Fast-response no-bias-bend liquid crystal displays using nanostructured surfaces

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We present results of a fast-response no-bias-bend (NBB) liquid crystal display, made possible by using a nanostructured alignment layer. Such alignment layers allow high pretilt angles of over 45° to be fabricated reliably. Thus, a stable bend configuration pi-cell can be achieved without applying any bias voltage to the cell. This NBB cell has a total on-off response time of less than 1.8 ms and is faster than the corresponding optically compensated bend cell with a low pretilt angle. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172732]

Many applications of liquid crystal displays (LCDs) require fast response times. For example, image blurring due to slow liquid crystal (LC) response is a still one of the major problems for LCD in video applications.[1] Time sequential color LCD also requires the LC response time to be fast. A ferroelectric LC has very fast response times but it lacks gray levels and requires difficult processing.[2] For mass production, nematic LC is still preferred.

Recently, the optically compensated bend (OCB)[3] mode has been explored as a fast LCD mode. OCB is essentially a pi-cell. The pi-cell operates between the bend deformation (B-state) and the near homeotropic state at high voltage. Many studies have been devoted to the study of this interesting LCD mode for fast switching applications.[4–9] Its response time can be very fast since there is no backflow involved in its switching. On-off response times of less than 1 ms have been achieved.

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 high 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 a nontrivial exercise. Since the S-state and the B-state are topologically inequivalent, nucleation has to be initiated. Many techniques have been proposed to prime the pi-cell into the B-state.[10,11] For a multiplexed display, it is quite difficult to convert the interpixel areas to the B-state since there is no voltage across the cell. As a result, the optical performance of the LCD is degraded.

In this letter, we propose and demonstrate an OCB cell which is in the stable B-state at no bias voltage. Its operation does not require any holding voltage. Thus, the driving and operation of this no-bias bend (NBB) LCD can be greatly simplified. The NBB cell is made possible by using a special alignment layer to induce a high pretilt angle of near 50° in the LC cell. The exact value of the required critical pretilt angle depends on the elastic constants of the LC material.

The formation of a pure bend cell at large pretilt angle has been discussed previously, e.g., by Boyd *et al.*[12] and Xu *et al.*[13] The major issue of this NBB cell is how to obtain the high pretilt angle reliably. Traditionally, the best method of obtaining large pretilt angles reliably is by SiO_2 evaporation.[14] However, this technique is not amenable to mass production and to large display panels. In this letter, we show that by the application of nanostructured surfaces as the alignment layers,[15,16] a stable NBB cell can be obtained with good optical properties.

The basic idea of the new alignment layer is to form a random distribution of nanosize domains of homogeneous and vertical alignment materials. Provided that these domains are small, the LC molecules will realign themselves to achieve a uniform pretilt angle near the alignment surface. This pretilt angle is formed due to elastic energy minimization, and its value depends on the area ratio of the vertical and homogeneous domains. It has been shown that such surfaces can have excellent anchoring energies as well as good thermal stability.[15] With these alignment layers, NBB cells can be readily fabricated. Since the details of the special alignment surface have been given in Ref. 15, in this letter, we shall concentrate on the design and properties of the NBB cell.

In order for the B-state to be more stable than the S-state, the elastic deformation energy of the B-state should be lower than that of the S-state. The elastic deformation energy is given by

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

where K_{11} and K_{33} are the splay and bend elastic constants, respectively. θ is the tilt angle which is a function of distance

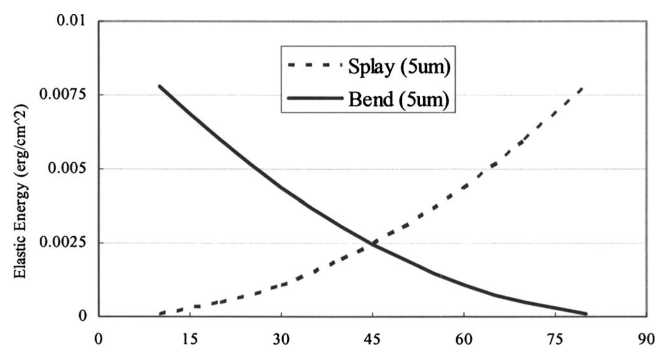

FIG. 1. Elastic deformation energies of the bend and splay cells as a function of the pretilt angle.

