Truly bistable twisted nematic liquid crystal display using photoalignment technology

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Truly bistable twisted nematic liquid crystal display has been fabricated using photoalignment. This display can be switched between the $-22.5°$ and $157.5°$ twist states by breaking the anchoring condition on one of the substrates. The application of a photoalignable polymer SDA-1 was able to achieve the weak anchoring energy necessary for switching. Both theoretical and experimental results show that this mode has excellent contrast ratio and wide viewing angles. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1630159]

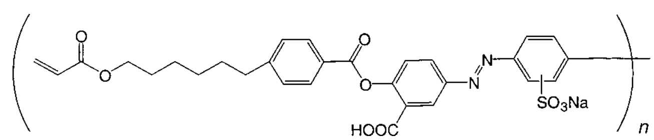
Bistable twisted nematic (BTN) liquid crystal displays (LCDs) traditionally have bistable twisted states that differ in twist angle by 2π.[1,2] The bistable twist states are ϕ and $\phi+2\pi$, where ϕ can be varied to optimize the optical properties of the BTN displays.[3] These BTN displays can be called 2π-BTN. Unfortunately, the ϕ and $\phi+2\pi$ states are metastable as there is an intermediate twist state of $\phi+\pi$ that is more stable. So, the 2π-BTN has not been useful. Recently, Dozov *et al.*[4,5] demonstrated 0 and π twist states switching by a combination of strong and weak surface anchoring. This type of BTN can be called π-BTN, and is truly bistable since there is no stable intermediate twist state which is more stable.

The Dozov π-BTN is more difficult to make than the regular 2π-BTN. Asymmetric anchoring is necessary for switching. Special alignment layers, such as SiO_x evaporation, have to be used. We have recently demonstrated a π-BTN using a three-electrode structure.[6] An in-plane electric field can be used to switch the π-BTN with ordinary surface alignment treatment. Moreover, we generalized the π-BTN to the case of ϕ and $\phi+\pi$ bistability, where ϕ can be used to optimize the optical properties of the π-BTN.[6] In this letter, we report the fabrication of transmittive π-BTN LCD using a photoalignable polymer. We also investigate the fabrication tolerance of such π-BTN. It will be shown that the cell gap is the most important factor in obtaining bistability.

The bistability of π-BTN is based on asymmetric anchoring of the liquid crystal (LC) cell. One side of the cell has to be strongly anchored while the other side has to be weakly anchored. However, the anchoring energy cannot be too small, otherwise there will be no alignment and no stable twist states at all. The strong anchoring surface is achieved by the usual rubbed polyimide (PI) layer. Such a PI layer provides a strong polar anchoring energy of 1.5×10^{-3} J/m^2 and a pretilt angle of 5°.[7]

Recently, Skarp *et al.*[8] reported the use of photoaligned layer to achieve weak anchoring. We have also experimented with many alignment layers in order to achieve asymmetric anchoring. Certainly, photoalignment is one way of achieving this asymmetric anchoring. However, it was found that the anchoring energy of the photoalignment layer is very important in making the π-BTN.

A polymer, SDA-1, has been developed.[9,10] Its formula is shown below.



We found that the anchoring energy of this polymer can be adjusted from a high value of 8.5×10^{-4} J/m^2 to smaller values by changing the exposure time. By carefully adjusting the exposure time, we achieved an anchoring energy of 4.5×10^{-4} J/m^2, which was suitable for obtaining π-BTN bistability. The pretilt angle was also about 5°. All of the polar anchoring energies were measured using a method we recently developed.[7]

The LC used for fabricating the π-BTN LCD was ZLI5700-100 with a birefringence Δn of 0.1581. For fabricating the demonstration cell, we chose the mode with $d\Delta n$ of 0.266 μm and $\phi=-22.5°$.[6] The cell thickness was therefore 1.5 μm. The ideal d/p ratio, from a heuristic point of view, should be given by

$$\frac{d}{p}=\frac{-22.5°+90°}{360°}=0.1875. \tag{1}$$

However, as the high twist state usually has a higher elastic energy, the LC has to be doped in a way that the high twist state is more favored (larger d/p) to balance the elastic energy of the two twist states. Therefore, the d/p ratio was adjusted to be about 0.3 in order to achieve bistability.

