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Pulse Sequence Addressing for Gray-Scale Bistable Cholesteric Displays

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In the study of the transition dynamics, we found that the reflectance of bistable cholesteric displays depended on the addressing sequence of the bipolar pulses. Two different pulse amplitudes corresponding to the high and low voltages about the quiescent point were chosen. By a proper permutation of such pulses, the final reflectance of even difference could be obtained for gray-scale display applications. In contrast with the root-mean-square (rms) modulation techniques, this scheme proposed for the first time does not primarily depend on the rms voltage. In this paper, we study the electro-optics and the domain characteristics, and propose a phenomenological proposition to describe this effect. We shall also extend our previous driving scheme to demonstrate the gray-scale control at 5 ms/line addressing.

KEYWORDS: bistable cholesteric display, gray-scale, addressing scheme

1. Introduction

For the bistable cholesteric display (BCD), there are two long-lived stable states, which are often referred to as the focal-conic and the planar states. The former scatters light weakly whereas the latter reflects light according to the selective Bragg condition. Intermediate reflectance is due to the distributed helical axis and the different domain size of the planar cholesteric texture.[1,2] The reflection spectrum of the BCD can be tuned to any of the 3 primary colours. The reflectivity is so high that it can reflect almost 50% of one-handed circular polarized light. Therefore, a stacked multicolour BCD with different handed twists can reflect as much as 100% of the ambient light. Recently more than 30% reflectance in a stacked multicolour BCD has been reported independently by researchers at Kent State University and Minolta.[3–6] Techniques based on amplitude and the pulse width modulations have been proposed and incorporated into their driving schemes. However such schemes usually require high drive voltage and large switching current that are not cost-effective for VLSI implementation of the display drivers.[7,8]

In these regards, we study the feasibility of gray-scale control using different sequences of high and low bipolar pulses during each addressing interval.[9] Since this control can be encoded in the data stream, the cost of this scheme can be reduced drastically. However, for 8 levels gray-scale control at least 3 bipolar pulses are required. Consequently, the addressing time per line has to be lengthened and it is 5 ms in the present discussion. We argue that this is a secondary issue because the slow response time and long settling time are the major concerns for the video-rate applications. Optimization of the liquid crystal properties should help to improve these dynamic responses. The waveform of the pulse sequence addressing is described in §2, whereas the dynamic response of the gray-scale reflectance and the photographs of the macro-domains are discussed in §3.

2. Waveform of Pulse Sequence Addressing

The addressing waveform in our previous scheme is extended to include several bipolar pulses within the writing cycle as shown in Fig. 1. T_w denotes the total writing time and T_c is the clearing time. For the former, the frequency is 1 kHz and the slew-rate should be set below 0.4 V/μs so that the increase in the drive voltage can be kept less than 8%.[8] Lower frequency allows more room to reduce the slew-rate with a negligible effect on the rms voltage and 50 Hz is elected for the latter. For a coherent discussion,[7] the voltage across a pixel P_{ij} is normalized with respect to the drive voltage and all voltages are quoted in the peak-to-peak values. The voltage difference is also determined by the phase relationship between the i-th row R_i and the j-th column C_j. The corresponding equations are given below.

$$r_H = r_q + r \qquad r_L = r_q - r \tag{1}$$

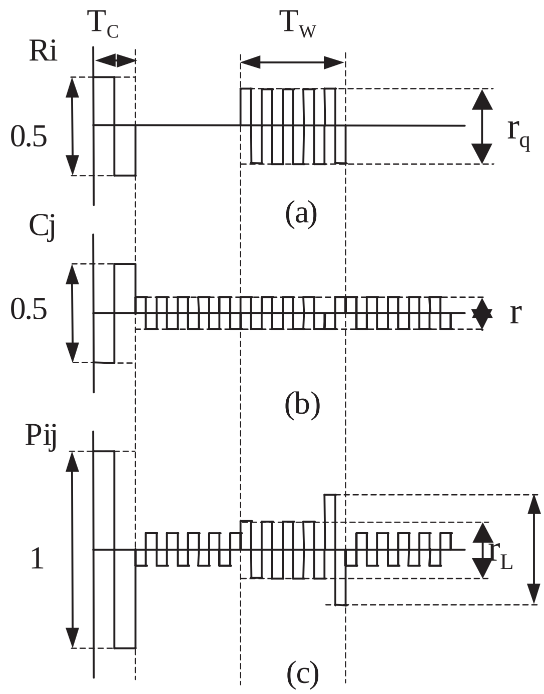

Fig. 1. Waveforms of pulse sequence to address the gray-scale BCD.

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where the suffix represents a high or low voltage. r_q and r are the quiescent point voltage and the data voltage respectively.

