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Analysis of the operation mode of reflective liquid crystal display devices with front film compensation

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The front film compensated reflective liquid crystal display device was studied in normally black and normally white operation conditions using a dynamic parameter space method. The electro-optical response and reflectance spectra were also studied for different operation modes. We show that high quality normally white or normally black modes can be obtained by placing the fast axis of a quarter wave plate at 45° or 0° to the input director direction. The viewing angle characteristics of the optimum modes are wide and symmetrical.

1. Introduction

Research interest in reflective liquid crystal display devices has been growing recently. Reflective liquid crystal display (LCD) devices have important potential applications in personal information tools such as personal digital assistants (PDA). Transmissive devices usually require backlighting which is a source of significant power consumption. Nowadays the most widely used reflective LCDs use two polarizers and one diffuse reflector. This type of reflective LCD has very low light efficiency, since light travels four times through the polarizers. An optically ideal reflective LCD has one front polarizer and one reflector. The liquid crystal is sandwiched between two glass plates coated with ITO, acting as transparent electrodes. The liquid crystal has a twisted structure; incident natural light passes the front polarizer, and is reflected back by the reflector, the light passing the front polarizer twice. This type of reflective device has a brighter 'bright' state than conventional two polarizer reflective devices.

We have analysed the operation modes of reflective liquid crystal devices without compensation [1]. In this article our attention will focus on the compensated reflective liquid crystal devices. Sonehara studied a reflective display with an input polarizer and a rear mirror [2]. Fukuda *et al.* proposed and demonstrated a reflective display using a retardation film [3]. Wu and Wu proposed a 'mixed mode' reflective display device using a quarter wave plate [4]. We will discuss the case of reflective LCD devices with front compensation (quarter wave plate placed between the front polarizer and the liquid crystal cell) as illustrated in figure 1. The case of reflective LCD devices with rear compensation (quarter wave plate placed between the liquid crystal cell and the mirror reflector) will be studied in a separate paper.

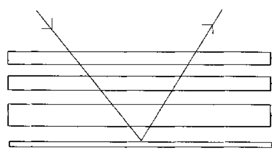

Figure 1. Illustration of the reflective liquid crystal display device with front compensation.

A systematic computer simulation of reflective LCD devices with front compensation will be given in terms of the dynamic parameter space method [5]. The parameters defining the parameter space are the thickness and birefringence product $d\Delta n$, the liquid crystal twist angle ϕ, and the angle between polarizer and input director β. These three parameters basically determine the optical properties of liquid crystal devices. The liquid crystal material parameters K_{11}, K_{22}, K_{33}, $\varepsilon_\perp$ and $\varepsilon_\parallel$ are closely related to the dynamic response, so they will not be included in the parameter space. The dynamic parameter space method essentially consists of a series of transmission or reflectance contour plots in $\{\phi, d\Delta n, \beta\}$ space with one of the parameters fixed while a varying voltage is applied. This method is based upon very efficient programming for the calculation of director profile by the variation technique [6]. Berreman's 4×4 matrix method is used to calculate optical properties [7]. Two types of contour plots will be shown in this paper, the reflectance contour plot and the contrast ratio contour plot. This contrast ratio is simply the ratio of reflectances between 'on' and 'off' states. The director

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distribution in the liquid crystal cell is calculated for the entire range of twist angle ϕ from 0° to 360° at a given voltage, and reflectance is calculated for each twist angle with $d\Delta n$ ranging from 0 to 2.5 μm.

