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# Bistable bend-splay liquid crystal display

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A bistable liquid crystal display based on the bend and splay configurations has been demonstrated. This display can be switched between the bend and splay deformation in a three-electrode configuration and has infinite bistable lifetime. It also has wide viewing angles, excellent contrast ratios, and very fast selection. Selection electric pulse duration of 50 $\mu$s can be used to switch this display, implying the possibility of a high information content applications. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1810215]

Liquid crystal displays (LCD) that exhibit two stable states under zero voltage bias are desirable for many practical applications. Such displays can be used in e-books as well as other low-power or even no-power devices. Additionally, bistable displays can be addressed using simple passive matrix multiplexing schemes without any cross-talk problems. Thus they are attractive alternatives for making low cost high resolution displays without active matrix addressing. Several bistable display technologies have been pursued, including bistable cholesteric display,[1,2] bistable twisted nematic display (BTN),[3–5] and ferroelectric liquid crystal displays.[6] For the BTN, there are several variants with a $\pi$ or $2\pi$ twist angle difference between the two stable states. The zenithal bistable display (ZBD) is interesting in that the surface anchoring condition can give rise to either a homeotropic or homogeneous alignment.[7] Another bistable display that relies on surface anchoring switching has also been demonstrated.[8] Each technology has its own merits and difficulties. All are being pursued actively at present.

Another interesting bistable liquid crystal display device based on bend and splay configurations was first developed by Boyd *et al.* in 1980.[9] It was shown that the bend and splay alignments could be bistable under some special alignment conditions. But in that device, both the top and bottom electrodes were interdigital. Special surface alignment patterns with alternative tilt (AT) structures were needed. The optical difference between the bend and splay states had to be achieved by the use of pleochroic dye dopants, so the display was colored and its optical contrast was poor. As well, the switching voltage was extremely high (~70 V) and the switching time was long (81 ms). Practical devices were not pursued due to these drawbacks.

In this letter, we shall present a bistable bend–splay display (BBS). Such bistable display device can show good black–white contrast without using any pleochroic dyes. Also the switching voltage can be as low as 10 V and the switching time can be as short as 50 $\mu$s. This display can therefore be driven by conventional driver electronics. The switching is achieved by a combination of horizontal and vertical electric fields where the horizontal electric fields are produced using only one set of interdigital electrodes. The alignment direction of liquid crystal molecules is also controlled to be perpendicular or parallel to the interdigital electrodes, so that no AT structures are needed and fast optical responses can be achieved. The BBS presented in this letter was demonstrated using a SiO$_x$ alignment layer.

For a parallel-aligned LC cell, the configuration will show bend and splay bistability when they have the same elastic deformation energy. As is well known, the elastic energy per unit wall area of a no-twist LC is given by

$$E = \frac{1}{2}\int_0^d (K_{11}\cos^2\theta + K_{33}\sin^2\theta)\dot{\theta}^2 dz, \qquad (1)$$

where $K_{11}$ and $K_{33}$ are the splay and bend elastic constants, respectively. $\theta$ is the tilt angle which is a function of distance $z$ inside the cell.

Under the condition that $\theta(z)$ is a nearly linear distribution (it is true for most LC materials), if the splay and bend cells have the same elastic energy and the pretilt angles on both sides of the cell are the same, then the following equation can be derived:

$$(K_{33} - K_{11})\sin 2\alpha + (\pi - 4\alpha)(K_{33} + K_{11}) = 0, \qquad (2)$$

where $\alpha$ is the pretilt angle.

By solving this equation, the condition for the pretilt angle such that the splay and bend deformation energies are the same can be obtained. For example, for MBBA, $K_{33}/K_{11}=1.3$. Hence $\alpha$ is about 47°. In general it can be shown that $\alpha$ is always between 45° and 58° for all values of $K_{33}/K_{11}$. Under the condition that Eq. (2) is satisfied, bistability can be obtained. Actually bistability can be achieved even if the deformation energies for the bend and splay cells are slightly different. There is actually another possible configuration for the parallel-alignment condition. It is a $\pi$-twist cell. It can be proved that this $\pi$-twist state has a much higher total elastic energy than both bend and splay state and thus can be ignored.[10] However, if sufficient chiral dopants are added, then the $\pi$-twist state and the splay state will be bistable. In this case, this is just the $\pi$-BTN.[3] In this letter, the LC is not doped.