In this paper, we shall mainly discuss the pulse sequence addressing scheme using five high and low bipolar pulses for an 8-level gray-scale modulation. The principle is to perturb the planar cholesteric texture in the vicinity of the planar to focal-conic transition threshold. When the applied voltage exceeds the threshold, the planar cholesteric texture will break up into small domains that scatter the light. They grow in the irregular patterns and under the influence of the electric field. If a field much higher than the threshold is applied, the focal-conic texture can be grown in tens of milliseconds. In fact, the response time of this transition is very fast, and can be less than 1 ms.[10] Consequently, any rapid changes in voltage will directly affect the planar cholesteric texture. On the other hand, if the field is removed during the growth, the transformation will slow down and cease to grow after a few hundreds of milliseconds. It is indeed the case when the surface is treated for the planar alignment. For the homeotropically treated surfaces, the pattern formation of focal-conic texture can be completed and stabilized in less than a hundred millisecond. Therefore, in both cases, the occurrence of a growth pulse followed by the holding pulses will influence the domain size and hence the reflectivity. In addition, the dependence on frequency is negligible and the amplitude of the holding pulses should be less than the threshold voltage. It has been found that the holding pulses are effective to promote the pattern formation of the focal-conic texture, although they can hardly induce the transformation on their own.

Two different pulse amplitudes, which correspond to the growth and holding voltages, can be chosen about the quiescent point of the state transition. For 5 encoded pulses, there will be totally 32 levels in the reflectance. When all the pulse voltages are low, the reflectance will be at the highest or the 31st level. When there is a high voltage pulse H among four low voltage pulses L, the reflectance will be reduced and determined by the occurrence of this high voltage pulse in the sequence. In other words, the 30th level will correspond to LLLLH, 29th level to LLLHL and so on. This trend happens for other cases when more high voltage pulses are involved. This effect becomes less prominent and the levels are getting less far apart, when more than two high voltage pulses are encoded. Therefore, the final reflectance is a nonlinear and discrete function of these encoded pulses. Nevertheless an optimal set of the sequences exists for the 5 ms/line addressing.

It is interesting to note that the multipulse sequence within the writing time is very much like multiplexing in a passive matrix liquid crystal display. However, the gray-scale in the BCD is dependent on the HL sequence for the same rms voltage. It can be seen, for example, that LLLLH and LLLHL have the same rms voltage but produce very different grayscales at the end of the writing period. We shall see in the next section that actually, both the rms voltage and the HL sequence are important in determining the final reflectance of the BCD.

To optimize the final gray-scale, r_q is found equal to 0.44 at 5 ms writing time. For the binary level BCD, good contrast and brightness have been observed when r_q is set equal to 0.5. Because in the latter case the dependence on the state transition characteristics is not critical, and the transient contribution due to the addressing pulses becomes less influential in the determination of the final reflectance. Taking the slew-rate into consideration, r_q can be set close to 0.5 by reducing the waveform slew-rate to 0.2 V/μs. Therefore, the 2-level amplitude control can be simplified to a sub-level design. The maximum output current and average power will be reduced approximately by half compared with the case at 0.4 V/μs.

3. Results and Discussions

For the measurement discussed in this section, a batch of test cells was fabricated in our laboratory. Unrubbed polyimide PIA3744 from Chisso Corp. was coated on the indium tin oxide (ITO) glass surface. Nematic mixtures MLC-6041 and chiral dopant S811 from Merck KGaA were used. The cell gap was about 4 μm and the cell reflected 543.5 nm laser light. To reduce the Fresnel reflections, the electro-optic characteristics were measured in a cross-polarization setup (see ref. 7). The p-wave was reflected by the polarized beam splitter (PBS) and incident normal to the test cell. The s-wave of the circularly polarized light reflected from the cholesteric helical structures was transmitted and detected by a silicon photo-detector. Voltage signal can be acquired and integrated by a Hewlett-Packard Infinium oscilloscope. Hence the reflectance and the dynamic responses can be measured accordingly. The PBS was broadband and purchased from Newport Corp.

