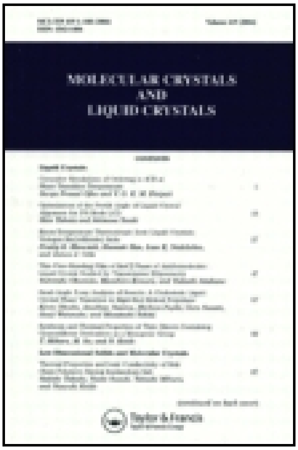

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Flow-Induced Dynamic Optical Crosstalk between Pixels in Liquid Crystal Devices

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We have observed dynamic optical crosstalk between pixels in a twisted nematic device that demonstrates the significance of switching-induced flow in pixelated devices. We studied these phenomena in detail, both experimentally and theoretically. Experimentally, we found that switching of one pixel in a linear array causes an optical response in neighboring pixels which are not switched. The optical crosstalk depends on several factors, including: switching voltage, voltage applied to the unswitched pixel, distance between the switched and unswitched pixel, and the location inside the unswitched pixel where the optical response is observed. Theoretically, we attempted to describe this behavior using a quasi-one-dimensional model based on the Erickson–Leslie equations. This simple model, while intuitively appealing, deviates markedly from the observed results.

Keywords: Erickson–Leslie equations; flow; optical bounce; optical crosstalk; pixel; quasi-one-dimensional model

INTRODUCTION

After Leslie [1,2] and Ericksen [3,4] gave the theoretical framework for the viscoelastic behavior of nematic liquid crystals, this theory was applied in simplified form by Brochard [5] and Peiranski *et al.* [6] to describe the dynamics of liquid crystal layers in magnetic fields, and the hydrodynamic equations were numerically solved by Van Doorn [7,8] and Berreman [9] to explain the time-dependent optical transmission during switching of twisted nematic (TN) devices. Flow-induced reorientation of the director in the middle region of a TN was observed in the numerical calculations and shown to be the origin of the so-called *optical bounce* observed in the transmission of a TN

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cell between polarizers [10,11]. The importance of hydrodynamic flow in the dynamic response of liquid crystal devices were really shown by van Doorn [12] and Berreman [13] in their illustrations of the tipping over of director and optical bounce due to backflow in TN cell. Since then, it has been recognized that liquid crystal flow during director reorientation can have a significant impact on switching dynamics. The optical bounce effect in TNs and the reduction in director relaxation (turn-off) time are the two primary examples. Both of these phenomena can be understood in a one-dimensional framework. Recently, Kelly *et al.* [14] gave the direct connection between simulation parameters and liquid crystal material properties. In their studies, the Ericksen–Leslie equations in the one-dimensional approximation of Berremen and van Doorn provide an excellent quantitative description of the dynamic response of TN devices including flow. Following the convention of Kelly, Nakamura *et al.* [15] included the backblow in their calculations for optimizing the active-matrix drives for liquid crystal displays. However, additional consequences of flow that result from pixelated (i.e., multidimensional) geometries have received little attention and are poorly understood.

In this article, we present our observations that the electrical switching of a pixel in a twisted nematic device can induce an optical response in neighboring pixels. This response is a transient effect that decays a short time after the switching occurs. The transient is of comparable magnitude for both turn-on and turn-off of the switching field, but of opposite sign. Additionally, the response is different at different locations in the effected pixel. We have traced the origin of this effect to the flow induced by director reorientation in the electrically switched pixel. We have tried to provide both a qualitative and quantitative description of this effect. Qualitatively, because of the incompressibility of the liquid crystal, flow in the activated pixel produces flow in neighboring pixels. This flow causes a director reorientation that can easily be detected optically. To make things quantitative, we attempted to describe this behavior using a quasi-one-dimensional model based on the Erickson–Leslie equations. The model does not agree with the empirical results. In particular, while the magnitude of the calculated optical response is comparable to the measured result with multipixel switching, the sign of the predicted response is the opposite of what is observed.

EXPERIMENT

The experimental measurements were performed on a nematic twist cell with a 2 mm of width and 1 cm of length, consisting of a one-dimensional

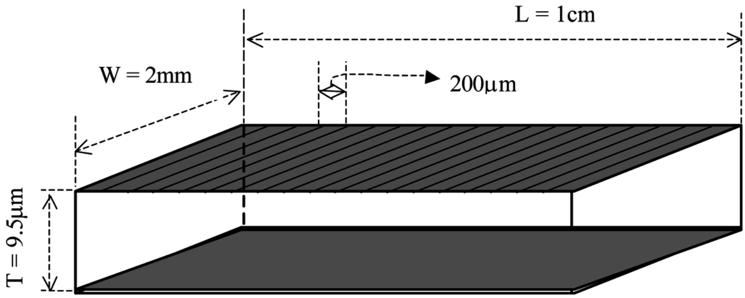

FIGURE 1 Schematic of the pixel geometry.

