8-28-1995

Transient Dielectric Study of Bistable Reflective Cholesteric Displays and Design of Rapid Drive Scheme

Xiao-Yang Huang
Kent State University - Kent Campus

Deng-Ke Yang
Kent State University - Kent Campus, dyang@kent.edu

J. William Doane
Kent State University - Kent Campus

Transient dielectric study of bistable reflective cholesteric displays and design of rapid drive scheme

Xiao-Yang Huang, Deng-Ke Yang,[a] and J. William Doane
Liquid Crystal Institute and Department of Physics, Kent State University, Kent, Ohio 44242

(Received 12 April 1995; accepted for publication 3 July 1995)

Transient dielectric measurement is used to study the transitions among the planar, focal conic, and homeotropic states of cholesteric liquid crystals. If the initial state is the field-induced homeotropic state, at low bias fields, the liquid crystal transforms to the planar state in a sequence of homeotropic-transient planar–planar; at high bias fields, the liquid crystal transforms to the focal conic state. The homeotropic-transient planar transition is on the order of 1 ms while the homeotropic-focal conic transition is on the order of 100 ms. Large hysteresis is observed in the transitions between the homeotropic and the focal conic state. Based on the rapid homeotropic-transient planar transition and the hysteresis effect in the focal conic-homeotropic transition, we have designed a drive scheme which can address bistable reflective cholesteric displays at the speed of one line per millisecond. © *1995 American Institute of Physics.*

The bistable reflective cholesteric display is a recent breakthrough in the application of cholesteric liquid crystal materials.[1–4] Because of its superior reflective direct viewing legibility (high resolution at more than 200 dpi) and cost-effectiveness, this technology appears promising for such applications as electronic newspapers, books, and viewers. The technology confronts, however, a major problem: The addressing time per line is about 50 ms with the currently available passive matrix drive scheme,[3] which is too slow for a page-size display.

Bistable cholesteric displays have two stable states at zero field. One is the Bragg reflecting planar state (P state) where the helical axes are perpendicular to the cell surface. The other is the scattering focal conic state (F state) where the helical axes are more or less parallel to the cell surface. The liquid crystal can be switched between these two states by ac voltage pulses.[3] Under a low voltage pulse, the material is driven from the planar state to the focal conic state and remains in the focal conic state after the pulse. Under a high voltage pulse, the material is driven from the focal conic state to the homeotropic state (H state), and relaxes into the planar state after the pulse.

The transition from the homeotropic state to the planar state takes place in two steps: homeotropic state→a transient planar state (P^* state) with the pitch $P=(K_{33}/K_{22})P_0$ →the stable planar state with intrinsic pitch P_0. The homogeneous H-P^* transition is on the order of 1 ms while the heterogeneous H-F transition is on the order of 100 ms and has a large hysteresis. Based on these experimental results, we have developed a novel *dynamic drive scheme* which is capable of addressing a 1000-line matrix display in about 1 s.

The mixture used in our experiment reflects green light ($\lambda=520$ nm) and has a positive dielectric anisotropy $\Delta\varepsilon$. The cell gap is controlled by 5 μm glass fiber spacers.

The dynamic process of the transitions in the cholesteric material is studied by monitoring the evolution of cell capacitance during transitions. The cell capacitance is given by $C_{lc}=(A/d)\varepsilon_\perp\varepsilon_\parallel/(\varepsilon_\perp\cos^2\theta+\varepsilon_\parallel\sin^2\theta)$, where θ is the angle between the liquid crystal director and the cell normal; d and A are the cell thickness and area, respectively. In the H state, $\theta=0°$ and $C_{lc}=C_{max}=\varepsilon_\parallel A/d$ (which is 17 nF in our experiment). In the P state, $\theta=90°$ and $C_{lc}=C_{min}=\varepsilon_\perp A/d$. In the F state, C_{lc} taken some intermediate values. In the experimental setup the cell is in series with a large capacitor of fixed capacitance $C_0=500$ nF$\gg C_{lc}$ so that the voltage applied to the cell is $V_{lc}=C_0V_{in}/(C_0+C_{lc})\approx V_{in}$. During the transition the input voltage V_{in} is precisely controlled and the voltage V_0 across the fixed capacitor is measured. The cell capacitance can be calculated by $C_{lc}=V_0C_0/(V_{in}-V_0)$. This system is calibrated with a HP 4284A LCR meter and has a time resolution of 0.05 ms and an accuracy of 0.5%.[5]

