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Optically compensated double-layer electrically controlled birefringence liquid crystal display with wide-viewing-angle cone

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An electrically controlled birefringence liquid crystal display has a problem over narrow viewing angle. To solve this problem, the authors proposed a double-layer electrically controlled birefringence liquid crystal display with a wide-viewing-angle cone under an applied voltage. In this device, each liquid crystal layer compensates the variation of retardation as a function of viewing angle. However, the optical compensation occurs only when certain voltages are applied. The objective of this paper is to propose a novel film compensated double-layer electrically controlled birefringence liquid crystal display that has a wide cone of view in any state. This device is based on the concept of compensation of retardation.

1. Introduction

Electrically controlled birefringence liquid crystal displays using liquid crystals with negative dielectric anisotropy (N_n-type liquid crystal) are attracting attention due to their very high contrast, sharp threshold characteristic and good gray-scale capability [1]. Thus, they are suitable for the multiplexed dot-matrix liquid crystal displays. The electrically controlled birefringence liquid crystal displays, however have a problem over narrow-viewing-angle cone for practical use. This is because a liquid crystal has an anisotropy of birefringence.

As a solution to this problem in the on state, Yamamoto *et al.* proposed a new electrode structure which enabled a wide viewing angle and high contrast [2]. In this structure, multi-domains of liquid crystal are induced and the transmittance of the cell is averaged over all directions of liquid crystal orientation. On the other hand, Yang discussed a two-domain electrically controlled birefringence mode [3]. They used a new homeotropic alignment technology in which the electric field direction controls the tilt direction of the liquid crystal molecules. Human eyes average the transmittances in multi- or in two-domains of the electrically controlled birefringence display, and therefore it is slightly difficult to obtain uniform electro-optical characteristics in any direction. Contrary to these methods, we proposed a double-layer electrically controlled birefringence mode liquid crystal display that has a wide cone of view under the applied voltage. This device is based on the new concept of self-active optical compensation [4, 5]. Also, an optical phase compensation medium was proposed in order to improve the narrow-viewing-angle cone of the conventional electrically

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controlled birefringence liquid crystal displays in the off state, and a full colour dot-matrix liquid crystal display was developed [6]. However, the optical phase compensation of this method occurs only when no voltage is applied.

The objective of this paper is to propose a novel film compensated double-layer electrically controlled birefringence mode liquid crystal display that has a wide cone of view in any state.

2. Double-layer electrically controlled birefringence liquid crystal display

It is important for the electrically controlled birefringence liquid crystal displays that the retardation is adjusted not to depend on the viewing angle. Figure 1 shows cross-sectional structures of conventional electrically controlled birefringence and double-layer electrically controlled birefringence cells with a wide-viewing-angle cone based on the concept of compensation of retardation [4, 5]. In this case, the cell thickness for double-layer electrically controlled birefringence is assumed to be half that of electrically controlled birefringence. Thus, double-layer electrically controlled birefringence gives the same retardation as electrically controlled birefringence in the off state in the normal direction ($\alpha = 0°$). The double-layer electrically controlled birefringence cell is constructed with two stacked electrically controlled birefringence cells that have the same electro-optical characteristics. The important point about the double-layer electrically controlled birefringence cell is that the two cells are stacked such that the molecules in each of the electrically controlled birefringence cells tilt in opposite directions in the activated state and that the same voltage is applied to both cells. Therefore, the variation of the retardation for double-layer electrically controlled birefringence is suppressed in the oblique direction. It is the outstanding merit of the double-layer electrically controlled birefringence cell that the retardation depends only weakly on the viewing angle. Double-layer electrically controlled birefringence will make it possible to fabricate wide-viewing-angle liquid crystal displays compared with conventional electrically controlled birefringence cells.

