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Design Optimized Bistable Twisted Nematic Liquid Crystal Display

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The difference between the equilibrium and switching d/p ratio of a bistable twisted nematic (BTN) liquid crystal display is shown by computer simulation. It is clearly indicated that the optimized d/p ratio has to be determined by the switching rather than equilibrium d/p ratio. It is also shown that the switching d/p ratio is related not only to the pre-tilt angle, but also to liquid crystal viscosities, which indirectly indicates how temperature will affect the BTN device, and that there exists an optimized delay time for the device-driving waveform which will narrow the selection pulse and increase the matrix driving scanning speed. Further, the trade-off between the width of the waveform selection pulse and cell thickness tolerance is considered. By applying the determined optimized conditions and using the multidimensional alignment method, a long-term bistable BTN effect can be demonstrated. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1379347]

I. INTRODUCTION

The bistable twisted nematic liquid crystal display (BTN-LCD) has become increasingly attractive, since Berreman and Heffner first showed that it could be switched between two topologically equivalent twist states by specially shaped electrical pulses.[1] The BTN-LCD exhibits optical bistability, fast response time, high contrast ratio and wide viewing angle.

The BTN device is based on a gross mismatch of the natural twist of the liquid crystal director and the boundary conditions of the two liquid crystal cell imposed by rubbing surfaces. The rubbing direction and ratio of the cell thickness to the intrinsic pitch (d/p) are two critical parameters. For antiparallel rubbing, the director field can have an equilibrium twist state which is an integer multiple of π. Figure 1 shows in the equilibrium state, if the pre-tilt angle is 0°, the disclination line in the wedge cell at the interface between the 0 and π twist states (position A) and π and 2π twist states (position B) appear at d/p of 0.25 and 0.75, respectively. The lowest elastic energy of the 0, π and 2π twist state appears at d/p ratios of 0, 0.5, and 1. The elastic energy distribution in the wedge cell is shown in Fig. 2.

Among the three twist states, the 0 and 2π states are topologically equivalent and can be continuously transformed from one to the other without a disclination appearing. However, because the boundary conditions impose an inherent splay in the π state, neither the 0 nor 2π states are topologically equivalent to it. The transition between these states can only occur through the nucleation of a defect and the subsequent motion of a disclination line.[2]

The basic operating principle of a 0–2π bistable device is to eliminate the π twist state either temporarily or permanently, and take advantage of the short switching time required for two topologically equivalent twist states to be transformed from one to the other. Special waveforms are used to switch the device to the desired state. Figure 3 shows

the typical BTN driving waveform for selection of 0 and 2π states, where t_r, t_d, and t_s are the width of reset pulse, delay time, and selection pulse, respectively. When waveform (a) was applied to the wedge cell, the π twist state was temporarily removed, and the wall between 0 and 2π twist states formed at position C. When waveform (b) was applied to the wedge cell, the wall between 0 and 2π twist state formed at position D. Therefore, if a d/p ratio between C and D (d/p switching window $\overline{CD}$) is chosen and the waveforms above are applied, the devices can be switched between 0 and 2π state. In Figs. 3(a) and 3(b), the waveform contains a large amplitude of reset pulse which will align the liquid crystal directors to homeotropic state and removes the splayed π state. The amplitude of the selection pulse determines the strength of the flow effect, which will ultimately determine the director twist state. Unfortunately, Fig. 2 indicates that the lowest energy state in the d/p switching window is the π twist state. The unwanted π twist state will grow through the nucleation process, which can start from dust particles or from substrate defects, and erase the former display information. The multidimensional alignment structure had been used to prevent the nucleation of the π twist state to achieve long-term bistability.[3,4]

II. OPTIMIZATIONS BY COMPUTER SIMULATION

There are several articles studied on optical optimization for transmittive[5,6] and reflective[7,8] BTN displays, optimization of panel parameters and driving waveforms.[9,10] In this article, optimized BTN device parameters were obtained by computer simulation with commercially available software {Dr. Dwight W. Berreman [electronic mail: dwberreman @alo.com and phone: (732) 701-1325]} that includes the effect of backflow.