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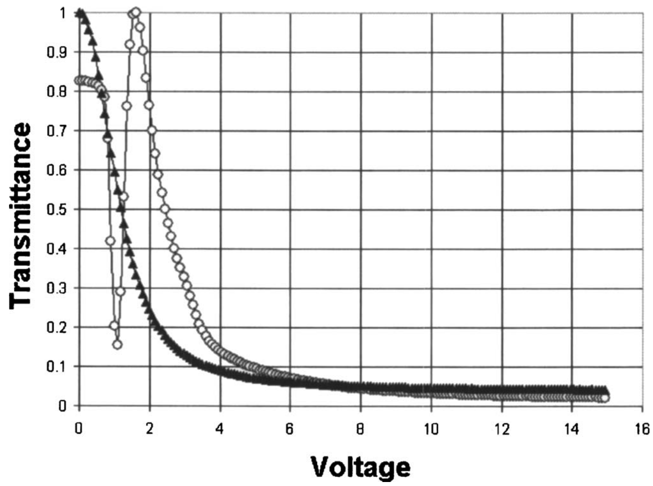

FIG. 2. TVCs of the NBB cell (triangles) and the OCB cell (circles). Both cells have the same thickness of 5 μm.

z inside the cell. For the LC used in this experiment, K_{11} and K_{33} are nearly equal. Thus, the solution of $\theta=\theta(z)$ is nearly linear for both the bend and splay states. Therefore, the elastic energy can be calculated easily using Eq. (1). Figure 1 shows the calculated deformation energies for the B-state and the S-state where K_{11} and K_{33} are equal to 10 pN. It shows that for pretilt angle larger than 45°, the bend deformation has a lower total elastic energy than the splay deformation. If $K_{33}=2K_{11}$, the pretilt angle where the bend and splay deformations have the same energy becomes 50°. Thus, in all cases, a pretilt angle of 50° is sufficient to have a stable B-state at no bias.

The optics of the NBB cell is slightly different from that of the OCB cell in that there is no holding voltage. Thus, the director deformations of the low voltage states are quite different. The transmittance of the LCD is given by the effective birefringence:

$$T=\sin^2\frac{\pi}{\lambda}\int_0^d \Delta n(z)dz=\sin^2\frac{\pi d}{\lambda}(\langle n_e\rangle - n_o), \tag{2}$$

where λ is the wavelength, d is the thickness of the LC layer, and $\Delta n(z)$ is the birefringence of the LC layer given by

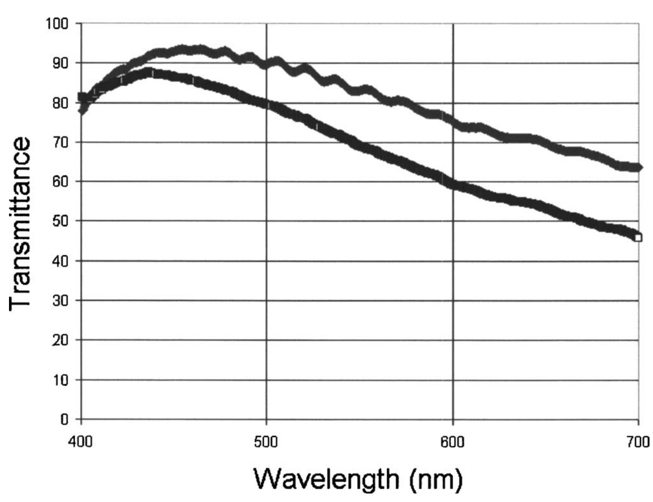

FIG. 3. Measured transmission spectra of the NBB cell and the OCB cell.

