layers. The bands are usually magenta or green but sometimes yellow, cyan or even blue. They are in general very difficult to observe or to photograph, since they only appear in a cell's dark state, and the color and luminance variations that make up the bands are quite small though apparent to a dark-adapted eye. When a FLC film's thickness is not uniform but is wedged with a gradient not along the smectic layer normal or is thicker or thinner toward the center of the cell, then the loci of the color bands are perturbed and seem to run along contours of constant film thickness.

Clark [4] has hypothesized that there is unextinguished light due to interference between light reflected by the pixel mirrors and the very small amount reflected by the small refractive index non-uniformity at the chevron plane, and that the differently colored bands occur, because the distance of the chevron plane from the pixel mirrors is not constant, as for example if the chevron plane were tilted within the planar FLC film. This hypothesis is sufficient to explain the observations and the following result. Clark and Jones [5] changed the geometry of cells by mechanically twisting them from planarity which produced a measurable rotation of the color bands, and their results were consistent with the expected rotation of color bands as they follow contours of constant distance. Model optical calculations also reproduce the colors of the color bands best if the chevron is assumed to lie below the mid-plane of the FLC film, and the calculations suggest that the chevron varies in height above the mirrors from 300–450 nm across a 17 mm display. Furthermore, combinations of different modes of non-uniform FLC film thickness together with a tilted chevron plane cause the model to produce color band contours like those observed [6].

The potential cause of tilted chevron planes is not certain. It may be that tilt occurs, because of a systematic variation of the pretilt angles at the two rubbed polyimide surfaces. Rieker [7] showed that different pretilt angles at the two alignment surfaces results in the chevron being asymmetrically located within a FLC film. Alternatively, Clark [4] has suggested that the chevron plane might be tilted as a result of differential thermal contraction between the Si and glass substrates as the temperature of the cell is lowered below the SmA-SmC* phase transition, while the edges of the smectic layers are pinned as the surfaces. In this case, the FLC responds to the accumulated strain by a continuous change of the slope of the chevron plane with temperature. Notwithstanding a lack of detailed understanding of the mechanism, all the color band evidence points to the chevron being asymmetrically located within the FLC film, most likely closer to the silicon substrate than to the glass window.

Xue [8] reported an ion pumping effect in FLC cells, having conducted experiments to elucidate the phenomenon, and they proposed a microscopic mechanism to explain the observations. The mechanism involves asymmetric switching together with alternating electrical fields when, for example, adjacent dark and bright stripes are displayed. However, no source was identified for the asymmetric switching which is needed to cause an asymmetry in the switching-induced flow of charged ions parallel to the smectic layers. It seems possible that the combination described here of the asymmetric chevron plane and the polar surface interaction could be capable of causing that asymmetric flow.

Judging the validity of the conjecture we have made regarding the asymmetry would be aided by appropriate model calculations. Many model calculations, applied to a variety of situations and using different sets of approximations, have been made which calculate the director field of chevron cells, for example by Maclennan [9] and Vaupotic [10]. In every case, the chevron plane was assumed to be at the mid-plane of the FLC film, and the optical response was not calculated from the time-dependent director field. Similarly, Xue [3] built on the earlier work of Handschy [1] to study the anisotropic domain wall propagation which occurs during switching of chevrons but did not treat chevron asymmetry nor the calculate the complete optical response. Thus there are apparently no model results which incorporate all the aspects necessary to judge the present conjecture. In addition to the nematic and smectic elastic constants which are usually included in models, the calculation of the director field would need to include the polar surface interaction, the asymmetric chevron and initial states like, $\mathbf{n}^{+}$ and $\mathbf{n}^{-}$, which are driven by electric fields. One would, furthermore, need to augment the calculation of the optical response from the time dependent director field with homogeneous nucleation and subsequent propagation of the chevron switching domains.

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