The electro-optical characteristics were simulated in order to compare the optical properties of double-layer electrically controlled birefringence with those of electrically controlled birefringence. At first, the orientation of the liquid crystal molecules under the applied voltage was calculated by Frank's continuum theory [7]. After that, the optical properties of the liquid crystal displays were calculated by Berreman's

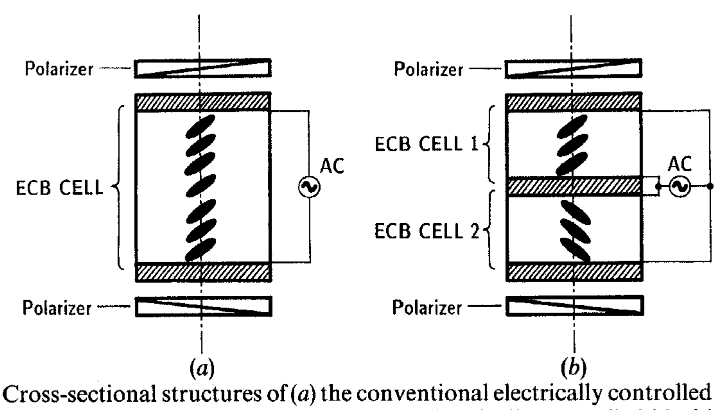

Figure 1. Cross-sectional structures of (a) the conventional electrically controlled birefringence liquid crystal display and (b) the double-layer electrically controlled birefringence liquid crystal display. In the figure electrically controlled birefringence is abbreviated to ECB.

4×4 method [8, 9]. In this paper, we did not take account of refraction and reflection. Figure 2 shows the definition of the coordinate system used in these calculations, where the z axis sets parallel to the normal direction to the substrates and the viewing direction is expressed by the polar angle α and the azimuthal angle β.

In the theoretical calculations, it was assumed that the molecules would align in the $\beta = 45°$ plane under the applied voltage. The two polarizers were crossed, and their polarizing directions were parallel to the x and y axes, respectively. The transmittance was computed for a liquid crystal having typical values for the bend/splay ratio, $k_{33}/k_{11} = 1{\cdot}50$, a perpendicular/parallel dielectric constant ratio, $\varepsilon_{\perp}/\varepsilon_{\parallel} = 2{\cdot}33$ and an anisotropy of refractive index, $\Delta n = 0{\cdot}143$. It was also assumed that the wavelength was $\lambda = 550$ nm and the retardation in the normal direction to the substrates ($\alpha = 0°$) was $\lambda/2$ under the applied voltage.

The viewing angle dependence of the retardation R of conventional electrically controlled birefringence and double-layer electrically controlled birefringence cells in the plane of $\beta = 45°$ is shown in figure 3. The retardation of the double-layer electrically

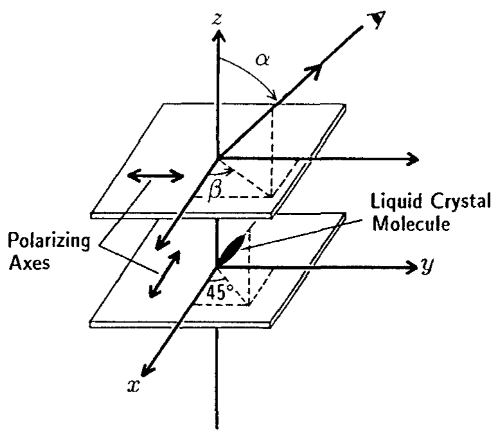

Figure 2. Definition of the coordinate system used in the simulation.

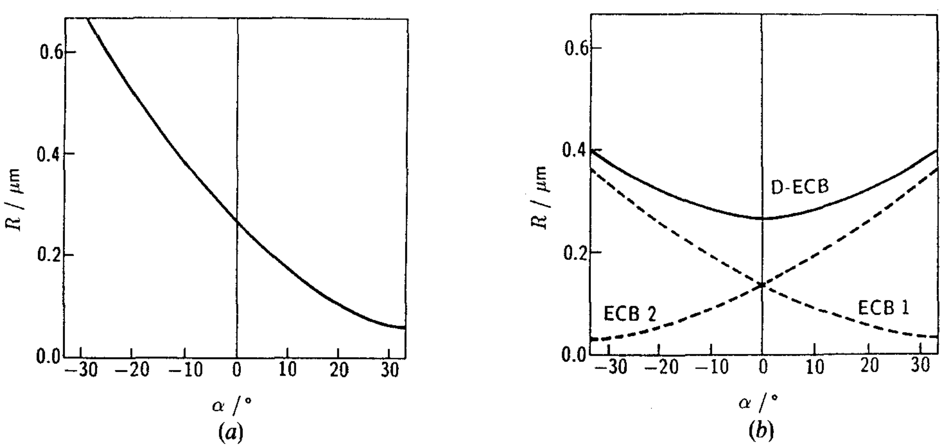

Figure 3. Viewing angle (α) dependence of the retardation of (*a*) the conventional electrically controlled birefringence cell and (*b*) the double-layer electrically controlled birefringence cell obtained by simulations in the plane of $\beta = 45°$, with voltage ($\Delta nd/\lambda = 1/2$).