2. Normally white mode

The simple geometry for the reflective device with front compensation was adopted in studying the normally white mode. The input director and the polarizer were assumed to be along the same direction. Liquid crystal material parameters used in the calculation are listed as follows. $K_{11} = 12.4 \times 10^{-10}\,\mathrm{J\,cm^{-1}}$; $K_{22} = 6.0 \times 10^{-10}\,\mathrm{J\,cm^{-1}}$; $K_{33} = 17.1 \times 10^{-10}\,\mathrm{J\,cm^{-1}}$; $\varepsilon_{\perp} = 6.6$; $\varepsilon_{\parallel} = 13.8$; pretilt angle was 2°; cell thickness d was 5.0 μm. Pitch p varied with twist angle and was equal to $2\pi d/\phi$. The director profile was calculated for each twist angle from 0° to 360°, and its optical properties were calculated by the Berreman's 4×4 matrix method. Assuming the reference direction is the input director direction, a positive ϕ direction means that director twists in an anti-clockwise fashion from the input director.

The quarter wave plate was treated as a layer of anisotropic medium in Berreman's 4×4 matrix method, its $d\Delta n$ was equal to $\lambda/4$. The angle between the fast axis of the quarter wave plate and the input director direction was 45°. The wavelength used in all calculations was 550 nm.

Figures 2 and 3 show reflectance contour plots of this reflective device at 'off' state and 'on' state, respectively. The voltages applied at 'off' and 'on' were 0.0 and 4.0 V, respectively. In all contour plots $d\Delta n$ is in microns. The reflectance was normalized to the reflectance of an aluminum mirror and the front polarizer attached to the aluminum mirror. The reflectance was normalized

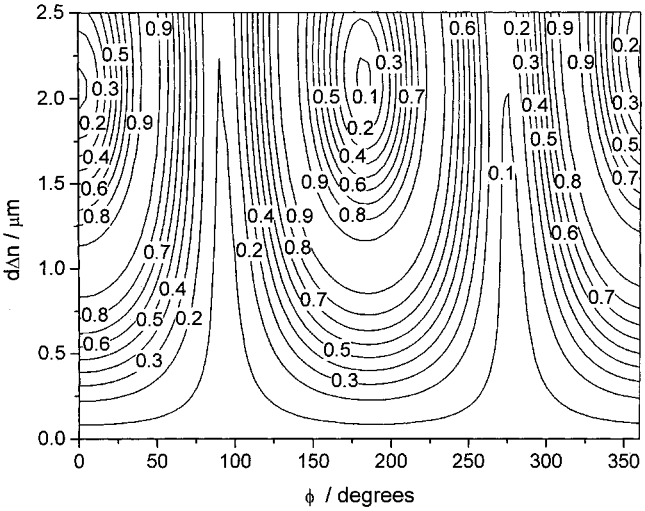

Figure 3. Reflectance contour plot at the 'on' state for the normally white mode.

in the same way for all of this investigation. Figure 4 shows the contrast ratio contour plot ($R_{\mathrm{off}}/R_{\mathrm{on}}$).

Three possible operation modes from figure 4 may be discussed. They were mode A at ($\phi = 90°$, $d\Delta n = 0.25$ μm), mode B at ($\phi = 90°$, $d\Delta n = 0.65$ μm) and mode C at ($\phi = 90°$, $d\Delta n = 0.90$ μm). The electro-optical responses for the three modes were also calculated as shown in figure 5. Mode A has good electro-optical properties. Modes B and C have abrupt changes of reflectance as the driving voltage increases. Figure 6 shows the reflectance spectra for mode A at 'off' and 'on' states. The voltage applied to the 'on' state was 2.5 V. The reflectance spectra show good dispersion. Mode A is similar to the 'mixed mode' reported by Wu and Wu [4]. The viewing angle dependence of the contrast ratio is shown in figure 7 for mode A.

