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Crucial influences of K_{33}/K_{11} ratio on viewing angle of display mode using a bend-alignment liquid-crystal cell with a compensator

Chen-Lung Kuo, Tetsuya Miyashita, Makoto Suzuki, and Tatsuo Uchida
Department of Electronic Engineering, Faculty of Engineering, Tohoku University, Sendai 980-77, Japan

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The critical splay-to-bend-alignment transition in a liquid-crystal cell treated by parallel rubbing (π cell) was investigated to improve the optical performance of the display mode using this cell with a compensator. By analyzing the free energy in liquid crystal cells, it was found that nematic media with a smaller K_{33}/K_{11} ratio can reduce the transition voltage considerably, and therefore, also reduce the required optical anisotropy of the liquid-crystal cell. The significantly improved viewing angle for this mode, achieved by using these newly designed parameters, is also confirmed theoretically and experimentally. © *1996 American Institute of Physics.*[S0003-6951(96)03411-X]

It is well known that the twisted-nematic (TN) mode, which is commonly used in active matrix liquid-crystal displays (AMLCD), has a serious problem of angular dependence of the image quality.[1] Contrast degradation and gray-scale inversion, as observed obliquely from the vertical viewing zone, are caused mainly by the optical asymmetric properties of liquid crystals. To solve these problems, we have recently proposed an OCB (optically compensated bend) mode, mainly comprising a bend-alignment LC cell [or π cell (Ref. 2), treated by parallel rubbing on both sides of substrates] and a retardation compensator as depicted in Fig. 1.[3] Due to the simple structure of LC cells and their symmetric properties on the director-tilt plane, we can always design a compensator to remove the light leakage of the dark state within the full viewing angle range, and thus get an excellent optical performance in the horizontal direction (defined as *XZ* plane in Fig. 1).[4] However, in the vertical direction (*YZ* plane), optical performance is not as good as in the horizontal one. Besides, the bend alignment of a π cell can be obtained only when the applied voltage is larger than the critical voltage V_{CR}; e.g., 1.8 V for LC cells using Merck nematic mixture ZLI-1132 and 10° pretilt.[4] This critical transition reduces the effective dynamic range of retardation (i.e., the difference between black and white levels) in the bend state and also increases the required cell thickness. Both of these two changes generally harm the optical performance.

Thus this letter's goal is to analyze the critical splay-to-bend transition in a π cell to further extend the viewing angle of OCB modes. The critical influences of elastic constants of nematics on the reduction of the critical voltage and on the off-axis light leakage in dark states are discussed.

To obtain the desired bend alignment as shown in Fig. 1, the surface pretilt on either substrate of LC cells must be in opposite directions. Under these boundary conditions, there are three possible alignment configurations: splay, bend, and π twist, where the latter two states have very similar optical properties and free-energy values under the same applied voltage, as reported in our previous work.[4] Thus we need to study the transition behavior by taking into account only the splay and bend structures. Figure 2 shows a typical example of director configuration inside the cell for splay and bend alignment, respectively, as calculated by using the program GLUE developed at Gent University, Belgium.[5] The boundary conditions used in calculating the splay structure are $\theta(z=0)=\alpha$ and $\theta(z=d)=-\alpha$ or $\pi-\alpha$, where θ, α, and d represent the tilt angle of LC director relative to the cell substrates, the surface pretilt, and the cell thickness, respectively. In calculating the bend structure, one more boundary condition, $\theta(z=d/2)=\pi/2$, is introduced. In the voltage-on state, the bend structure can still retain mirror symmetry around the middle layer ($z=d/2$), i.e., $\theta(d/2+z)+\theta(d/2-z)=0$ or π, which is very important to achieve a wide viewing angle. Our previous results indicate the splay alignment dominates in the voltage-off state while the bend (twist) one becomes more stable in the high voltage state.[4] The splay-to-bend transition voltage V_{CR} can be determined by comparing the free energies of splay and bend structures. The free-energy density is expressed by[6]

$$F=\frac{[(K_{11}\cos^2\theta+K_{33}\sin^2\theta)(d\theta/dz)^2-DE]}{2},$$

where K_{11} and K_{33} are the elastic constants of splay and bend, respectively. D and E are the electric displacement and field, respectively.