controlled birefringence cell is obtained by the summation of those of the electrically controlled birefringence cell 1 and 2. The result is shown by the solid line in figure 3 (*b*). The double-layer electrically controlled birefringence has a weak dependence on viewing angle. It is confirmed that each electrically controlled birefringence cell (1 and 2) compensates the variation of the retardation of the other. Figure 4 shows the viewing angle dependence of the transmittance of the double-layer electrically controlled birefringence and the electrically controlled birefringence cell. The double-layer electrically controlled birefringence cell depends weakly on the viewing angle. In addition, the viewing angle dependence of the transmittance of the double-layer electrically controlled birefringence cell has a symmetrical characteristic with respect to the normal direction to the surfaces ($\alpha=0°$). Figure 5 shows the azimuthal angle dependence of the transmittance for double-layer electrically controlled birefringence and electrically controlled birefringence. β is the azimuthal angle defined in figure 2. The radial distance from the centre of the diagram corresponds to the transmittance. In this figure, it is assumed that the molecules align in the direction $\beta=45°$ under the

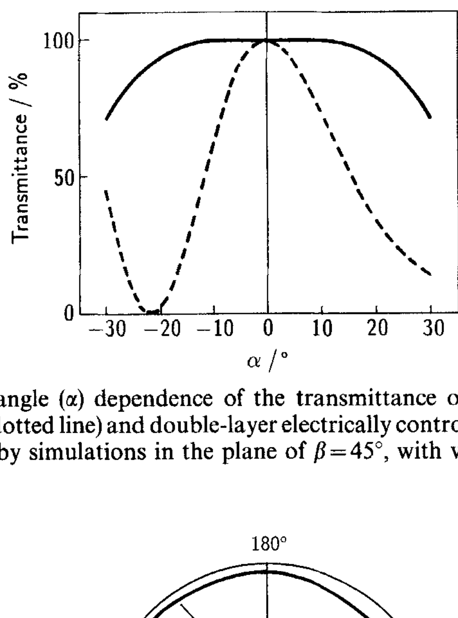

Figure 4. Viewing angle (α) dependence of the transmittance of the electrically controlled birefringence (dotted line) and double-layer electrically controlled birefringence (solid line) cells obtained by simulations in the plane of $\beta=45°$, with voltage ($\Delta nd/\lambda=1/2$).

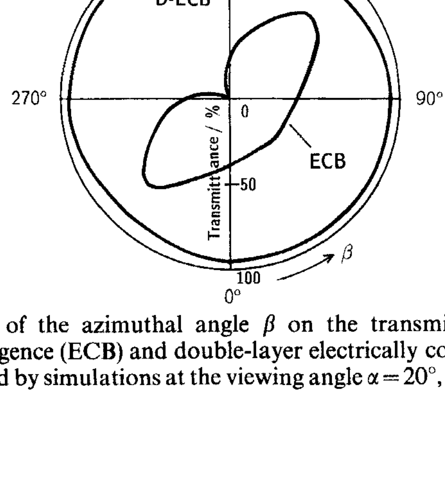

Figure 5. Dependence of the azimuthal angle β on the transmittance of the electrically controlled birefringence (ECB) and double-layer electrically controlled birefringence (D-ECB) cells obtained by simulations at the viewing angle $\alpha=20°$, with voltage ($\Delta nd/\lambda=1/2$).

applied voltage, and the viewing angle α is fixed at 20°. The simulated results show that double-layer electrically controlled birefringence gives a wide viewing angle cone compared with conventional electrically controlled birefringence in the on state.

3. Film-compensated double-layer electrically controlled birefringence

It is shown that the double-layer electrically controlled birefringence cell has an extremely wide-viewing-angle cone in the on state, but this compensation does not occur in the off state, because the liquid crystal molecules align almost perpendicular to the substrate. Therefore, the double-layer electrically controlled birefringence cell has a narrow viewing angle cone, the same as for electrically controlled birefringence. As a solution of this problem, Yamauchi *et al.* presented an optical compensation method by means of a polymer film for the electrically controlled birefringence cell in the off state [6]. As a result, the combination of the double-layer electrically controlled birefringence cell with optical compensation media has the possibility for an extremely wide-viewing-angle cone in any state.