First, the relaxation of the cholesteric liquid crystal from the field induced H state is studied. A high voltage (60 V) applied to the cell before $t=0$ switches the liquid crystal into the H state; then the voltage is turned off at $t=0$ and the liquid crystal relaxes. The cell capacitance C_{lc} versus time is shown in Fig. 1. At $t=0.9$ ms, the liquid crystal

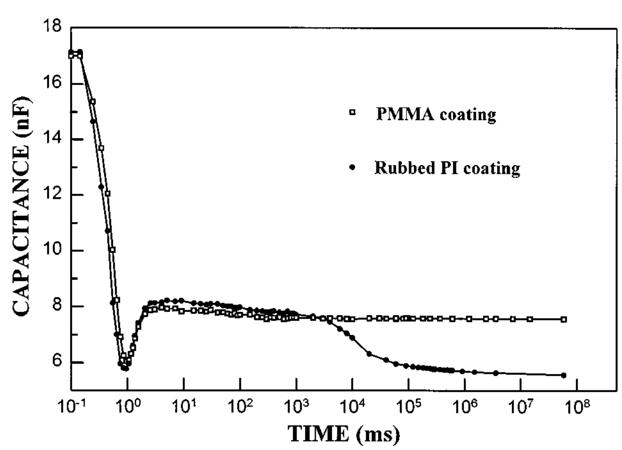

FIG. 1. The evolution of the capacitance of cholesteric liquid crystal cells from the homeotropic state when the applied voltage is switched off. The surface coating is rubbed polyimide or PMMA.

[a]Author for correspondence.

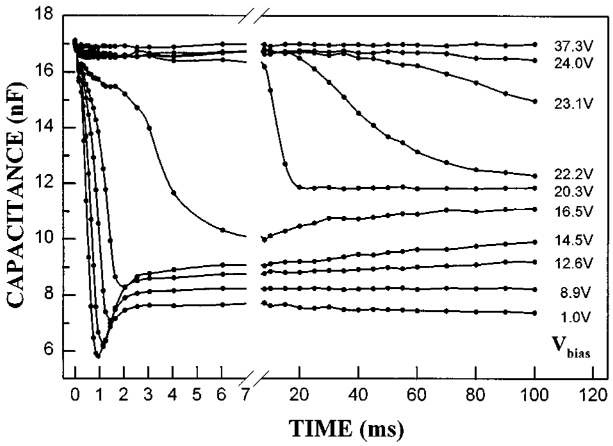

FIG. 2. The evolution of the cell capacitance when the cholesteric material relaxes from the *H* state under different bias voltages.

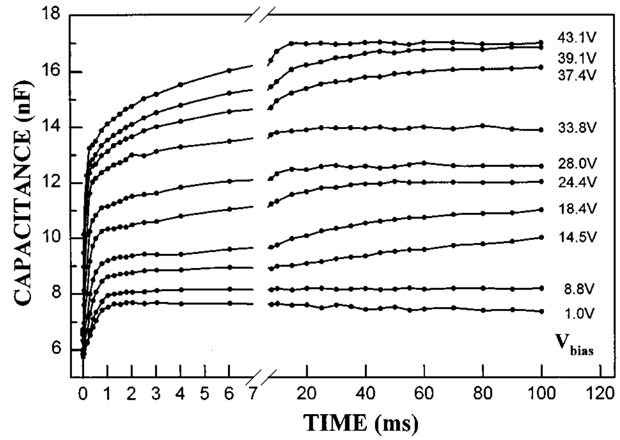

FIG. 3. The evolution of the cell capacitance when the cholesteric material transforms from the *P** state under different bias voltages.