array of pixels (Fig. 1). The width of pixels is 200 μm, and the gap between adjacent electrode stripes is very small compared with the size of pixels. The grating cell was filled with the Merck liquid crystal MLC6080 ($K_{11} = 14.4 \times 10^{-12}$ J/m, $K_{22} = 7.1 \times 10^{-12}$ J/m, $K_{33} = 19.1 \times 10^{-12}$ J/m, $\varepsilon_{\|} = 11.1$, $\varepsilon\perp = 3.9$, $\Delta_1 = 157$ mPa $*$ s, and $\Delta n = 0.173$ at 1550 nm). The liquid crystal thickness for this grating is 9.5 μm and the pretilt angle is 2.5 degrees. The rubbing directions are -45° and 45° on the upper and bottom surfaces, respectively. The cell was operated between crossed polarizers with the transmission axes of polarizers parallel to rubbing directions, i.e., normal white, e-mode configuration. The optical transmission with wavelength 1550 nm through the cell was used as the experimental probe. Dynamic optical crosstalk was measured optically by focusing a beam onto a single pixel and monitoring its time response with a photodetector. The optical response was measured at the center of the pixel except for studies on the dependence of the response on location within a pixel. The cell was connected through an electronic driver to a computer.

The transission-*versus*-voltage (T–V) curve of a typical pixel is shown in Fig. 2. We also show the measured transmission dynamics for a pixel when it is switched between 0 V and 8 V (Fig. 3).

From the T–V curve, it is obvious that voltages between 2 V and 4 V, where the optical response is most sensitive to changes in the director orientation, should be chosen for the observed pixel to maximize the optical response due to the flow induced by the electrical switching of other pixels. We chose to fix the voltage 2 V, 2.5 V, 2.8 V, and 3.0 V on the electrically static pixel when a neighboring pixel was switched. Figure 4 shows the optical response of the pixel with different fixed voltages when a nearest neighbor pixel is switched. The results indicate that the higher the fixed voltage on the static pixel, the larger is the optical response when the neighboring pixel is switched.

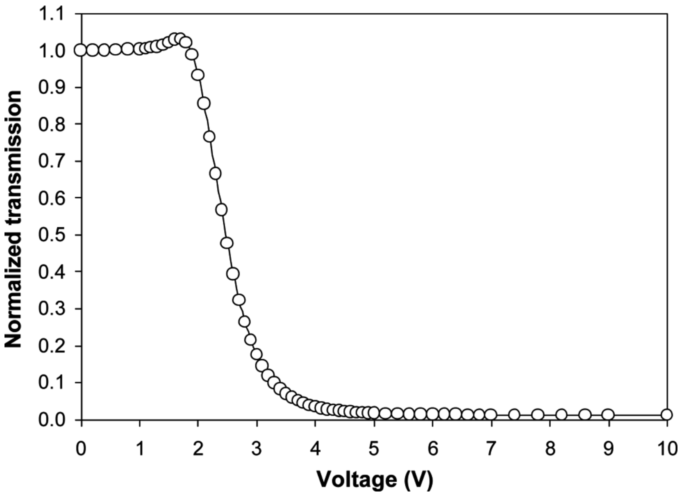

FIGURE 2 T–V curve of a pixel in the TN array.

For the switching pixels, we chose switching voltages of 4 V, 6 V, and 8 V, expecting stronger flow behavior to be induced by the higher applied voltage. Figure 5 shows the optical response of a pixel with a fixed voltage of 2.5 V when a pixel was switched between 0 V and different voltages. Figure 5 shows that the higher switching voltage on a pixel does lead to a larger optical bounce on the unswitched pixel. From the figure, we also see that the peak optical bounce on the neighboring pixel shifts toward later times as the switching voltage increases.

The optical response at distances 1/4 of the pixel height off of the central line of pixel was also measured. When a pixel was switched between 0 V and 4 V, and between 0 V and 8 V, we monitored the optical response at these locations, and found that the optical bounce had higher values than at the center of the pixel (Fig. 6). That is, optical response at the different positions in a pixel are different when a neighboring pixel is switched.

Switching a pixel not only induces optical response in the neighboring pixel but also the other pixels. We monitored the optical response at the center of a pixel while switching different pixels, and found that the optical bounce would decrease with increasing distance between the affected pixel and the switching pixel (Fig. 7). The relation between the optical response for the affected pixel and the distance between the affected pixel and the switch pixel is nonlinear.