A. Switching *d/p* ratio versus equilibrium *d/p* ratio

From Fig. 2 we noticed that when a BTN device is in the equilibrium energy state, there exists an optimized d/p ratio, which equals 0.5. In this case, the 0 and 2π twist state have

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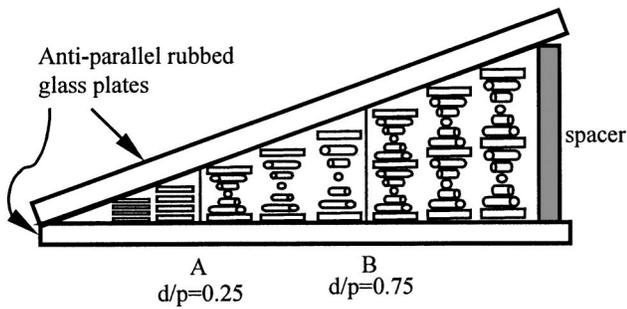[a)]Electronic mail: pbos@kent.edu

FIG. 1. Side view of liquid crystal twist states in a wedge cell.

the same elastic energy, and the device will be stable at both states. Here the d/p ratio for the equal energy point is called the equilibrium d/p ratio. Berreman was the first one to point out that the BTN device works under a certain optimum d/p ratio considerably above the intersection of the energy curves of 0 and 2π states,[1] but the effect of cell pre-tilt angle and liquid crystal viscosity was not considered. In experiments we did find if the equilibrium d/p ratio was chosen, the device will not be switched from the 0 to 2π twist state. To investigate the liquid crystal director switching behavior, the parameters of liquid crystal ZLI-4792 were used for the simulation. The viscosity parameters are: $\gamma 1 = 0.092$, $\eta 1 = 1/2(-\alpha_2 + \alpha_4 + \alpha_5) = 0.103$ Pa s, $\eta 2 = 1/2(\alpha_3 + \alpha_4 + \alpha_6) = 0.0115$ Pa s, $\eta 3 = 1/2\alpha_4 = 0.035$, $\eta 12 = \alpha_1 = 0$, where $\gamma 1 \alpha_1$, α_2, α_3, α_4, α_5, α_6 were obtained from Ref. 11. In order to get the minimum value of switchable d/p ratio, here which is called switching d/p ratio, only reset pulse was applied. It is found by the simulation that if using the equilibrium d/p ratio, the device cannot be switched between 0 and 2π, which agreed with the experimental results. Figure 4 shows when the device pre-tilt angle is $5°$, the minimum switching d/p ratio should be 0.589, but the calculated corresponding equilibrium d/p ratio is about 0.502. It clearly indicates that the equilibrium d/p ratio cannot be used for design BTN device, the optimized d/p ratio must be determined by the device switching d/p ratio.

Figure 5 shows the differences between switching and equilibrium d/p ratio with respect to different pre-tilt angles. The dots show the minimum value of d/p that will allow a
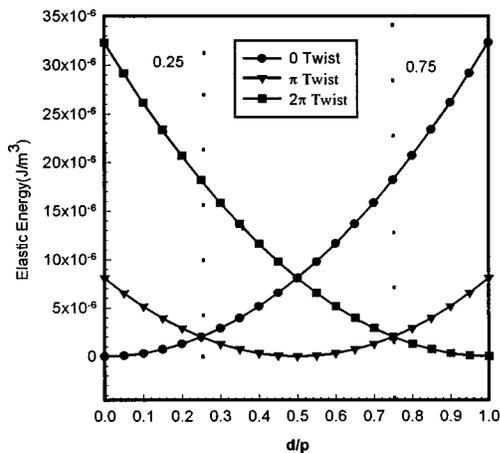