transforms into the P^* state, and $C_{\rm lc}$ decreases to a minimum value which is slightly higher than that of the *P* state (about 5.5 nF). This indicates that in the P^* state, the average polar angle of the liquid crystal directors is close to but not exactly 90° because of defects in this state. The transition time τ_{HP*} is 0.9 ms which is consistent with the theoretical predicted value of $\gamma P_0^2/K_{22}$.[6,7] The P^* state is not stable because the free energy of the liquid crystal has not yet reached its minimum. The liquid crystal relaxes further into the stable *P* state. This relaxation is a nucleation process and defects are involved. During this relaxation, the liquid crystal directors in defect regions tilt back to the cell normal and $C_{\rm lc}$ increases about 10%. For a cell with a rubbed polyimide (PI) alignment layer, the final stable *P* state is perfect and all the defects are annihilated; θ is 90° and $C_{\rm lc}$ reaches the minimum value. For this cell only the *P* state is stable at zero field. For a cell spin coated with PMMA [poly(methyl methacrylate), which is a weak alignment layer],[8] $C_{\rm lc}$ cannot reach the minimum because the defects in the *P* state are stabilized by the surface. For this cell, both the *P* state and the *F* state are stable at zero field. This bistable cell is used in further experiments.

The effect of bias voltage on the transitions of the cholesteric liquid crystal from the field induced *H* state is studied. The liquid crystal material is first aligned into the *H* state by a high voltage (60 V), then the voltage is switched to a bias voltage $V_{\rm bias}$ lower than V_C (which is critical voltage for the *F*-*H* transition and is 40 V for the cell) at $t=0$. Figure 2 shows the evolution of cell capacitance under different bias voltages. The bias voltage can be divided into three regimes. In the low regime ($V_{\rm bias}<15$ V), the liquid crystal transforms from the *H* state to the P^* state in about 1 ms. Then the liquid crystal relaxes either to the stable *P* state if the $V_{\rm bias}$ is below 9 V or to the *F* state if $V_{\rm bias}$ is higher than 9 V. In the middle regime (15 V$<V_{\rm bias}<$25 V), the voltage is higher than $V_{HP*}=(2/\pi)\sqrt{K_{22}/K_{33}}V_C$ (the critical voltage for the *H*-P^* transition) and the fast *H*-P^* transition becomes impossible. The liquid crystal relaxes into the *F* state through the slow diffusion process initiated by irregularities. The *H*-*F* transition time, depending on the bias voltage, varies from 20 to a few hundred milliseconds. In the high regime ($V_{\rm bias}>25V$), the *H*-*F* transition becomes either impossible or too slow (with a transition time longer than 1 s). The critical voltage for the *H*-*F* transition is 25 V while the critical voltage V_c for the *F*-*H* transition is 40 V. The hysteresis is 15 V.

The effect of bias voltage on the transitions from the P^* state is also studied. Once the liquid crystal is in the P^* state, depending on the amplitude of the bias voltage, it can either relax to the *P* state or be driven into the *F* state. A high voltage is applied to align the liquid crystal into the *H* state before $t=-1$ ms; the voltage is switched to 1.5 V between $t=-1$ ms and $t=0$ ms to allow the liquid crystal to transform into the P^* state; then the voltage is switched to the bias voltage $V_{\rm bias}$. The evolution of cell capacitance under different bias voltages is shown in Fig. 3. If $V_{\rm bias}<9$ V, the liquid crystal relaxes to the stable *P* state, the capacitance increases first and then decreases slowly with time. If 9 V$<V_{\rm bias}<$40 V, the liquid crystal transforms from the P^* state to the *F* state, the capacitance increases to values which depend on the bias voltage.

A *dynamic drive scheme* is designed for bistable reflective cholesteric displays based on the above experimental results. This drive scheme consists of three phases; preparation, selection, and evolution, as shown in the inset in Fig. 4. The basic wave form is 2 kHz ac square wave. In the preparation phase, a high voltage V_p aligns the liquid crystal into the *H* state. In the 1 ms long selection phase, either a low voltage ($<V_{HP*}$) is applied to initiate the transition from the *H* state to the P^* state or a high voltage ($<V_{HP*}$) is applied to hold the liquid crystal in the *H* state. In the evolution phase, the voltage amplitude V_e is carefully chosen according to Figs. 2 and 3 so that the liquid crystal in the P^* state can evolve to the stable *F* state and the liquid crystal in the *H* state can be metastably held there. At the end of the evolution stage, the liquid crystal is in either the *F* state or the *H* state. Upon the removal of voltage, the liquid crystal either stays in the *F* state or transforms from the *H* state to the *P* state; therefore, the final state of the display can be controlled by the voltage in the selection pulse. Figure 4 shows the effect of the selection voltage on the reflectance and capacitance of the display cell measured 800 ms after the volt-