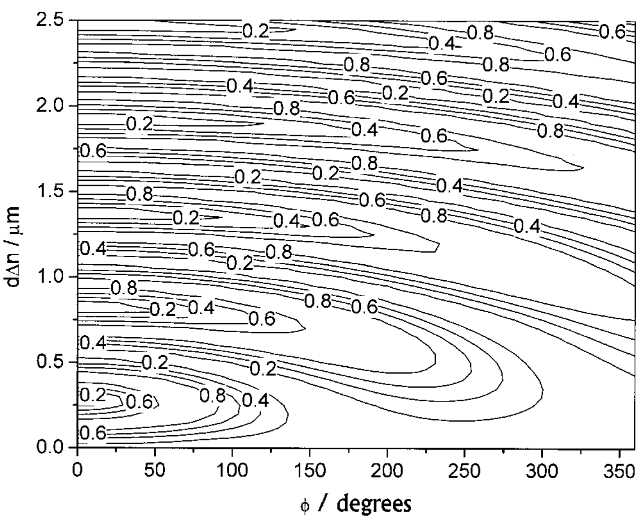

Figure 2. Reflectance contour plot at the 'off' state for the normally white mode.

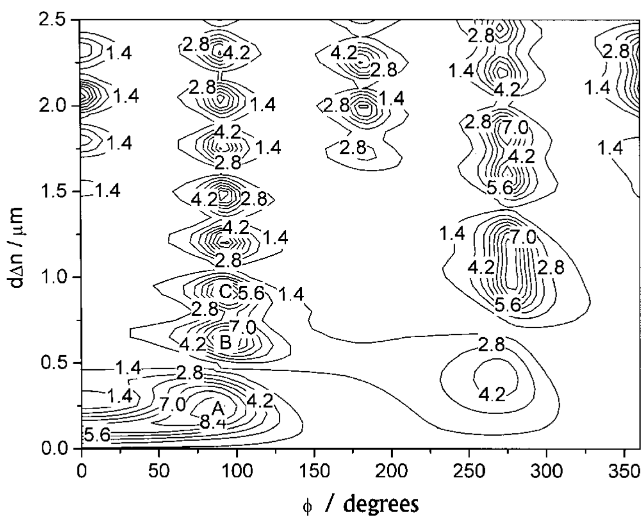

Figure 4. Contrast ratio contour plot ($R_{\mathrm{off}}/R_{\mathrm{on}}$) for the normally white mode.

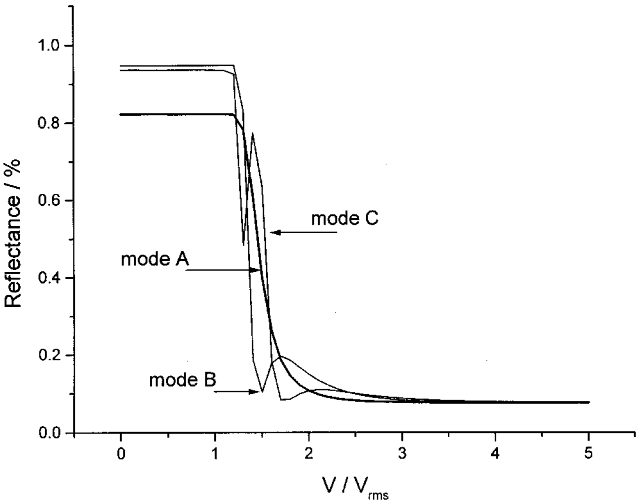

Figure 5. Electro-optical response for the normally white mode.

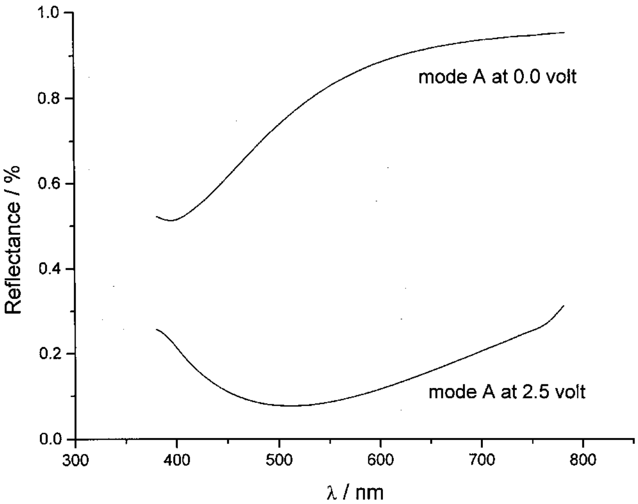

Figure 6. Reflectance spectra for mode A.