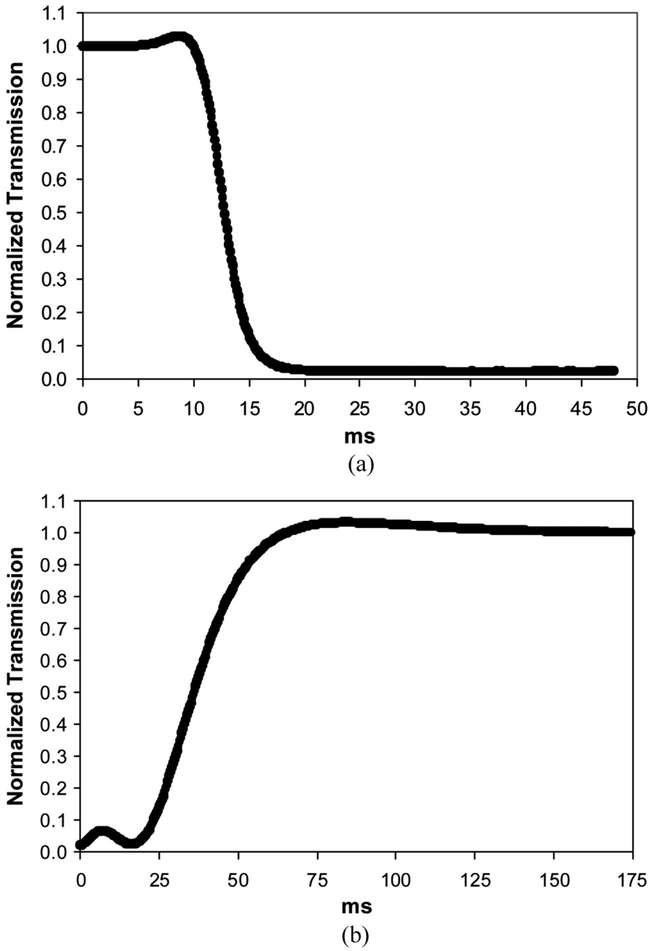

FIGURE 3 Transmission *vs* time with the switching between 0 V and 8 V, (a) switch on from 0 V to 8 V, and (b) switch off from 8 V to 0 V.

We switched pixels on both sides of a static pixel and equidistant from it. We found that each had the same effect on the pixel (Fig. 8). The two peaks in the response result from a delay between switching the two pixels. With increasing distance between the two switched pixels, the two peaks (optical bounces) corresponding to the switching at different sides will separate widely. This is merely an artifact of the drive circuitry.

The optical bounce increases when multiple pixels are switched simultaneously (Figs. 9b, 9d). When the number of switching pixels

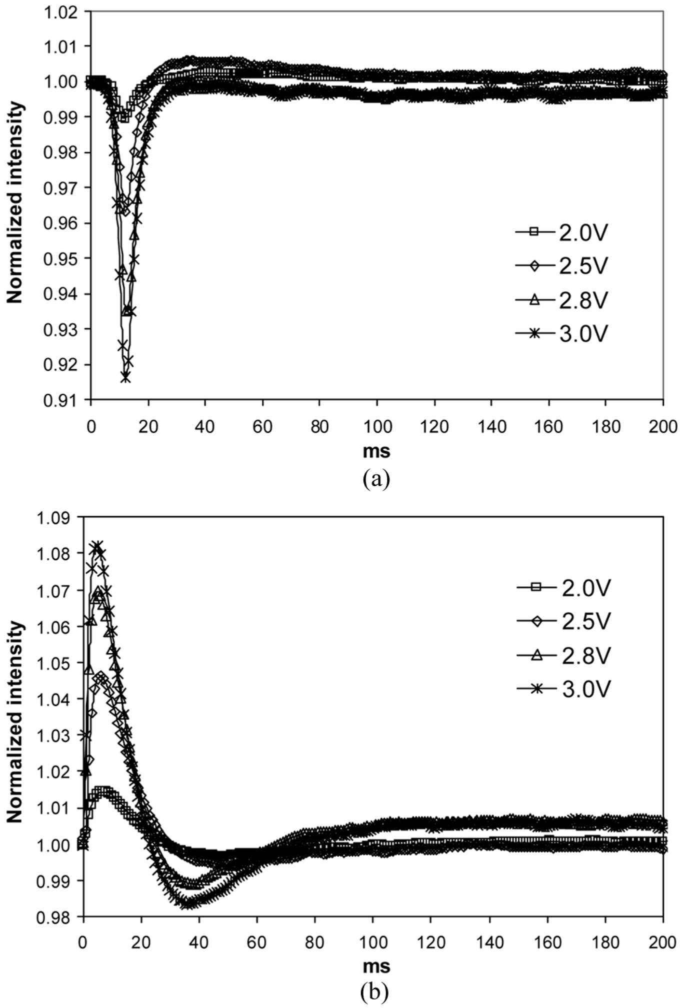

FIGURE 4 The optical response of the neighboring pixel with different fixed voltages when a pixel is switched, (a) switch on from 0 V to 8 V, and (b) switch off from 8 V to 0 V.

reaches some value, the optical bounce tends toward saturation. Because of the switching delay mentioned above, the switching pixels were not switched at exactly the same time, which leads to wider peaks here than for the case of a single switched pixel. In addition, the peaks for multiple pixel switching should be higher than the observed values if the pixels are switched simultaneously.