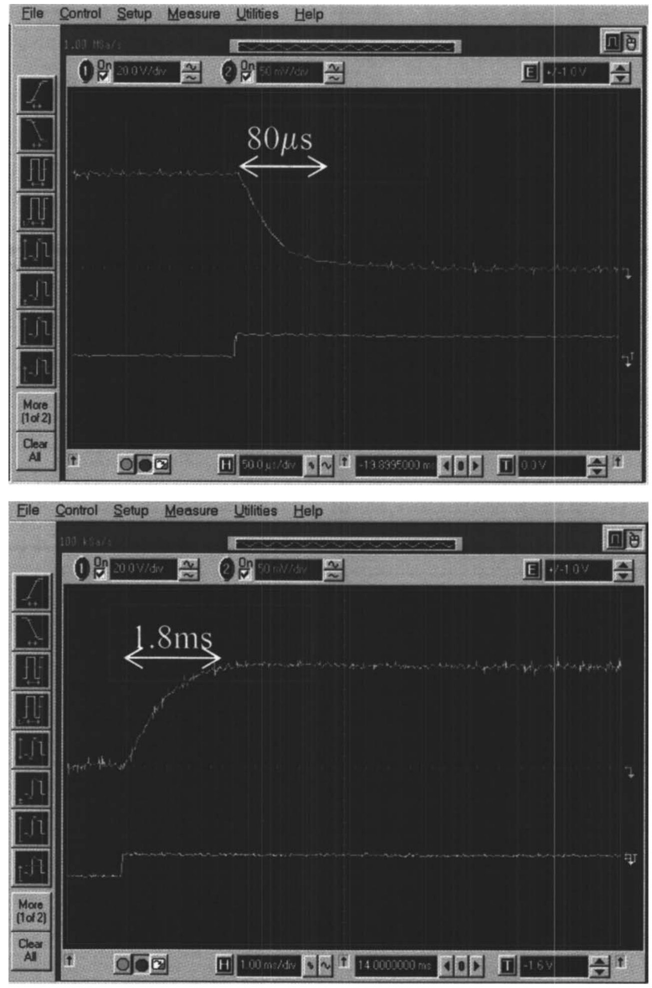

FIG. 4. Oscilloscope trace of switching of the NBB cell.

$$\Delta n(z)=n_e[\theta(z)]-n_o. \tag{3}$$

The extraordinary refractive index is given by

$$\frac{1}{n_e^2(\theta)}=\frac{\cos^2\theta}{n_e^2}+\frac{\sin^2\theta}{n_o^2}, \tag{4}$$

where n_e is the ordinary refractive index and n_o is the extraordinary refractive index of the LC material. In Eq. (2), $\langle n_e\rangle$ is the average extraordinary index of the LC cell.

The effective birefringence of the NBB cell is smaller than that of the conventional OCB cell. As an example, if $\theta=45°$, $n_e=1.72$, and $n_o=1.5$, corresponding to a Δn of 0.22, $\langle n_e\rangle$ can be calculated to be 1.5346. Thus, the effective birefringence is only 0.0346. With a cell gap of 5 μm, the peak transmittance or optical efficiency according to Eq. (2) is 70% at 550 nm. In general, if the pretilt angle increases, the peak transmission will decrease as well. Thus, according to Eq. (1), K_{11} has to be as close to K_{33} as possible in order for θ to be near 45°.

To verify the above estimates, we made a NBB cell with a pretilt of 50°. A LC with a birefringence of 0.22 was used. A conventional OCB cell was also made for comparison. Both cells have a cell gap of 5 μm. The same LC was also used. The OCB cell was made with conventional homogeneous PI and has a pretilt angle of 5°. The polarizers are such that both displays operate in the normally bright state. Figure 2 shows the normalized transmission versus voltage curve