Figure 6 shows a cross-sectional structure of the film-compensated double-layer electrically controlled birefringence cell. The film is stacked between the double-layer electrically controlled birefringence cell and one polarizer. In this case, a polymer film with negative birefringence is considered as the compensation film used by Yamauchi *et al.* [6]. In the off state, the film-compensated electrically controlled birefringence mode displays a black state in any direction by the optical compensation effect. On the other hand, the property in the on state is affected by the film. Therefore, the design of the retardation of the compensation film is very important in order to get high contrast at any viewing angle. Figure 7 shows the viewing angle dependence of the retardation R of the double-layer electrically controlled birefringence cell and the novel film-compensated double-layer electrically controlled birefringence cell obtained by the simulations. $\Delta nd/\lambda$ shows a retardation value in the normal direction to the cell. The $\Delta nd/\lambda$ values of 1/2 and zero in the figure correspond to the retardation in the on and off states, respectively. Dashed lines relate to the properties for double-layer electrically controlled birefringence without compensation in the on/off state. Liquid crystal molecules have a positive birefringence and the retardations depend on the viewing angle in the off state especially. The total retardation is obtained by summation for the double-layer electrically controlled birefringence cell and retardation film. As the compensation film is negative in birefringence, the retardation decreases in the oblique

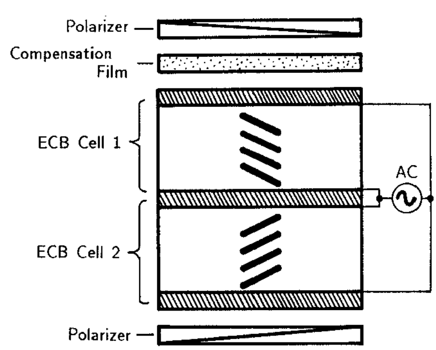

Figure 6. Cross-sectional structure of the novel film-compensated double-layer electrically controlled birefringence liquid crystal display. In the figure electrically controlled birefringence is abbreviated to ECB.

direction. The shaded area shows the effect of the compensation medium. The results for the novel film-compensated double-layer electrically controlled birefringence mode with compensation are shown by the solid lines. It is confirmed that the variations in the retardations in the novel film-compensated double-layer electrically controlled birefringence mode are suppressed in not only the off state, but also in the on state. The role of the compensation film is suppression of the fluctuation in the retardation of the double-layer electrically controlled birefringence mode are suppressed in not only the off state, but also in the on state.

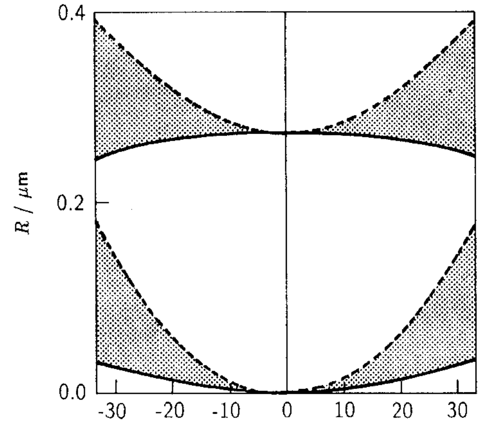

Figure 7. Viewing angle (α) dependence of the retardation R for double-layer electrically controlled birefringence and film-compensated double-layer electrically controlled birefringence obtained by simulations in the plane of $\beta = 45°$. The broken lines indicate the characteristics of the double-layer electrically controlled birefringence cell without a compensation medium. The bold lines indicate the characteristics of the film-compensated double-layer electrically controlled birefringence cell with a compensation medium. The upper pair of lines in the figure relate to a voltage of $\Delta nd/\lambda = 1/2$ and the lower pair of lines to zero voltage.

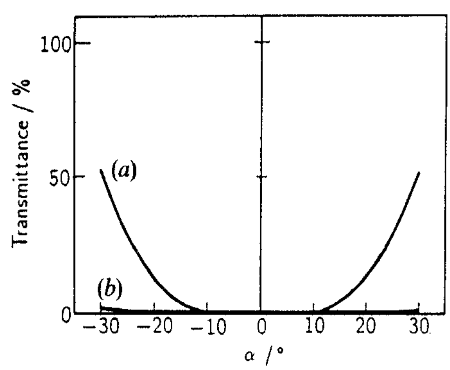

Figure 8. Viewing angle (α) dependence of the transmittance of some kinds of electrically controlled birefringence liquid crystal displays by simulations in the plane of $\beta = 45°$, without voltage ($\Delta nd/\lambda = 0$). Line (*a*) represents both the conventional and double-layer electrically controlled birefringence and line (*b*) both the film-compensated and the film-compensated double-layer electrically controlled birefringence.