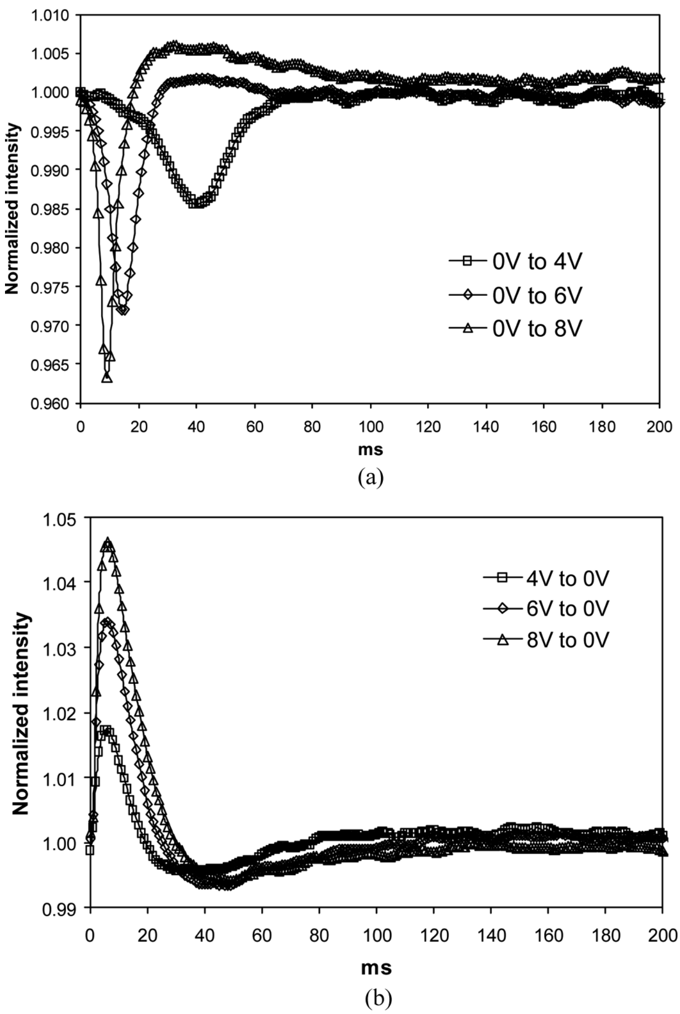

FIGURE 5 The optical response of a neighboring pixel with fixed voltage 2.5 V when a pixel is switched between 0 V and 4 V, 6 V, 8 V. (a) Switch on, and (b) switch off.

THEORY

Flow phenomena in nematics can be understood based on ELP theory. For a multidimensional problem, the equations are quite complicated and difficult to solve. The flow that results from a pixelated liquid crystal structure is multidimensional; thus the really understanding to the

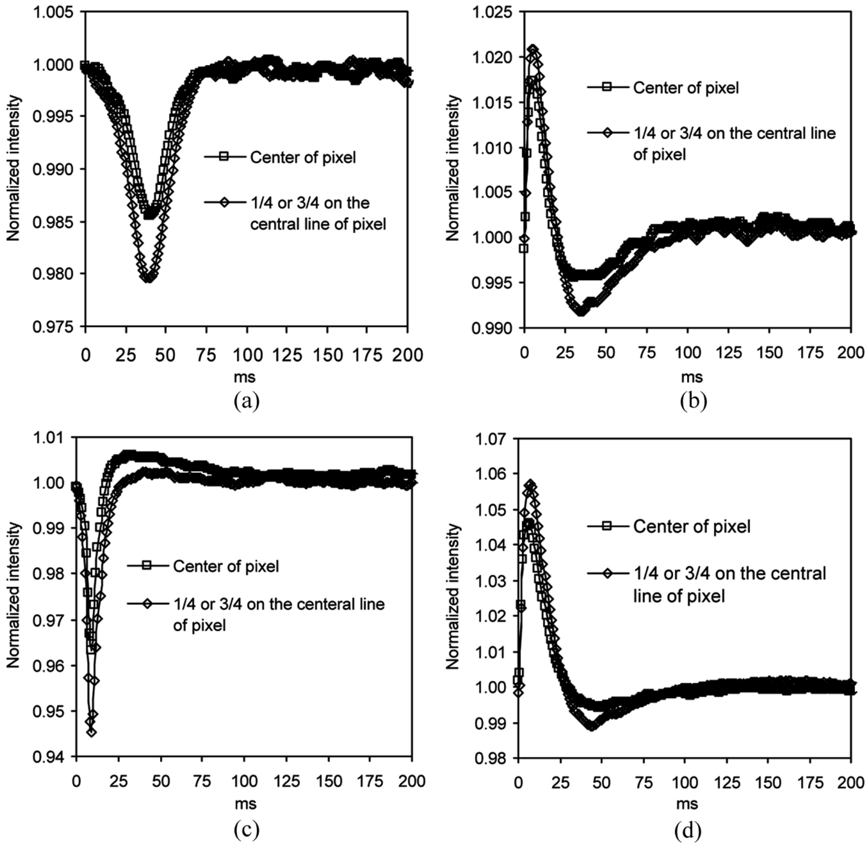

FIGURE 6 The optical responses at different positions of a neighboring pixel when a pixel is switched between 0 V and 4 V, 8 V. (a) Switch on from 0 V to 4 V, (b) switch off from 4 V to 0 V, (c) switch on from 0 V to 8 V, and (d) switch off from 8 V to 0 V.

flow phenomena in liquid crystal devices with pixelated structures needs to handle the multidimensional problems. Here, we attempt to describe the flow behavior using a quasi-one-dimensional model based on the Erickson–Leslie equations.