From the circuit point of view, a smaller driving voltage is preferred to reduce power consumption. Furthermore, the dummy range of retardation variation below V_{CR} should be compensated by the increment of cell thickness to keep suf-

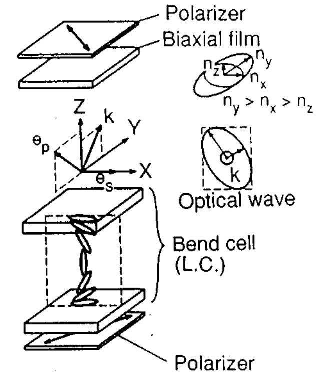


FIG. 1. Composition of OCB-mode LCD. *XZ* and *YZ* planes are defined as the horizontal and vertical viewing directions, respectively.

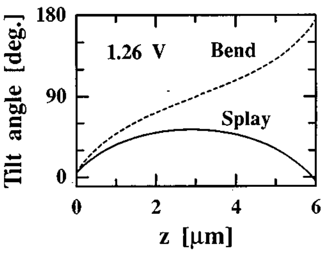


FIG. 2. Simulation results of LC director configuration. Parameters are $K_{33}/K_{11}=0.8$, $\Delta\epsilon=15$, $d=6$ μm.

ficient variation of transmission between dark and bright states. The increase of cell thickness will then slow down the switching speed. We found the most effective way to reduce the transition voltage and increase the effective dynamic range of retardation is to select LC media with a smaller K_{33}/K_{11} ratio. Referring to the director structures activated by a voltage near the transition value in Fig. 2, the tilt angle θ for the bend alignment structure is larger than that for the splay one. This reveals that the contribution of the bend deformation term ($K_{33}\sin^2\theta$) to the free-energy density for the bend structure is larger than that for the splay one, being opposite as the splay deformation term ($K_{11}\cos^2\theta$) is concerned. Consequently, smaller values of K_{33}/K_{11} can favor the bend alignment and decrease transition voltage. The simulation results (solid curve) in Fig. 3 show that V_{CR} is an increasing function of K_{33}/K_{11}. To design a display with a maximum modulation of brightness, LC cells should provide a half-wave retardation variation between V_{CR} and 6 V (the upper limit for general drivers). According to this criteria, the required $(\Delta nd)_{\mathrm{LC}}$ for OCB cells is illustrated by the dotted curve in Fig. 3. Here, Δn and d represent the optical anisotropy and cell thickness of liquid crystals, respectively. As a result, a lower transition voltage from a smaller K_{33}/K_{11} value can allow a thinner cell thickness without sacrificing the transmission.

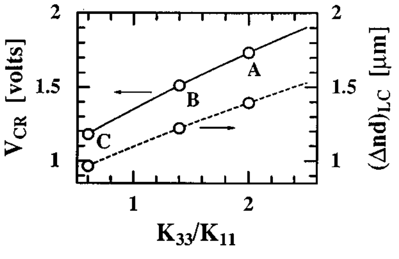


FIG. 3. Simulation results of V_{CR} and required birefringence $(\Delta nd)_{\mathrm{LC}}$ vs K_{33}/K_{11}. Other parameters are the same as those used in Fig. 2.

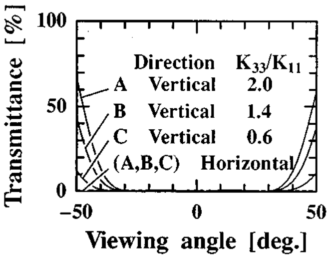
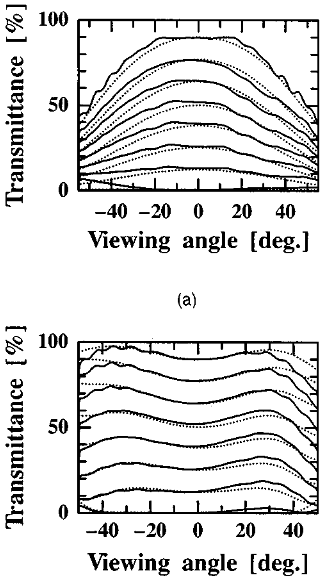


FIG. 4. Simulation results of transmission of dark state in vertical (solid lines) and horizontal (broken lines) directions with the corresponding parameters indicated by the same capitals in Fig. 3.