The large pretilt angle that is required for bend–splay bistability can be obtained in one of several ways. It has been reported that both photoalignment[11,12] and normal polyimide rubbing[13,14] can be used to produce pretilt angles from 0 to 90°. Another method that can produce strong anchoring at large pretilt angles is by means of SiO$_x$ evaporation.[15,16] The latter method is more controllable and is adopted in this study. For depositing the SiO$_x$ alignment layer, the glass

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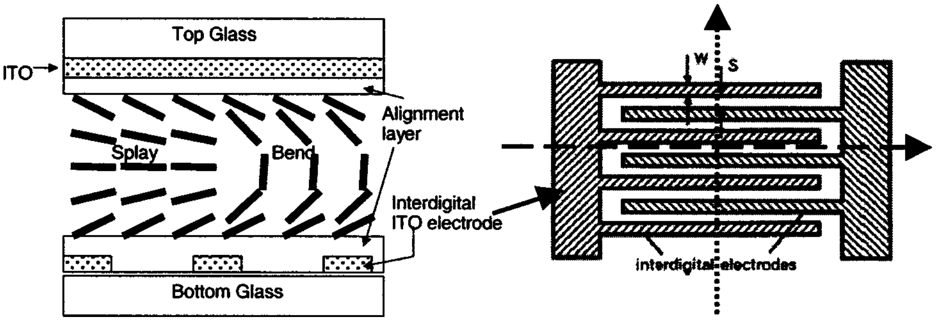

FIG. 1. The basic BBS cell structure.

plate with ITO electrodes was coated by oblique $SiO_x$ evaporation at an evaporation angle of 85°. The thickness of the $SiO_x$ layer was 60–150 nm. Under this condition, the pretilt angle was around 45° as measured by the traditional crystal rotation method. The experimental data reported here are all based on such $SiO_x$ alignment layers.

The basic cell structure of the BBS display is shown in Fig. 1. It was essentially a three-terminal device consisting of the top common electrode and the interdigital bottom electrodes. The bottom interdigital electrodes were made of ITO with 4-$\mu$m-wide fingers at a spacing of 6 $\mu$m. Thus the pitch was 10 $\mu$m. The cell gap was 3.2 $\mu$m and Merck liquid crystal ZLI5700/7500-000 was used in our experiment. The LC alignment direction can be either parallel or perpendicular to the bottom interdigital electrodes, as shown in Fig. 1. The performance for these two different alignments can be quite different.

Optically, the BBS cell behaves as a typical electrically controlled birefringent display. The two bistable states have different birefringence. The bend state, with a smaller birefringence, is chosen as the dark state. The transmission is given by

$$T=\cos^2(\alpha-\gamma)-\sin 2\alpha \sin 2\gamma \sin^2 \delta, \tag{3}$$

where $\alpha$ and $\gamma$ are the polarizer and analyzer angles; $\delta$ is the phase retardation of LC cell given by

$$\delta=\frac{\pi}{\lambda}\int_0^d (n_e(\theta)-n_o)dz. \tag{4}$$

By simulation, it is shown that the optimal contrast and brightness can be obtained with a $d\Delta n$ value of 0.31 $\mu$m and $\alpha$ and $\gamma=\pm 45°$ to the alignment direction of the liquid crystal.

The driving method is shown in Fig. 2. The top electrode is biased at a common voltage $V_c$. Electrical pulses are applied to the interdigital electrodes. The opposing digits are given voltages of $V_1$ and $V_2$, respectively. The combination of $V_1$, $V_2$ and $V_c$ can produce either a vertical or horizontal electric field on the liquid crystal molecules. In the simplest case, $V_c$ is kept constant at ground. Two electrical pulse trains $V_1$ and $V_2$ are applied to the bottom electrodes. When $V_1$ and $V_2$ are the same, the electric field inside the liquid crystal cell is in the vertical direction. This results in a homeotropic alignment of the LC molecules. When these electric fields are released, the LC molecules near the top and bottom alignment layers will re-align and introduce a surface flow in the same direction. Then the liquid crystal alignment will favor the bend state. The switching behavior of the LC molecules in this case is independent of the alignment directions.