First, because the cell thickness (9.5 μm) and the gap between adjacent electrode stripes are very small compared with the size of pixels (200 μm), the one-dimensional approximation should give a valid description for an electrically switched pixel. With one Cartesian dimension normal to the cell, here taken to be z, there are three equations for the director components and two equations for the flow [14].

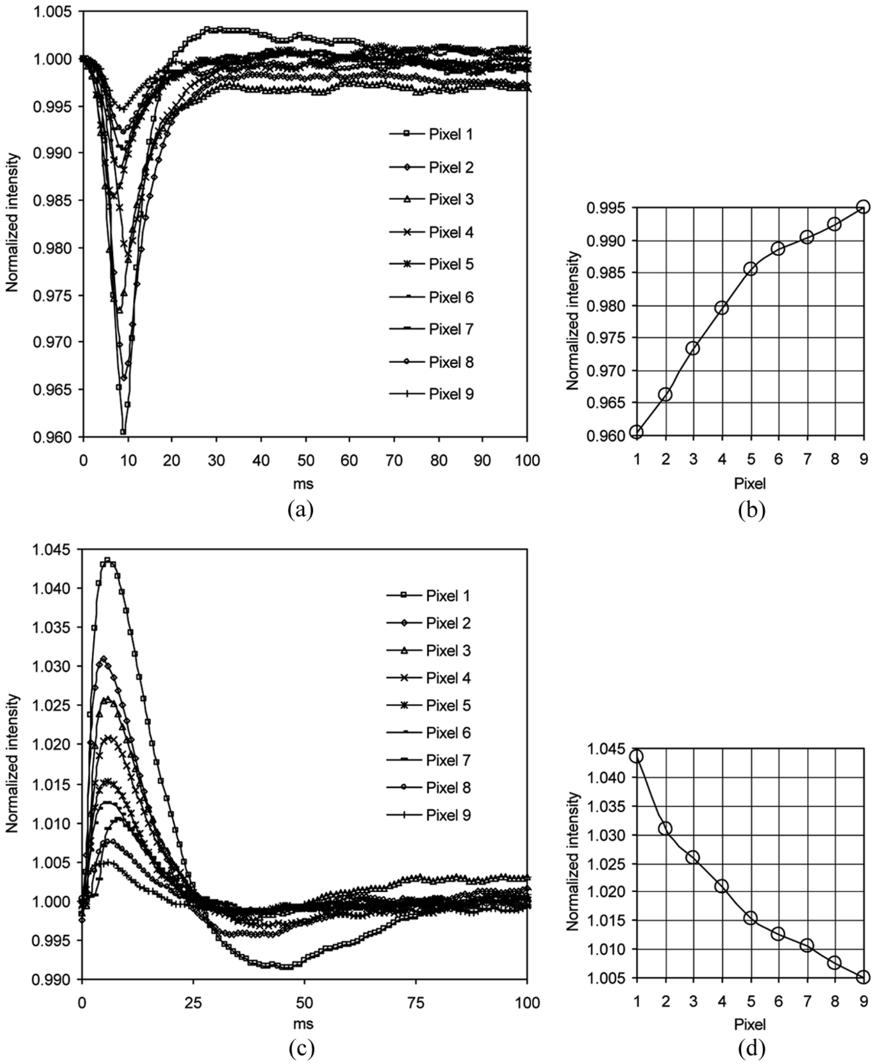

FIGURE 7 The optical response of affected pixel (pixel 0) *vs* the switching pixel, (a) dynamic optical response for switching on from 0 V to 8 V, (b) the response intensity for switching on from 0 V to 8 V, (c) dynamic optical response for switching off from 8 V to 0 V, and (d) the response intensity for switching off from 8 V to 0 V.

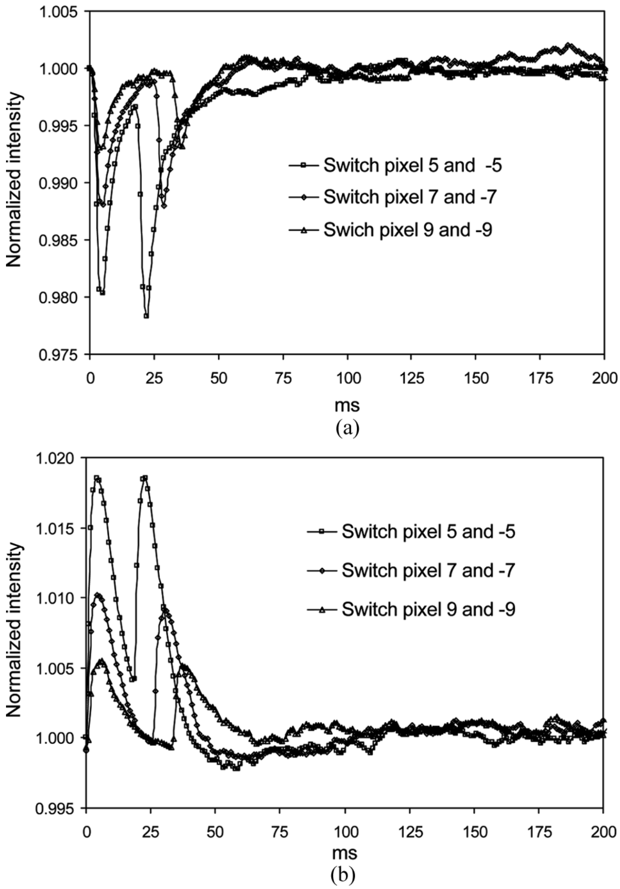

FIGURE 8 Symmetry of backflow and optical response with switching on both sides of the affected pixel, (a) switch from 1.466 V to 10 V, and (b) switch from 10 V to 1.466 V.