The birefringence value of $(\Delta nd)_{\mathrm{LC}}$ plays an important role in the optical properties of liquid-crystal displays. For example, the TN mode using the first minimum $[(\Delta nd)_{\mathrm{LC}} \sim 0.5$ μm] Mauguin condition shows a wider viewing angle than that using the second minimum condition $[(\Delta nd)_{\mathrm{LC}} \sim 1.0$ μm].[7] Here, we would also like to discuss the influence of K_{33}/K_{11} associated with $(\Delta nd)_{\mathrm{LC}}$ on the viewing angle of OCB modes. Unlike TN modes, where only discrete values of $(\Delta nd)_{\mathrm{LC}}$ satisfying the Mauguin condition can be used, continuous change of $(\Delta nd)_{\mathrm{LC}}$ for OCB modes is possible. To obtain a wide angle view, first of all, a dark state with the least light leakage should be obtained. We selected the corresponding V_{CR} as the dark state voltage for bend-alignment cells of different K_{33}/K_{11} and designed the retardation film, according to our previously proposed design rule, to keep the best performances in the horizontal viewing direction.[4] The optical properties were calculated by using the extended Jones matrix methods.[8,9] The simulation results of transmission in the dark state are shown in Fig. 4. As indicated by the broken lines, an excellent dark state in the horizontal direction always can be obtained, for all cases. However, the amounts of off-axis light leakage in the vertical direction are strongly dependent on LC parameters as illustrated by the solid curves. Clearly, the birefringence of a bend cell in the dark state can be better compensated by using a small $(\Delta nd)_{\mathrm{LC}}$ cell with LC materials of a smaller K_{33}/K_{11} ratio.



(a)

(b)

FIG. 5. Experimental (solid curves) and simulation (broken curves) results of viewing-angle-dependence transmission in (a) horizontal and (b) vertical viewing directions. Bias voltages are from 1.2 V (dark state) to 6 V (bright state). Parameters of the compensator are $(n_y-n_x)d=280$ nm and $(n_y-n_z)d=590$ nm, while the parameters used for the simulation are $(n_y-n_x)d=280$ nm and $(n_y-n_z)d=530$ nm, respectively. The LC material used in experiments is Merck nematic mixture ZLI-3405 with $K_{33}/K_{11}=0.8$. Other parameters of the LC cell are the same as those used in Fig. 2.

Gray-scale capabilities in LCDs are becoming increasingly important in the applications of multicolor and full-color displays. The gray-scale performances of an OCB made as calculated by using the above improved design of LC parameters with $K_{33}/K_{11}=0.8$ are shown by the dotted curves in Fig. 5. The horizontal direction [Fig. 5(a)] shows a nearly ideal gray-scale fidelity and high contrast, where ideal polarizers are used in the simulation. Even in the vertical direction [Fig. 5(b)], under the definition of CR (contrast ratio)$\geqslant$20 and no gray-scale inversion, a wide viewing angle of about 100° is attainable.

According to the aforementioned design, we also prepare a real OCB cell to check the viewing angle dependence of optical properties. Within the available measurement range of our setup, excellent gray-scale fidelity was confirmed as indicated by solid curves in Fig. 5. Since the properties of our compensator have a little deviation from the required values, and because the contrast ratio of crossed polarizers also becomes a little worse in the oblique direction, slight leakage still appears in off-axis direction. Nevertheless, the general properties are very close to the simulation ones. Under the definition of contrast ratio larger than 20 and no gray-scale inversion, we have a viewing angle of 100° in both directions. A remarkable factor of more than two and a half times improvement in the vertical viewing angle over the conventional TN mode is exhibited.[1]

In conclusion, we have illustrated that the critical splay-to-bend transition voltage for a parallel-rubbing liquid-crystal cell can be reduced by selecting nematic materials with smaller K_{33}/K_{11} ratio. Due to the expansion of the available voltage range, the required birefringence $(\Delta nd)_{\mathrm{LC}}$ of the OCB display mode can then be reduced. As a result, the off-axis light leakage as well as the viewing angle in vertical direction can be improved significantly.

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