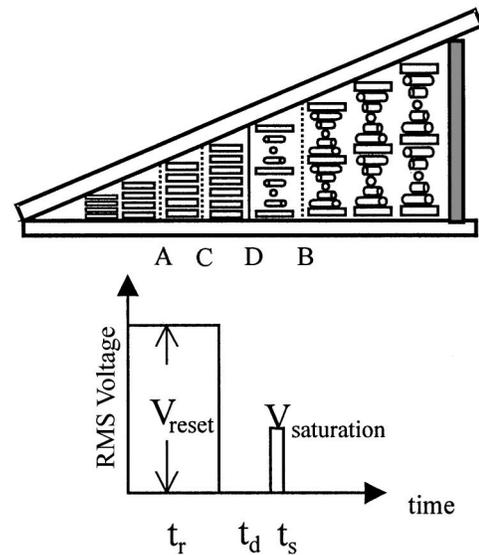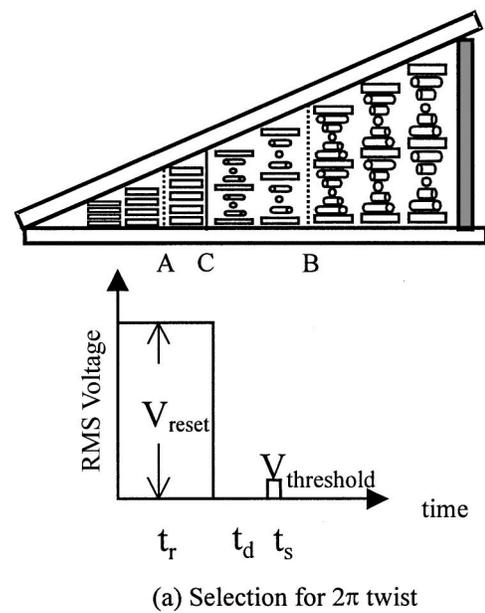FIG. 2. Energy distribution for liquid crystal ZLI-4792 at $0°$ pre-tilt angle.

(a) Selection for 2π twist

FIG. 3. Addressing waveform applied to the wedge cell.

switch to the 2π state, while the triangles show the d/p value where the 0 and 2π states are of equal energy with zero volts applied. The simulation results also indicate that the difference between equilibrium and switching d/p ratio has the tendency to increase as the pre-tilt angle increases. A wedge cell was built, and the addressing waveform, which only has reset pulse, was applied, and experimental results showed the minimum switching d/p is about 0.6, which agreed with the simulation results.

Modeling software (see first paragraph of Sec. II) was also employed to simulate how the switching d/p ratio changes with different liquid crystal viscosities. In the simulation, the rotational viscosity $\gamma 1$ is increased from 0.092 to 0.12 and 0.22 Pa s, and scaled to increase all other parameters of viscosity in the same factor according to the increasing factor of the $\gamma 1$ (because the other viscosities are not available). The simulation results shown in Fig. 6 indicate that when the liquid crystal viscosity increases, the switching d/p ratio tends to decrease. It also indirectly tells how the
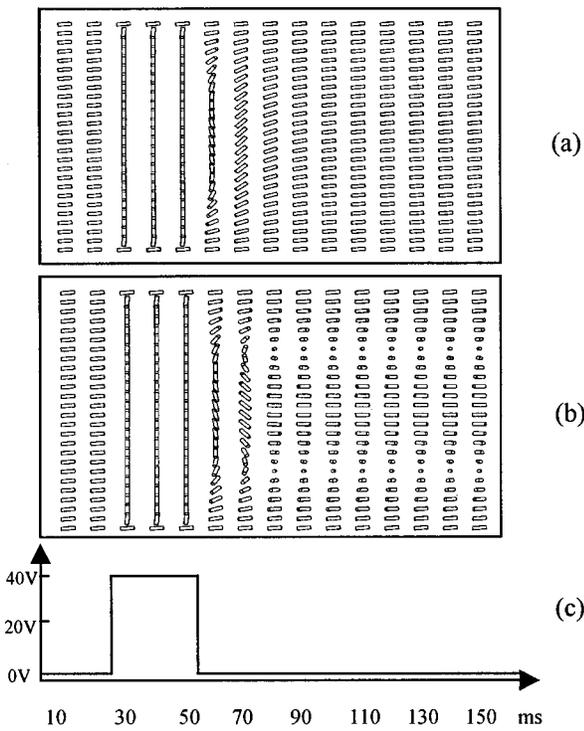
FIG. 4. Switching d/p ratio obtained by Berreman modeling software (a) $d/p=0.585$, $\theta_{\text{pret}}=5°$, (b) $d/p=0.589$, $\theta_{\text{pret}}=5°$, (c) addressing waveform with only reset pulse.
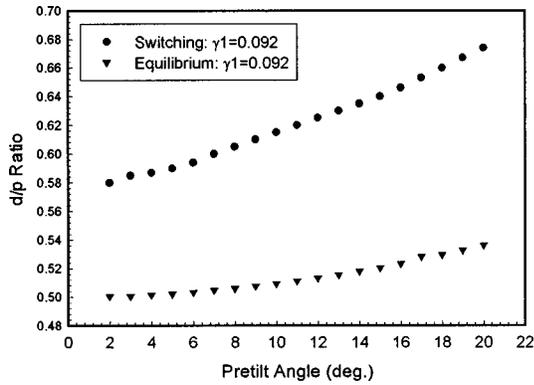