The equations for director components are written as:

$$\gamma_1 \frac{\partial n_x}{\partial t} = h_x - \lambda n_x - \alpha_2 n_z \frac{\partial V_x}{\partial z}, \quad (1)$$

$$\gamma_1 \frac{\partial n_y}{\partial t} = h_y - \lambda n_y - \alpha_2 n_z \frac{\partial V_y}{\partial z}, \quad (2)$$

$$\gamma_1 \frac{\partial n_z}{\partial t} = h_z - \lambda n_z - \alpha_3 \left(n_x \frac{\partial V_x}{\partial z} + n_y \frac{\partial V_y}{\partial z} \right), \quad (3)$$

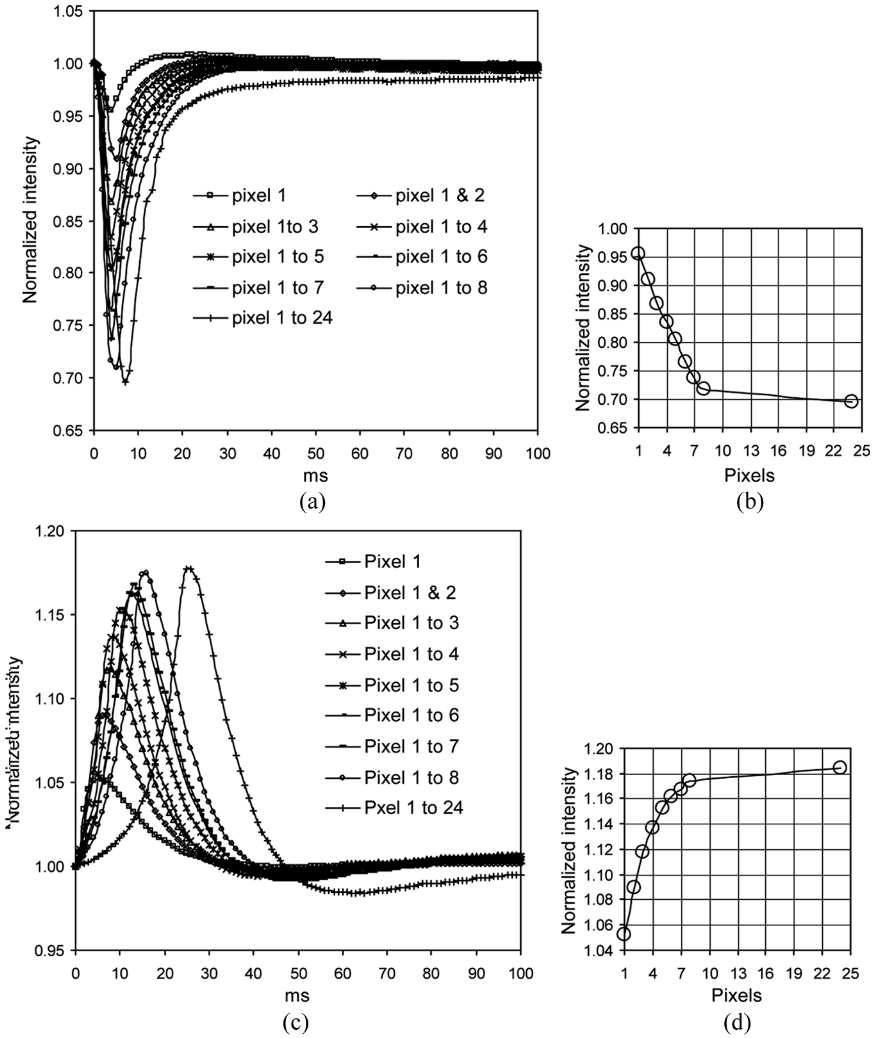

FIGURE 9 Optical response of the affected pixel with multipixel switching, (a) dynamic optical response with multipixel switching from 1.466 V to 10 V, (b) the response intensity with multipixel switching from 1.466 V to 10 V, (c) dynamic optical response with multipixel switching from 10 V to 1.466 V, and (d) the response intensity with multipixel switching from 10 V to 1.466 V.