Figure 8 shows the viewing angle dependence of the transmittance of the electrically controlled birefringence liquid crystal displays in the off state. The azimuthal angle β is fixed at 45°. The transmittance of the electrically controlled birefringence liquid crystal displays without optical compensation (the electrically controlled birefringence and the double-layer electrically controlled birefringence) depends strongly on the viewing angle. Contrary to these results, the transmittance of the electrically controlled birefringence liquid crystal displays with compensation (the film-compensated electrically controlled birefringence and the film-compensated double-layer electrically controlled birefringence) depend weakly on viewing angle. The optical compensation film works well for improvement of viewing angle dependence on electro-optical characteristics in the film-compensated double-layer electrically controlled birefringence mode.

Figure 9 shows the viewing angle dependence of the transmittance for film-compensated double-layer electrically controlled birefringence and film-compensated electrically controlled birefringence in the on state. The azimuthal angle β is fixed at 45°. The transmittance of the film-compensated electrically controlled birefringence cell depends strongly on the viewing angle. Contrary to these results, the transmittance of the film-compensated double-layer electrically controlled birefringence cell depends weakly on the viewing angle. In addition, the viewing angle dependence of the transmittance for film-compensated double-layer electrically controlled birefringence is slightly improved compared with that for double-layer electrically controlled birefringence (see figure 4). This property is easily understood by the viewing angle dependence of retardation for film-compensated double-layer electrically controlled birefringence as shown in figure 7. The viewing angle dependence of retardation in the on state is suppressed by the optical compensation.

Figure 10 shows a polar plot of transmittance as a function of azimuthal angle. It is confirmed that the film-compensated double-layer electrically controlled birefringence cell has an extremely wide-viewing-angle cone compared with the double-layer electrically controlled birefringence cell.

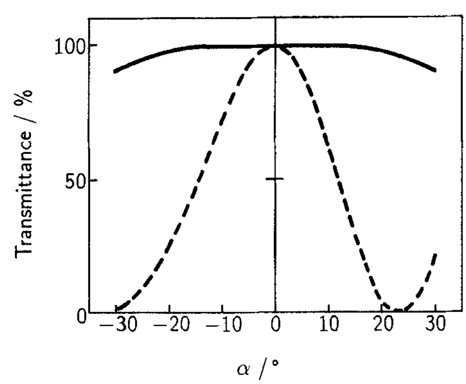

Figure 9. Viewing angle (α) dependence of the transmittance for film-compensated electrically controlled birefringence (broken line) and film-compensated double-layer electrically controlled birefringence (solid line) obtained by simulations in the plane of $\beta = 45°$, with voltage ($\Delta nd/\lambda = 1/2$).

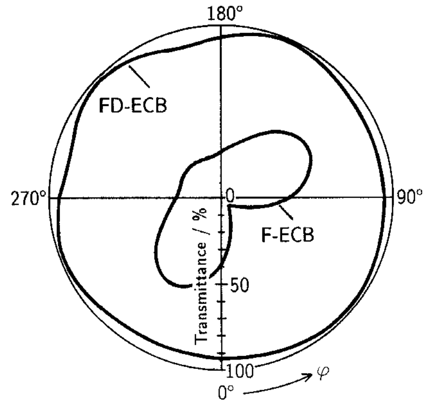

Figure 10. Azimuthal angle β dependence of the transmittance for film-compensated electrically controlled birefringence (F-ECB) and film-compensated double-layer electrically controlled birefringence (FD-ECB) at the viewing angle $\alpha = 20°$, with voltage ($\Delta nd/\lambda = 1/2$).

4. Conclusion

In this paper, improvement of the electro-optical characteristics of the electrically controlled birefringence mode is discussed. It is confirmed that the film-compensated electrically controlled birefringence liquid crystal display proposed in this paper will make it possible to fabricate wide-viewing-angle liquid crystal displays compared with conventional electrically controlled birefringence liquid crystal displays by stacking an optical compensation medium.

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