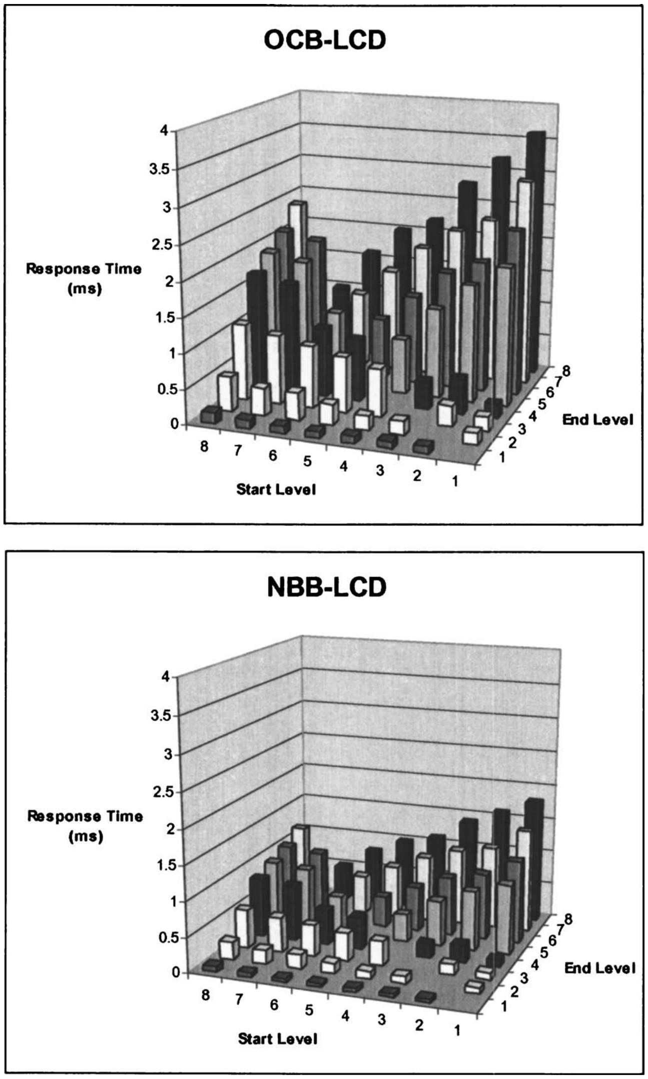

FIG. 5. Total switching times of the NBB cell and the OCB cell.

(TVC) of the NBB and OCB cells. The critical voltage needed to transform the splay cell to the pi-cell in the case of the OCB is 2.0 V. The TVC of the NBB cell decreases monotonically. On the other hand, since the birefringence of the OCB cell is large, the transmission curve goes through a maximum before decreasing to zero at high voltage. Figure 3 shows the bright state transmission spectra of the two cells. The scale of this figure is absolute. Thus, it can be seen that the transmittance of the NBB cell at 550 nm agrees quite well with the prediction of 70%.

Figure 4 shows oscilloscope pictures of the switching behavior of the NBB cell. It can be seen that the switching time from bend state to homeotropic state is extremely fast (80 μs). As the polar anchoring energy of our nanostructured surfaces is strong enough, the relaxation time of the pi-cell from homeotropic state to B-state is also very fast (1.8 ms). Thus, the total response time is 1.8 ms.

This total switching time of 1.8 ms is actually the worse case. For switching between gray levels, the switching time is smaller. Figure 5 shows the total response times for switching between various gray levels for the NBB cell. The eight gray levels correspond to evenly spaced transmission states with eight representing the maximum transmission and one representing the dark state. It can be seen that for most gray levels, the switching time is less than 1 ms.

As a comparison, we also show the switching times of an OCB cell in Fig. 5. The OCB cell was made of the same LC and had the same cell gap. The only difference was the pretilt angle. From that figure, it can be seen that the response time of the NBB cell is generally faster than the OCB cell. The longest switching time of NBB cell is only 1.8 ms while that of the OCB cell is more than 3.5 ms. In fact, a recent study shows that the response time of an OCB cell decreases steadily as the pretilt angle is increased.[16] This 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] Of course, the faster switching speed of the NBB cell does not come without a penalty, which is a smaller transmission or optical efficiency. However, with better choices of LC materials, the optical performance can be improved further.

In summary, we have demonstrated a functional B-cell at no bias voltage using the new alignment layer. This NBB cell has the merit of simpler operation than the OCB cell since no priming is needed. As well, the response time is faster. In our experiment, the total response time is 1.8 ms. In this letter, we showed results for a transmittive cell. For a reflective cell, the cell gap can be halved and the response time can be even faster. We have results showing 0.5 ms total response time for a LC on silicon microdisplay. Finally, it should be emphasized that this method of making the NBB cell is fully compatible with existing manufacturing techniques.[17]

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