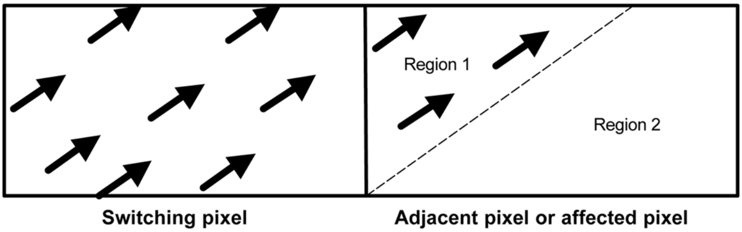

FIGURE 10 Quasi-one-dimensional model in a liquid crystal layer.

and the two equations for the flow can be written as:

$$\alpha_2 n_z \frac{\partial n_x}{\partial t} + \alpha_3 n_x \frac{\partial n_z}{\partial t} + \frac{1}{2}[2\alpha_1 n_x^2 n_z^2 + (\alpha_5 - \alpha_2) n_z^2 + \alpha_4 + (\alpha_3 + \alpha_6) n_x^2] \frac{\partial V_x}{\partial z} + \left[\frac{1}{2}(\alpha_3 + \alpha_6) + \alpha_1 n_z^2\right] n_x n_y \frac{\partial V_y}{\partial z} = C_1(t), \quad (4)$$

$$\alpha_2 n_z \frac{\partial n_y}{\partial t} + \alpha_3 n_y \frac{\partial n_z}{\partial t} + \frac{1}{2}[2\alpha_1 n_y^2 n_z^2 + (\alpha_5 - \alpha_2) n_z^2 + \alpha_4 + (\alpha_3 + \alpha_6) n_y^2] \frac{\partial V_y}{\partial z} + \left[\frac{1}{2}(\alpha_3 + \alpha_6) + \alpha_1 n_z^2\right] n_x n_y \frac{\partial V_x}{\partial z} = C_2(t), \quad (5)$$

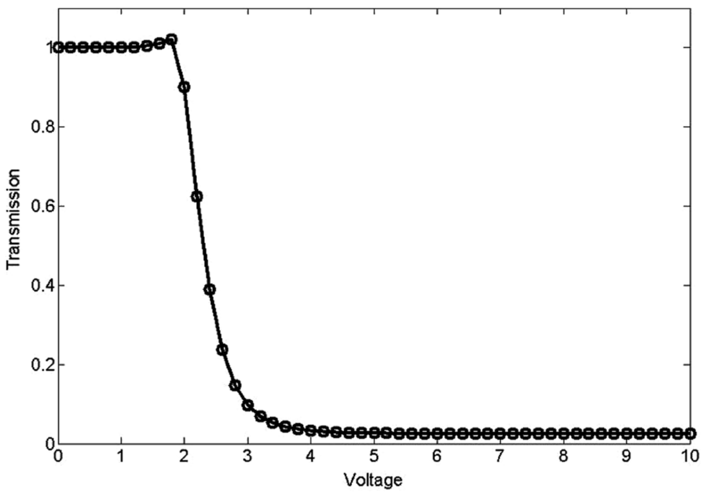

FIGURE 11 The calculated TV curve of pixels for the nematic twist grating cell.

where C_1, C_2 are constants of integration; λ is a Lagrange multiplier; γ_1 is the rotational viscosity; h is the molecular field. The flow in the switching pixels can be obtained by solving these equations numerically.

To model the optical bounce, we assume the flow is quasi-one-dimensional. We imagine that because the fluid is incompressible, the one-dimensional flow field in a switched pixel extends unchanged—both magnitude and direction—into neighboring regions surrounding the pixel. Based on this very crude model, the flow profile in neighboring

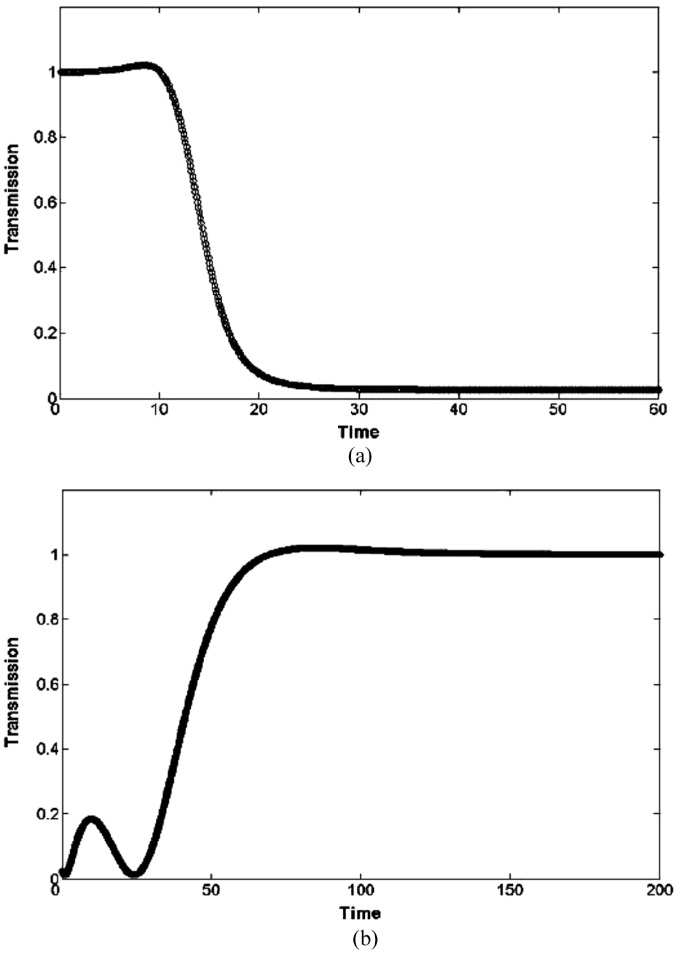

FIGURE 12 The calculated transmission *verses* time with the switching between 0 V and 8 V, (a) switch on, and (b) switch off.