FIG. 5. The difference between switching and equilibrium d/p ratio with respect to pre-tilt angle.
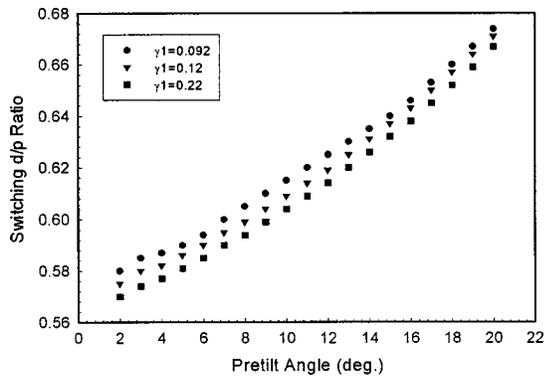

FIG. 6. The switching d/p ratio with different liquid crystal viscosities.
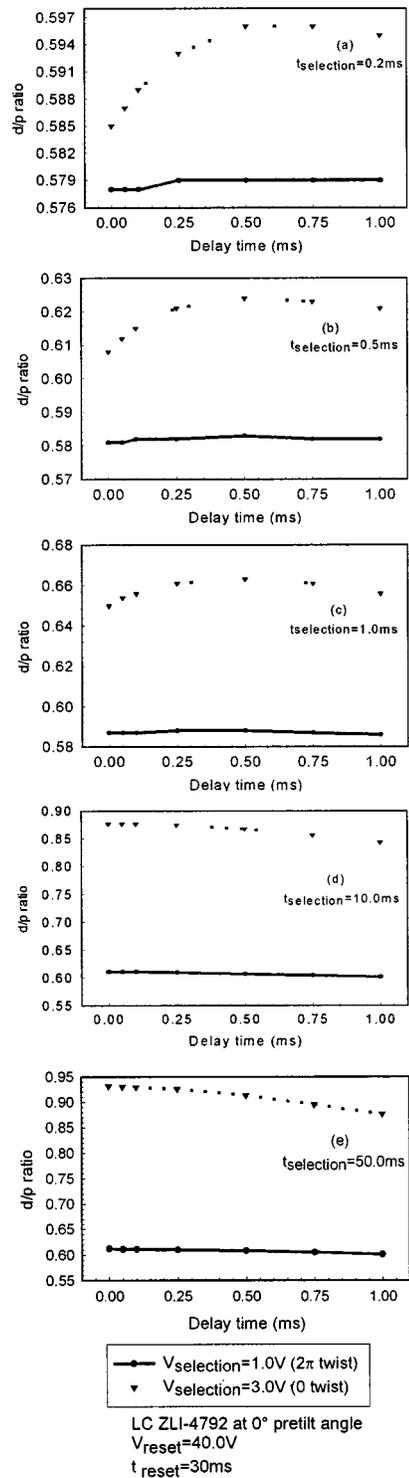

FIG. 7. Dependence of waveform delay time and width of selection pulse.

switching d/p will change with temperature. Usually as temperature increases, all liquid crystal viscosities will decrease, corresponding to the switching d/p ratio increase; as temperature decreases, all the liquid crystal viscosities will increase, corresponding to the switching d/p ratio decrease.