Figure 1 shows the bistable switching of one of the samples. It can be seen that both the on and off states show true stability with no decay of transmittance for a long time. We have checked that the bistability lasts for more than several days. Switching is effected in the same manner as in a conventional 2π-BTN. The driving electrical pulse consists of a reset pulse followed by a selection pulse. The amplitude of the selection pulse determines the final twist state of the device, according to the backflow dynamics.[5] The reset and

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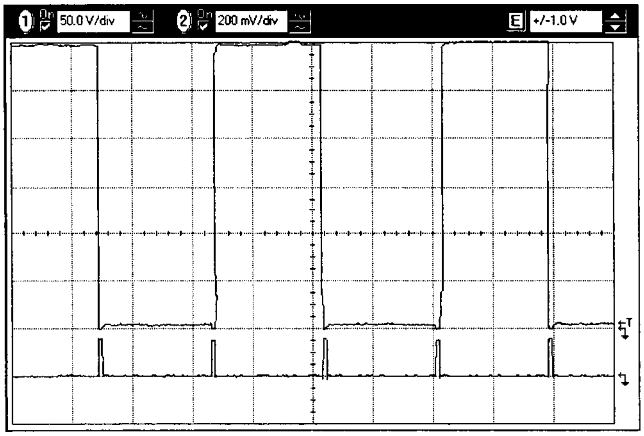

FIG. 1. Switching behavior of the π-BTN. Top: Optical response; Bottom: Switching pulse train.

selection pulses are both 0.2 ms in Fig. 1. Switching can be achieved with pulses as short as 0.1 ms. The measured contrast ratio from Fig. 1 is about 80. The switching time of the twist states is about 1 ms. It is very fast and is a direct result of the small cell gap used.

Figure 2 shows the measured as well as the simulated transmission spectra of the on and off states. It can be seen that the agreement is generally good except that the measured spectra have lower transmission. This is probably because of the use of imperfect polarizers. There are also interference fringes in the measured spectrum, which is evidently due to finite reflection of the indium tin oxide glass.

We also measured the bistable behavior as a function of the driving pulse duration. The results are shown in Fig. 3. Obviously, as the duration is reduced, the voltage required should increase due to a requirement on the tilting of the boundary LC layer at the weak anchoring side and sufficient backflow effect. However, this dependence is not straightly inversely proportional. Actually, for a pulse duration longer than 0.22 ms, there is not a great dependence of the voltage as the duration is further increased. The required reset voltage remains at 35 V. Thus, there is a minimum voltage requirement for this π-BTN. This can be understood physically since there is a minimum voltage required for the weakly anchored LC molecules to break its anchoring, i.e., for the tilt angle at the boundary to increase to a sufficiently large value. We performed such a simulation with the weak anchoring condition taken into account. In most LCD simula-

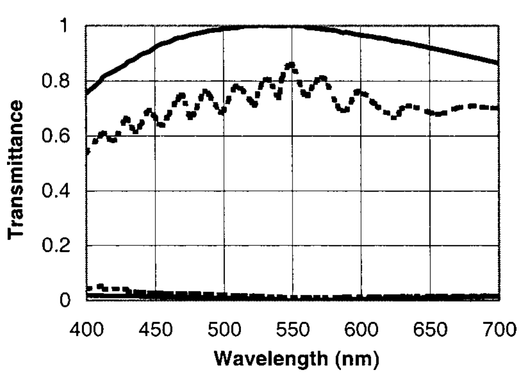

FIG. 2. Transmission spectra of the two stable twist states. Solid lines: Theory; dotted lines: Experimental data.

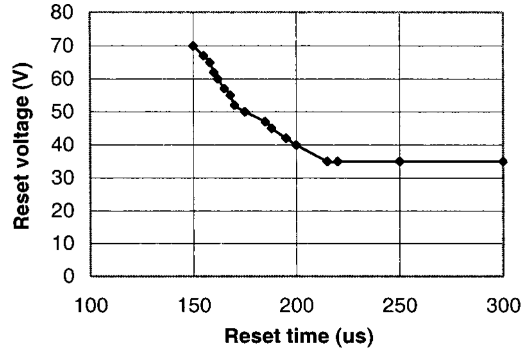

FIG. 3. Dependence of reset pulse voltage on reset pulse duration.

