Pi-cell liquid crystal displays at arbitrary pretilt angles

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(Received 26 September 2005; accepted 10 December 2005; published online 23 January 2006)

The pi-cell is studied as a function of its pretilt angle. It is shown experimentally and theoretically that the critical holding voltage decreases as the pretilt angle increases. At high pretilt angles, the critical holding voltage becomes zero and the bend cell becomes stable. The measured total response time of the pi-cell decreases with the pretilt angle as well. There is almost a factor of 2 difference between the total response time of conventional pi-cell and the no-bias bend cell. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2165284]

The pi-cell, also known as the optically compensated bend (OCB) mode liquid crystal display (LCD), is capable of fast total response times of less than 1 ms.[1–6] The pi-cell operates between the bend deformation (B state) at low voltage and the homeotropic state at high voltage. Its response time can be very fast since there is no backflow involved in its' switching.

However, the normal OCB cell is actually stable in the splay state (S state) because the pretilt angle is not high enough. Thus, an OCB display has to be converted (primed) to the B state first by applying a critical conversion voltage; then a holding voltage is needed to maintain the LCD in the B state. The transformation of a splay cell to the bend state is nontrivial. Since the S state and the B state are topologically inequivalent, nucleation has to be initiated. Many techniques have been proposed to prime the OCB cell into the B state.[7,8] For a large multiplexed display, it is quite difficult to convert the interpixel areas to the B state since there is no voltage across the liquid crystal (LC) cell in those regions. As a result, the optical performance of the LCD is degraded.

Obviously, the critical voltage needed to convert the S state to the B state depends on the pretilt angle of the LC cell. However, no systematic experimental study of this critical voltage has been reported. In this letter, we present theoretical as well as experimental results on the critical voltage needed to transform the S cell to the B cell, as a function of the pretilt angle. This study is made possible by our ability to make LC cells with arbitrary pretilt angles.

The fabrication of LC cells with any value of pretilt angle has been discussed previously. It is based on a new nanostructured alignment layer.[9,10] This alignment layer consists of a random distribution of nanoscale domains of homogeneous and vertical alignment materials that impart either vertical or horizontal alignment to the LC molecules. Due to elastic energy minimization, the LC cell will acquire a uniform tilt angle at a short distance above the alignment layer. It is noted that the process is very controllable and repeatable, once the fabrication procedures are fixed.[10]

We made a series of LC cells with various pretilt angles and measured their critical voltages. The thickness of the liquid crystal layer was 5 μm. The LC material used in the experiment was MDA-01-4679 from Merck with birefringence $\Delta n = 0.2001$, the elastic constants are $K_{11} = 14.5$ pN and $K_{33} = 15.3$ pN. The critical voltage is measured by observing the transmission spectrum of the LC cell in real time when a voltage is applied. Since the S cell and the B cell has very different effective birefringence, the transmission spectrum changes noticeably as the S to B transformation takes place. By slowly increasing the applied voltage and observing the change in the transmission spectrum, the critical voltage can be observed. It should be noted that the time needed to transform from the S state to the B state depends on the voltage applied. At the critical voltage, it takes a few minutes for the transmission spectrum to change. However, for slightly higher voltages, the transformation takes place rapidly in the matter of a few seconds or less.

Figure 1 shows the measured critical voltage as a function of the pretilt angle of the LC cell. It can be seen that at low pretilt, the critical voltage is slightly higher than 2 V. It decreases steadily as the pretilt angle is increased. A zero critical voltage occurs at a pretilt angle of 47°. This is actually the condition for the so-called no-bias bend (NBB) cell. For pretilt angles higher than this value, the stable alignment of the LC cell is a bend alignment rather than the splay alignment. This condition has been discussed in previous studies.[11,12] However, the lack of a reliable alignment layer for high pretilt angles made this NBB cell impractical. Presumably, with the new nanostructure alignment layer, this situation is changed.

The theoretical values of the critical voltage are obtained by calculating the elastic deformation energy of the LC cell

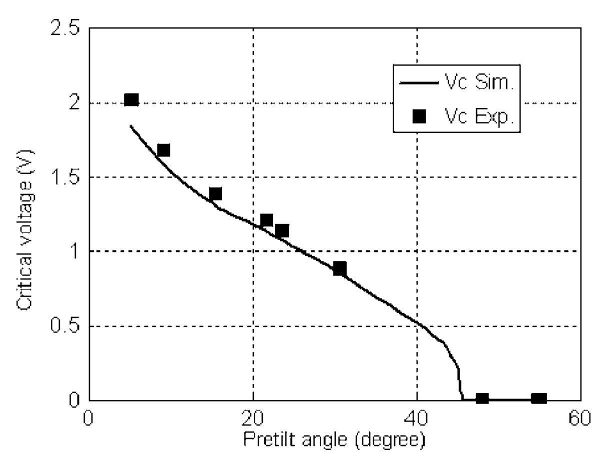

FIG. 1. Calculated and measured values of the critical holding voltage of an OCB cell.