When $V_1$ is opposite in sign to $V_2$, a nonuniform horizontal electric field is introduced inside the liquid crystal cell. This nonuniform transverse field will introduce an elastic stress. The switching behavior of the LC molecules in this case will depend on the alignment direction on the substrate surfaces. For an alignment direction perpendicular to the bottom interdigital electrodes, the movement of the LC is almost in the original LC alignment plane when $V_1$ and $V_2$ are on. The field-induced elastic stresses are bend and splay stresses. Conversely, if the alignment direction is parallel to the bottom interdigital electrodes, the LC molecules will rotate 90° first when $V_1$ and $V_2$ are on. The field-induced elastic stresses are mainly twist elastic stress. These field-induced elastic stresses are released by disclination lines. With the propagation of the disclination faults, the final splay state will be formed. If the LC is reasonably doped, the erase of the twist stress will give faster switching. For a passive matrix driving, $V_c$ will also participate in the driving process and can act as the addressing electrode.

In our first experiment, rectangular pulses of voltage $U(=|V_1|=|V_2|)$ and duration $\tau$ are applied. The bend–splay switching results are shown in Fig. 3. Here, $U=27$ V and $\tau=1$ ms. It can be seen that the transmission of the BBS cell

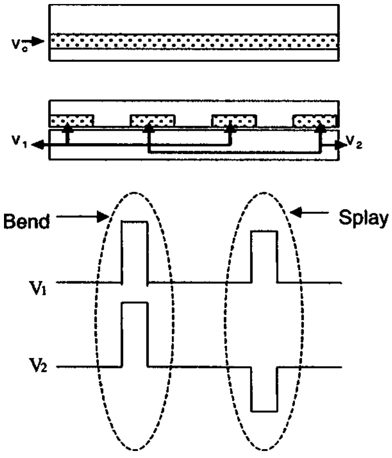

FIG. 2. The voltage driving scheme.

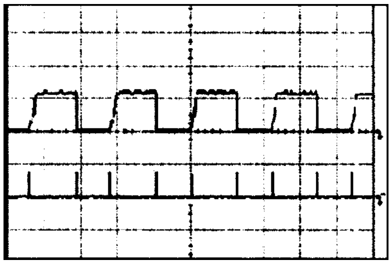

FIG. 3. Switching behavior of the BBS display.

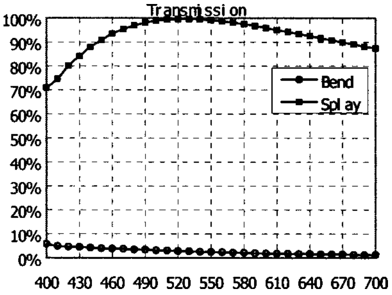

FIG. 4. Transmission spectra of the splay and bend states.

can be switched back and forth between the bend and splay states. Figure 4 shows the experimental transmission spectra of the splay and the bend states. It can be seen that the wavelength dispersion for this display is quite small. The dark state is quite dark, giving an experimentally measured CR of 45. Figure 5 shows one of our sample BBS displays at different viewing angles. It can be seen that the viewing angle is quite good. Also it is possible to improve the contrast further and the light transmission efficiency by adding a half-wave plate between the polarizers. From theoretical simulations, a *CR* of over 200 can be achieved with white light illumination. So optically, the BBS display has quite good performance. The optical responses are quite fast. For splay to bend switching, the typical response time is around 1ms, independent of the alignment directions. The reason for the fast switching is that there is no backflow effect at all. The response time for bend to splay switching is around 50 ms for the parallel alignment direction.

One very important parameter that measures the usefulness of a bistable display is the switching speed. (The switching pulse duration and the response time are different issues.) We varied the duration of the driving pulses $V_1$ and $V_2$, and measured the minimum voltage needed for switching to both states. Figure 6 shows the experimental results. Generally for a shorter pulse, a higher voltage is required. It can be seen that the smallest duration in our experiments that can achieve bend–splay switching is 50 $\mu$s. However, over 85 V is needed for that pulse duration. For a 1 ms switching pulse, the voltage needed is 27 V. The voltage needed for switching this 3.2 $\mu$m cell is less than 10 V for a 10 ms pulse. This is well suited for a matrix display using conventional driver electronics.