tions, the boundary condition is taken as $\theta(0)=\alpha$ and $\theta(d)=\beta$, where α and β are constants. However, it is well known that if the anchoring energy is finite, the boundary condition is dependent on the solution $\theta(z)$ itself and is obtained by solving the nonlinear equations;

$$\left(\frac{\partial f}{\partial \dot{\theta}} - \frac{\partial f_s}{\partial \theta}\right)_{z=0} = 0, \tag{2}$$

and

$$\left(\frac{\partial f}{\partial \dot{\theta}} + \frac{\partial f_s}{\partial \theta}\right)_{z=d} = 0, \tag{3}$$

where f is the elastic energy density and f_s is the surface anchoring energy per unit area for the LC. This is a self-consistent condition. Figure 4 shows the results of this calculation. The three curves represent θ at the middle of the cell, and at the LC cell surfaces. It can be seen that at the middle of the LC cell, the tilt angle approaches 90° very rapidly at 3 to 4 V. At the weaker anchoring side, the tilt angle increases steadily as the voltage is increased. It is $>50°$ at 10 V. At the stronger anchoring side, the tilt angle also increases slightly. Incidentally, Fig. 4 indicates that the boundary condition of a fixed pretilt angle is never correct for a realistic LCD. The tilt angle on the surface, even with rubbed PI, always increases as the LC is deformed. The pretilt angle is unchanged only if the anchoring energy is infinite.

From Fig. 4, it can be seen that the anchoring on the weak photoalignment side is completely broken at a voltage

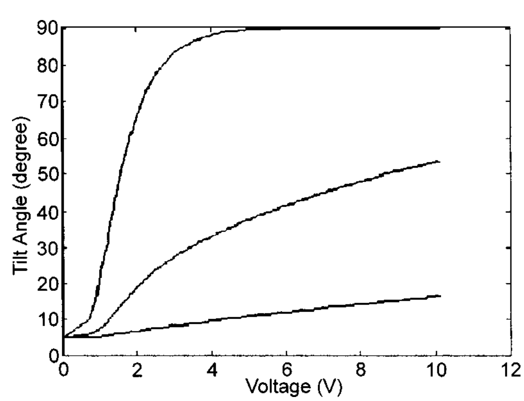

FIG. 4. Calculated dependence of LC tilt angle θ on the applied voltage for the LC cell used in the experiment. From the top: θ at middle of the cell, θ at weak anchoring side, and θ at strong anchoring side.

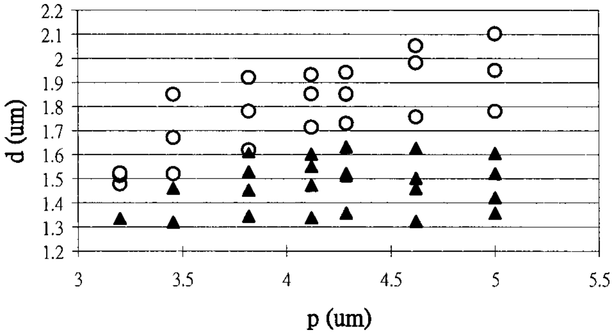

FIG. 5. d, p for stable switching; circles: No switching; triangles: Bistable switching.

of higher than 20 V. After this reset condition, the LC alignment can relax to either of the twist states depending on the dynamics. From Ref. 11, it follows that, depending on the backflow direction, the ϕ or the $\phi+\pi$ twist state can be obtained.

We prepared many samples and examined their bistable switching behavior. In particular, the d/p ratio for achieving bistable behavior was studied. Figure 5 summarizes the results. It was found that in order to achieve bistability, the d/p ratio is not the only consideration. Actually, the absolute cell thickness is the more important factor. It can be seen that the cell gap has to be below 1.6 μm, regardless of the value of p. Again, this is understandable from the point of view of a minimum voltage required to increase the tilt angle at the weak anchoring side to near 90° for switching. For a large cell gap, a large electric field or very high voltage is required in order to achieve anchoring breaking. Thus, there is a maximum value required for the cell gap.

In summary, we have demonstrated that the photoalignment material SDA-1 is useful in obtaining bistable switching in a π-BTN. We have studied the switching behavior of this permanently bistable π-BTN. This display has optimized optical properties and can be switched at a relatively low voltage of 35 V with a pulse width of less than 0.25 ms.

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