B. Optimizing waveform delay time

The optimized waveform should contain a relatively low reset pulse and narrow selection pulse. One of the ways
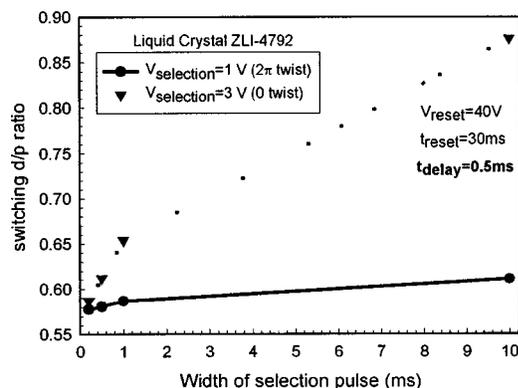
FIG. 8. The d/p switching window width of selection pulse.

to obtain the lower reset pulse is to choose a larger $\Delta\epsilon$ liquid crystal material,[3] proper choice of the waveform delay time t_d can reduce the width of the selection pulse.[7] Modeling software (first paragraph of Sec. II) was used to simulate the waveform delay time effect and to investigate the dependency of the delay time and width of the selection pulse. Figure 7 shows how the switching d/p window changes when the waveform delay time and the width of selection pulse changes. It indicates that when the width of selection pulse is within a certain range, there exists an optimized delay time for a wider d/p switching window, and it is independent of the width of the selection pulse. In Figs. 7(a), 7(b), and 7(c), when the delay time $t_d = 0.5$ ms, they all have a maximum d/p switching window in spite of different selection time. But when the width of selection pulse exceeds a certain value, as in Figs. 7(d) and 7(e), a delay time $t_d = 0.0$ ms yields a wider switching window. Because our ultimate goal is to obtain a narrow selection pulse and to increase the addressing speed, it is necessary to find an optimized nonzero delay time for narrower selection pulse.

C. Optimizing switching *d/p* ratio

The optimized switching d/p should yield a BTN device with a good contrast ratio and fast scanning speed. In other words, we need to first optimize the device optical property by choosing a proper Δnd value[2–5] and then adding a proper amount of chiral material to yield an optimized pitch, which yields optimized d/p ratio, to obtain a fast scanning speed.

From scanning speed point of view, the width of the selection pulse of the waveform plays a very important role. The narrower the selection pulse is, the faster the scanning

speed will be. Figure 8 shows the simulated d/p switching window with respect to the width of the selection pulse. The triangle-dotted line curve (top) corresponds to position D of the wedge cell shown in Fig. 3(b), the circle-solid line curve (bottom) corresponds to position C of the wedge cell shown in Fig. 3(a). The results indicate that when the selection pulse is wider, the d/p switching window will be wider, which means a larger tolerance of the cell spacing requirement. So from a manufacturing point of view, there exists a trade-off between scanning speed and cell spacing tolerance. Therefore the optimized switching d/p ratio should be chosen near the left end side of the d/p switching window $\overline{CD}$ in Fig. 3, which is a bit greater than the d/p ratio of position C; then the device only needs narrow d/p switching or narrow selection pulse to work at both 0 and 2π twist states.

III. CONCLUSIONS

In summary, by using modeling software (see Sec. II), several useful parameters can be obtained for designing the optimized BTN liquid crystal display device. The differences between the equilibrium and switching d/p ratio were first systematically studied by computer simulation. There exists an optimized d/p ratio, which must be determined by the switching rather than equilibrium d/p ratio, and a trade-off between the device addressing speed and the tolerance of manufacturing the cell gap. An optimized delay time of the addressing waveform will increase the d/p switching window, which means it could either lower the tolerance of the cell spacing or increase the device addressing speed.

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