3.1 Electro-optic characteristics and dynamic response

A large bipolar pulse was superimposed on a periodic rectangular waveform of the same 4 ms period. The periodic rectangular waveform was used to study the effect of signal floor voltage on the planar to focal-conic transition. The reflectance was measured about 3 s after the pulse amplitude was incremented and was initialized to the same value between successive series of measurements. A long delay time was allowed to make sure that there was no slow long time constant relaxation before the measurement was taken. In Fig. 2, the solid circle curve represented the pure pulse case and the signal floor voltage was zero. This characteristic was similar to those observed at different writing times.[7] It was clear that the quiescent point r_q, when the signal floor volt-

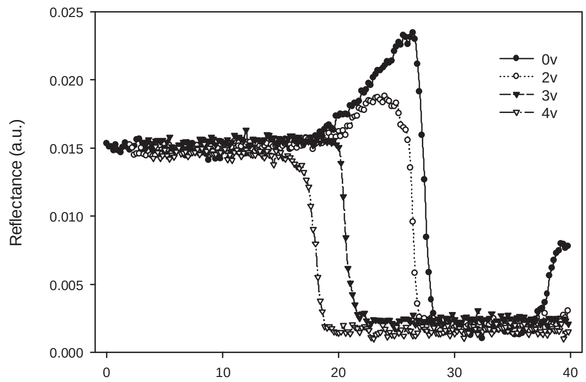

Fig. 2. Reflectance against pulse amplitude at different signal floor voltages. The frequency of both bipolar pulse and signal floor voltage is 250 Hz, whereas the writing time is 4 ms.

age was 4 V peak, was about half of the drive voltage. For the optimal gray-scale control, r_q and r were found equal to 0.44 and 0.14 respectively. The former was determined by the heuristic approaches, whereas the latter was based on our previous studies.[7)] In this case, the drive voltage was 36.4 V peak though. Usually, high data voltage was effective to destabilize the fluctuation in the vicinity of the planar to focal-conic transition threshold, so that the levels in reflectance associated with different pulse sequences can be more far apart.

In Fig. 3, the waveform of the pulse sequence addressing was designated as input and only the case of all high voltage pulses was shown for clarity. The responses from the highest to lowest reflectance were ordered in accordance with those described in the legend. H and L represented high and low pulses [see eq. (1)] and were equal to 0.58 and 0.3 respectively. In this case, the writing time, frequency and data voltage were respectively 5 ms, 1 kHz and 0.14. It is surprising that the reflectivities associated with the two sets of pulse-sequences: {LLLLH, LLLHL, LLHLL, HLLLL} and {LLLHH, HLLHL} are distinctly different from one another. Since the rms voltage associated with these pulse sequences degenerates to two different values, it is the rapid temporal responses that will matter. It is not likely due to the Carr-Helfrich effect,[11,12)] since the frequency dependence of the transition is not critical and the frequency spectra are similar for any set of the pulse sequences. Nevertheless, ion segregation cannot be neglected for the liquid crystals of positive and negative dielectric anisotropies.[13–15)]

On the other hand, due to the long homeotropic-planar relaxation time, there was an 80 ms delay after the 20 ms clearing time. Shorter than this delay, the final reflectance would deviate from the appropriate value and it depended on the liquid crystal temporal characteristics. Again this problem was rooted in other driving schemes and it became very complex when the transitions among different gray-levels were necessary. Optimization based on this scheme was however simpler since the initial state was always the highest level planar state.

3.2 Domain characteristics

By making use of the waveforms described in the second section, different topological textures were obtained in accordance with different permutation of the pulses. In Fig. 4(a), when all the pulse voltages were low, a planar cholesteric texture that reflected the green spectrum of the ambient light was observed. The domain boundaries of the planar texture were also visible when it was observed under the optical microscope. When all the pulse voltages were high, the texture became focal-conic [Fig. 4(c)]. To demonstrate the effect on the domain size-dependent reflectivity, the pulse sequence that gave rise to the mid-level in reflectance was chosen. This led to an inhomogeneous texture composed of irregular planar and focal-conic domains. The reflectivity depended on the size and the helical axis orientation of the planar cholesteric domains shown in Fig. 4(b). Other permutations of the pulses would cause different domain sizes and hence different reflectivity.

Based on these findings, it is believed that the temporal gradient of the velocity tensor is central in the pulse-sequence induced gray-scale reflectivity. Because the apparent bulk viscosity of a cholesteric liquid crystal may often be 10^5 times larger than the friction coefficients defined in the Leslie equations.[16)] At the low voltage threshold, the flow due to the permeation effect is negligible along the cholesteric helical axis.

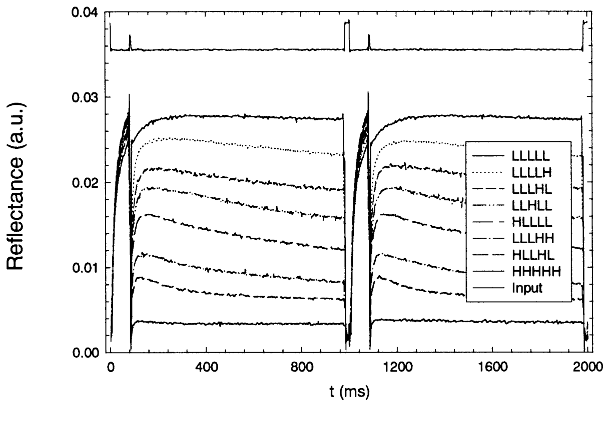

Fig. 3. Dynamic response of gray-scale control. The writing time is 5 ms and the clearing time is 20 ms. Both have the same frequency at 1 kHz. The high H, low L and data voltages are respectively 0.58, 0.3 and 0.14. The drive voltage is 36.4 V peak. The vertical axis represents the intensity and it has an arbitrary unit.