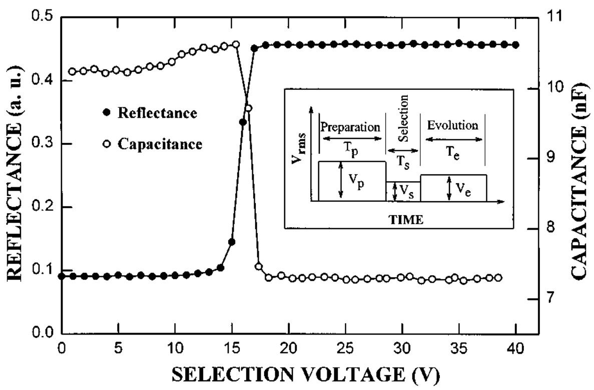

FIG. 4. The effect of the selection voltage in the dynamic drive scheme. The driving parameters are: V_p=60 V, T_p=60 ms, V_e=29 V, T_e=60 ms, and T_s=1 ms. The inset is the voltage sequence of the three-phase dynamic drive scheme.

age sequence. The results are independent of the initial state of the display (prior to the voltage sequence). The state with high capacitance but low reflectance is the *F* state while the state with low capacitance but high reflectance is the *P* state. High contrast ratio can be achieved by using an off-voltage lower than 12 V for selecting the *F* state and an on-voltage higher than 18 V for selecting the *P* state.

In this drive scheme, two different voltage levels are used over the 1.0 ms long selection phase to determine the final states of the pixels. Only one voltage level is used in the preparation phase and one in the evolution phase; therefore, a pipeline algorithm can be constructed for addressing a passive matrix display. In this algorithm, multiple lines are selected simultaneously for the preparation phase and the evolution phase. Good results can be achieved by using 60 ms for both the preparation and the evolution phase, and 1 ms for the selection phase. Therefore, up to 60 lines can be selected simultaneously in both the preparation phase and the evolution phase. The frame time for a *n*-line bistable reflective cholesteric display is $T_{\text{frame}}=T_p+nT_s+T_e$. The most recent data show that the selection time T_s can be as short as 0.5 ms, which implies the frame time for a 1000-line display is 620 ms. A prototype driving apparatus has been built and tested on 320×320 pixel displays.[9] Images with excellent contrast ratio are successfully generated at the frame time of 280 ms.

This research is supported in part by NSF under ALCOM Grant No. DMR89-20147 and by ARPA under Contract No. N61331-94-K-0042.

[1] G. A. Dir *et al.*, Proc. SID **13**, 106 (1972).
[2] W. Greubel, U. Wolff, and H. Kruger, Mol. Cryst. Liq. Cryst. **24**, 103 (1973).
[3] D.-K. Yang and J. W. Doane, SID'92 Tech. Digest **XXIII**, 759 (1992).
[4] D.-K. Yang, J. L. West, L. C. Chien, and J. W. Doane, J. Appl. Phys. **76**, 1331 (1994).
[5] X.-Y. Huang and D.-K. Yang, Digest of ALCOM Symposium on Stabilized and Modified Liquid Crystals, 1994 (unpublished), p. 122.
[6] D.-K. Yang and P. Palffy-Muhoray (unpublished).
[7] D.-K. Yang and Z.-J. Lu, SID'95 Tech. Digest **XXVI**, 351 (1995).
[8] Z.-J. Lu, W. D. St. John, X.-Y. Huang, D.-K. Yang, and J. W. Doane, SID'95 Tech. Digest **XXVI**, 172 (1995).
[9] X.-Y. Huang, D.-K. Yang, P. J. Bos, and J. W. Doane, SID'95 Tech. Digest **XXVI**, 347 (1995).