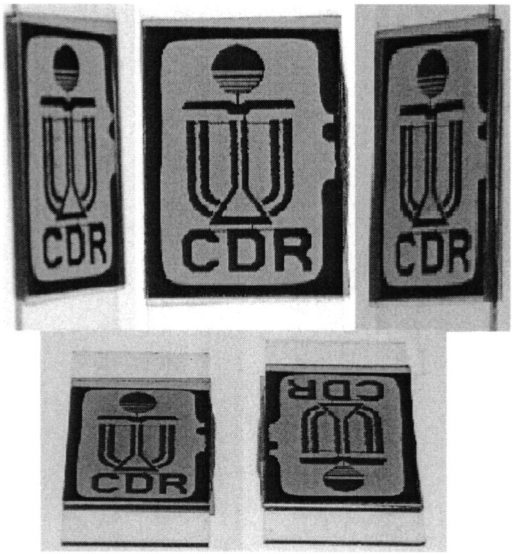

FIG. 5. A sample BBS display viewed at different angles.

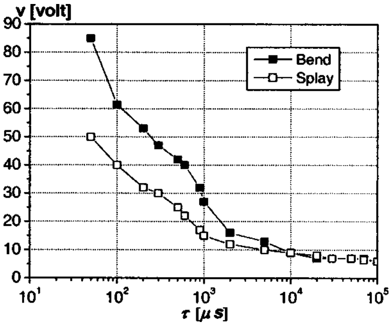

FIG. 6. The driving voltage required as a function of the duration of the selection pulses.

In summary, a bistable bend–splay display has been demonstrated. Such a display has good viewing angles, excellent contrast ratio, very fast selection, and low operating voltages than most of the other bistable displays. A selection pulse of 50 $\mu$s is possible, implying that at a frame rate of 50 Hz, 400 lines can be multiplexed with no cross talk. 4000 lines can be multiplexed if the frame rate is relaxed to 5 Hz. This is excellent for a high resolution text display. If the resolution can be reduced, the driving voltage can be reduced to a reasonable level as well.

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[1] W C Yip and H S Kwok, Jpn. J. Appl. Phys., Part 1 **40**, 4916 (2001).
[2] R. Q. Ma and D. K. Yang, J. Soc. Inf. Disp. **7**, 61 (1999).
[3] T. Z. Qian, Z. L. Xie, H. S. Kwok, and P. Sheng, Appl. Phys. Lett. **71**, 596 (1997).
[4] I. Dozov, M. Nobili, and G. Durand, Appl. Phys. Lett. **70**, 1179 (1997).
[5] B. Wang and Philip J. Bos, J. Appl. Phys. **90**, 552 (2001).
[6] V. Vorflusev, V. Kozenkov, and V. Chigrinov, Mol. Cryst. Liq. Cryst. Suppl. Ser. **263**, 2509 (1995).
[7] J. C. Jones, S. M. Beldon, and E. L. Wood, J. Soc. Inf. Disp. **11**, 269 (2003).
[8] B. Stebler, D. Demus, T. Lagerwall, and L. Komitov, U.S. Patent number 6,549,255 (2003).
[9] G. D. Boyd, J. Cheng, and P. D. T. Ngo, Appl. Phys. Lett. **36**, 556 (1980).
[10] G. Porte and J. P. Jadot, J. Phys. (Paris) **39**, 213 (1978).
[11] M. Stalder and M. Schadt, Liq. Cryst. **30**, 285 (2003).
[12] J. H. Kim, U.S. Patent No. 5,882,238 (1999).
[13] W. E. Estes, D. P. Higley, B. C. Auman, and A. E. Feiring, U.S. Patent number: 5,186,985 (1993).
[14] R. W Filas and J. S. Patel, Appl. Phys. Lett. **50**, 1426 (1987).
[15] T. Uchida, M. Ohgawara, and M. Wada, Jpn. J. Appl. Phys. **19**, 2127 (1980).
[16] H. A. van Sprang and R. G. Aartsen, Appl. Phys. Lett. **56**, 251 (1984).