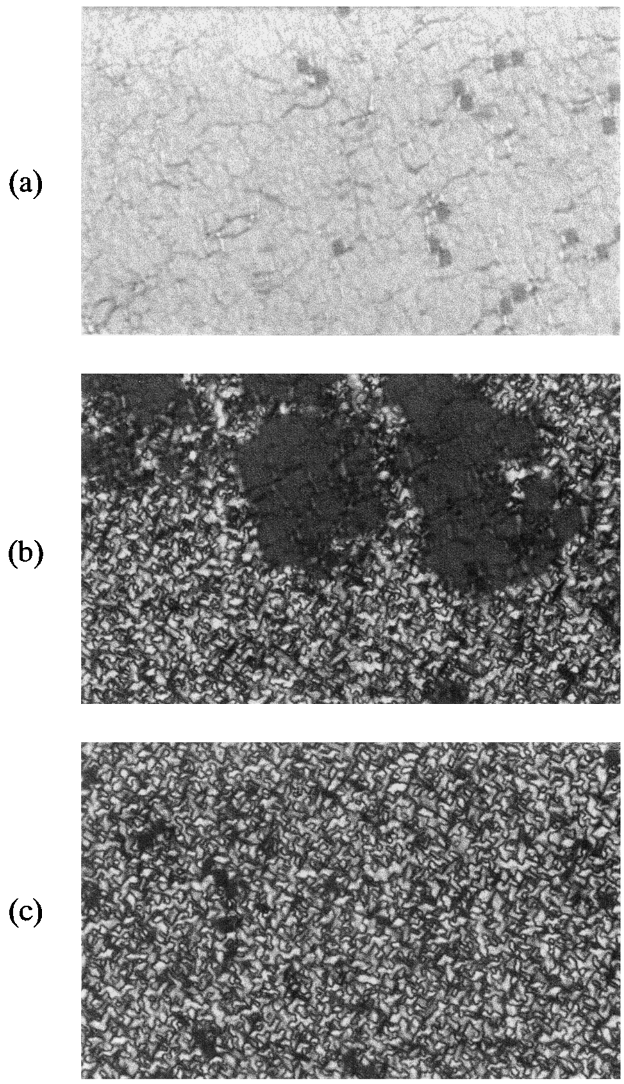

Fig. 4. Photographs of different topological domains: (a) planar, (b) coexistence of planar and focal-conic, (c) focal-conic. The magnification is 50 and the grey round dots are the spacers.

Above this threshold, the applied electric field will give rise to the viscous stress tensor that favours the flows orthogonal to the cholesteric helical axis. According to the hydrodynamic equations, the temporal changes in the flow gradients will couple with the stress and pressure gradient tensors that influence the final configuration of the liquid crystal director. Therefore, in the vicinity of the transition threshold, it is possible that the focal-conic domain formation and hence the gray-scale reflectivity can be induced by the rapid pulses of the same rms voltage. These flow gradients, can vary by many orders of magnitude due to the viscosity, and, are responsible for the slow response of optical reflectivity. Consequently, there will be a slow roll-off when the planar texture has not been transformed to the focal-conic texture completely.

4. Conclusions

The electro-optic and the domain characteristics of the cholesteric liquid crystal have been studied in the vicinity of the planar to focal-conic transition threshold. When a train of high and low bipolar pulses was applied, we found that the domain size of the planar cholesteric texture depended on the addressing sequence of the pulses. These high and low pulses should be chosen about the quiescent point of the transition. The gray scale could be attributed to the temporal dependence of the flow gradients orthogonal to the helical axis orientation, when the transition threshold was exceeded. Therefore, the occurrence of the first high pulse would trigger the planar to focal-conic transition and the final domain size would be influenced in addition by the low voltage pulses of the pulse train. By proper permutation of such pulses, final reflectance of even difference could be obtained for gray-scale display applications. In this paper, we extended our previous driving scheme to incorporate the pulse sequence addressing for gray-scale control. This capability was demonstrated for an 8-level BCD in the 5 ms/line addressing for the first time. Combining with the low electrical requirements, the proposed addressing scheme is one of the most cost-effective solutions for the binary and the gray-scale bistable cholesteric displays. It is a better choice for the intermediate information content displays.

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