pixels depends on the direction of flow in the switching pixel as well as position inside the pixel. For example, in Fig. 10, we illustrate uniform flow in a liquid crystal sublayer in a switching pixel on the left. This flow impinges into Region 1 of the adjacent pixel but there is no flow in Region 2.

Using the one-dimensional approximation, we can obtain the T–V curve and the dynamic optical transmission of the switching pixels.

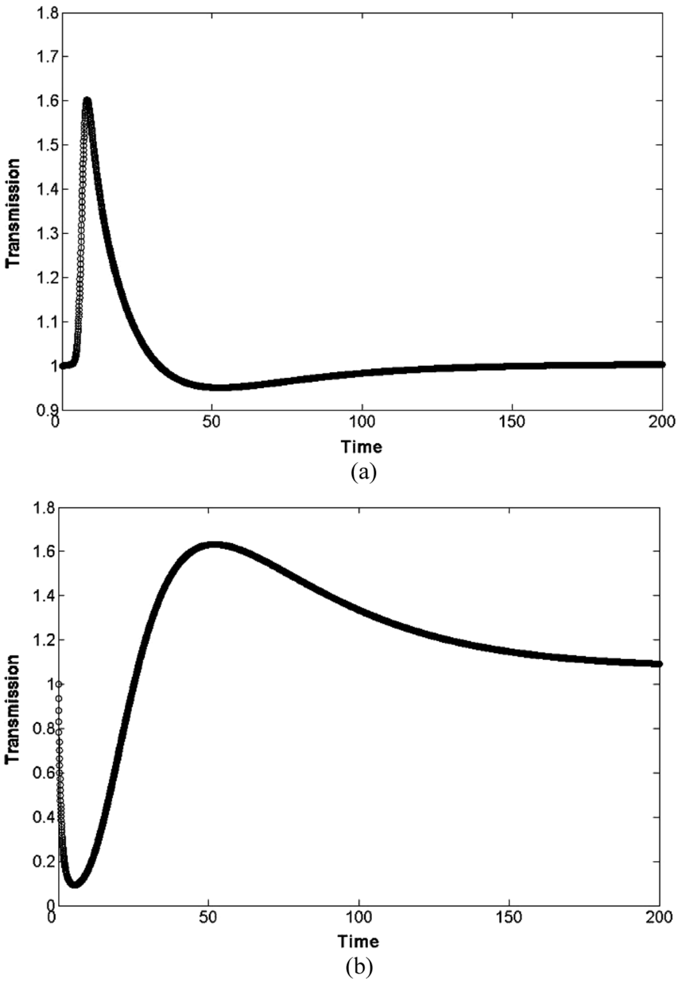

FIGURE 13 The calculated results for the optical response in a neighboring pixel with fixed voltage 2.5 V when a pixel is switched between 0 V and 8 V, (a) switch on from 0 V to 8 V, and (b) switch off from 8 V to 0 V.

Figure 11 shows the calculated T–V curve, and Fig. 12 is the optical transmission *versus* time of a switching pixel with the switching between 0 V and 8 V. Comparing Figs. 11 and 12 with Figs. 2 and 3, it is evident that the calculation results are in substantial agreement with the experiment.

Based on the quasi-one-dimensional model for the effected pixels, the calculation results for the optical response in the neighboring pixel with a pixel switched between 0 V and 8 V are shown in Fig. 13. The voltage on the adjacent pixel was fixed at 2.5 V. Comparing with the experimental measurements, the model does not agree with the empirical results. In particular, while the magnitude of the calculated optical response is comparable to the measured result for multiple pixels switching (Fig. 9), the sign of the predicted response is the opposite of what is observed.

SUMMARY

We have presented experimental observations of flow-induced dynamic optical crosstalk between pixels in a TN array. The transient is of comparable magnitude for both turn-on and turn-off of the switching field, but of opposite sign. The optical response is different at different locations in an affected pixel. We have tried to provide both a qualitative and quantitative description of this effect. Basically, because of the incompressibility of the liquid crystal, flow in the activated pixel produces flow in neighboring pixels. This flow causes a director reorientation that can easily be detected optically.

We attempted to describe these observations using a simplified quasi-one-dimensional model based on the Erickson–Leslie equations. This model does not agree with the empirical results. Although the magnitude of the calculated optical response is comparable to the measured results when multiple pixels are switched, the sign of the predicted response is the opposite of what is observed. Theoretical understanding of this flow phenomenon in the liquid crystal devices with pixelated structure will require a multidimensional framework.

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