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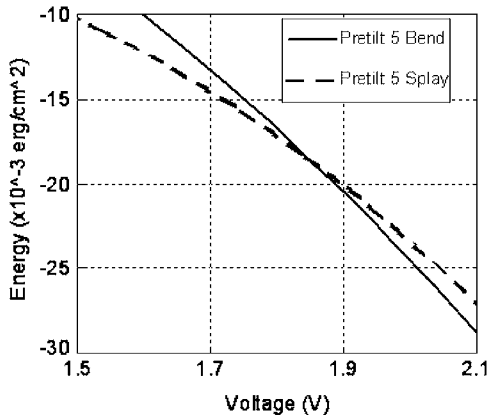

FIG. 2. Dependence of the total elastic energy of an LC cell on applied voltage. Dashed curve—splay cell; solid line—bend cell.

as a function of applied voltage. At any applied voltage, the deformation energy density f_s of a nontwist cell is given by

$$f_s = \frac{1}{2}K_{11}\sin^2\theta\left(\frac{\partial\theta}{\partial z}\right)^2 + \frac{1}{2}K_{33}\left[\cos^2\theta\left(\frac{\partial\theta}{\partial z}\right)^2\right] + \frac{D_z^2}{2\varepsilon_0(\varepsilon_\parallel\cos^2\theta+\varepsilon_\perp\sin^2\theta)},$$

where

$$D_z = \frac{\varepsilon_0 V}{\displaystyle\int_0^d \frac{dz}{\varepsilon_\parallel\cos^2\theta(z)+\varepsilon_\perp\sin^2\theta(z)}},$$

and K_{11} and K_{33} are the splay and bend elastic constants and d is the cell gap. We plot the elastic deformation energy as a function of the applied voltage for the B and S deformations. When the two curves meet, that should be the voltage value where the S cell will begin to transform to the B cell, i.e. the critical voltage. An example for the case of 5° pretilt is shown in Fig. 2. The dashed curve is the result for the S state and the solid line is for the B state. The solid curve in Fig. 1 shows the calculated critical voltage as a function of the pretilt angle. It can be seen that there is excellent agreement between the calculated and the measured results.

Thus, at large enough pretilt angle, the LC cell is a NBB cell. This NBB cell eliminates the need for S to B transformation in conventional OCB displays. In a previous study, we have shown that the total on-off response time of the NBB cell is faster than an OCB cell with the same cell thickness.[9] Here, we made OCB cells of the same thicknesses and study the systematic dependence of the response time on the pretilt angle. Figure 3 shows the measured total switching time for the worst case of switching between the bright and dark states. It can be seen that the response time changes systematically as the pretilt angle is changed. The switching time for the NBB cell at 50° pretilt is 1.8 ms, which is almost a factor of 2 lower than the 5° pretilt case.

The results can be explained by the fact that with a higher pretilt angle, the rotation angle of the LC molecules required is smaller for the NBB cell. This fact has also been predicted by the simulation of Walton *et al.*[4] In practice, however, the comparison of the switching times is not too meaningful. For smaller pretilt angles, the effective birefringence is larger so that the cell gap can be smaller. For a smaller cell gap, the response time should be faster. Thus, the results presented in Fig. 3 are only useful in understanding the switching behavior of the OCB cell.

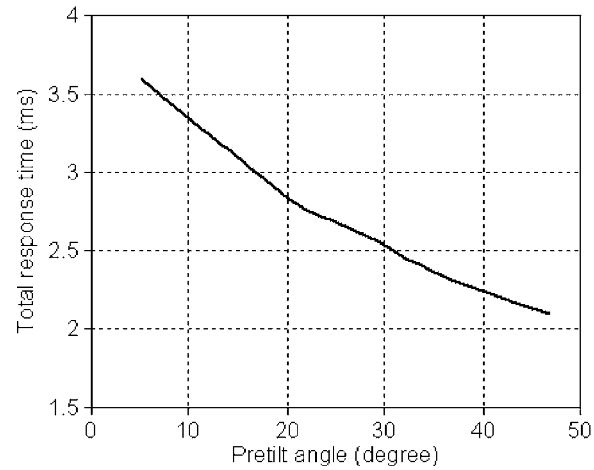

FIG. 3. Maximum switching time (on plus off time) of the OCB cell as a function of pretilt angle.

As mentioned, the faster response time of the NBB display does not come without a penalty. Since the average tilt angle is larger for a larger pretilt cell, the total retardation of an OCB cell with a larger pretilt angle is smaller. The calculated retardation δ of the B cell at the critical holding voltage at 550 nm for a 5 μm cell is shown in Fig. 4. Since the optical efficiency of an ECB cell is given by $\sin^2\delta$, it can be seen that for pretilt angles larger than 30°, the optical efficiency of the LC cell cannot reach 100%. Presumably, this problem can be solved by having LC with a larger birefringence. But larger birefringence usually means larger viscosity and slower response. Thus, there is some compromise to be made in the design of a practical NBB display.

In summary, we have studied the behavior of the critical holding voltage as a function of the pretilt angle of the LC cell. We observed a decrease of the critical voltage to zero experimentally which agrees well with theoretical predictions. We also observed a systematic decrease of the switching time of the OCB cell as a function of pretilt angle. This investigation is possible with the newly developed alignment layer that allows the fabrication of LC cells with any pretilt angle.

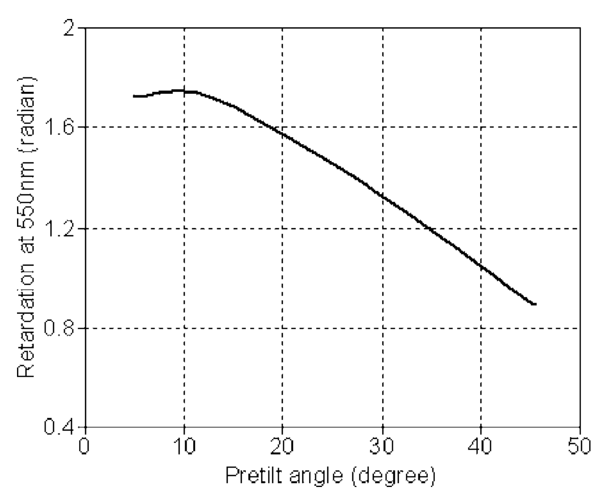

FIG. 4. Total retardation of the bend cell at the critical voltage as a function of pretilt angle.

This research was supported by the Hong Kong Government Innovation and Technology Fund.

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