The characteristic of the viewing angle is symmetric. The contrast ratio is greater than 4.0 within a viewing angle of $\pm 40°$.

3. Normally black mode

The polarizer and input director were also assumed to be along the same direction for the analysis of normally black modes. The angle between the input director and fast axis of the quarter wave plate was 0°. The contrast ratio contour plot (R_{on}/R_{off}) is shown in figure 8. The voltages applied at the 'off' and 'on' states were 0.0 and 4.0 V, respectively. From this figure, two modes can be seen, D at ($\phi = 60°$, $d\Delta n = 0.20\,\mu m$) and mode E at ($\phi = 185°$, $d\Delta n = 0.60\,\mu m$). Their electro-optical responses are shown in figure 9, and reflectance spectra in figure 10. The voltage applied at the 'on' state for the two modes is 2.5 V. Mode D has a better

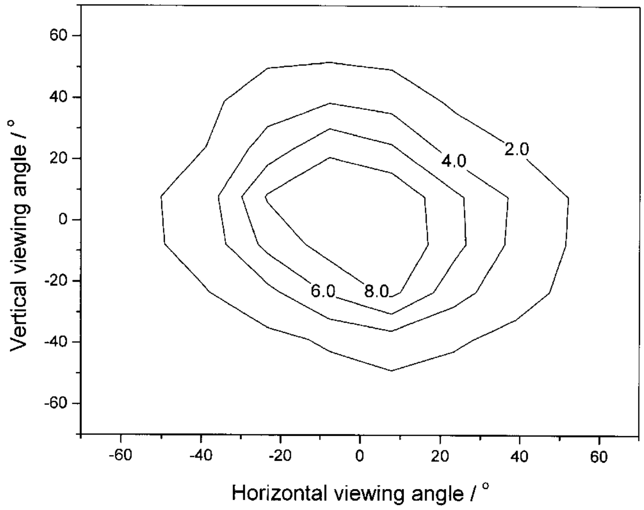

Figure 7. Viewing angle dependence of the contrast ratio for mode A.

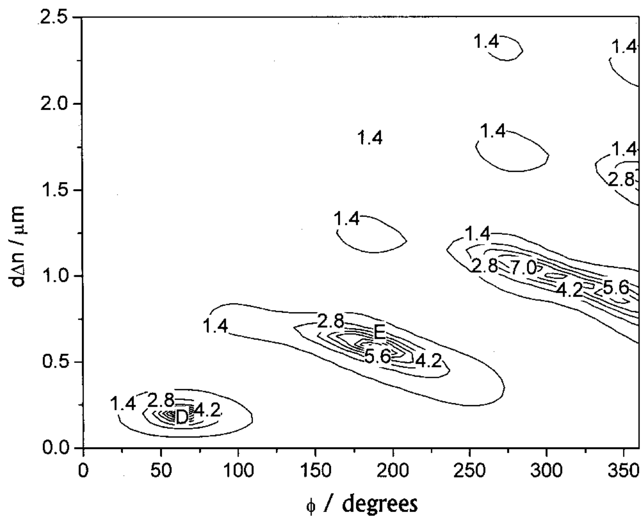

Figure 8. Contrast ratio contour plot (R_{on}/R_{off}) for the normally black mode.

dispersion property than as mode E. The viewing angle dependences of the contrast ratio are shown in figures 11 and 12, respectively, for modes D and E. Mode D has a wider viewing angle characteristic; its contrast ratio is larger than 4.0 within a viewing angle of $\pm 60°$. In comparison with the normally white operation, the normally black operation has mode E operating in the supertwisted region, which means a better multiplex property.

4. Discussion and conclusions

The front film compensated reflective liquid crystal display device was analysed in terms of the dynamic parameter space method. For the front compensation,

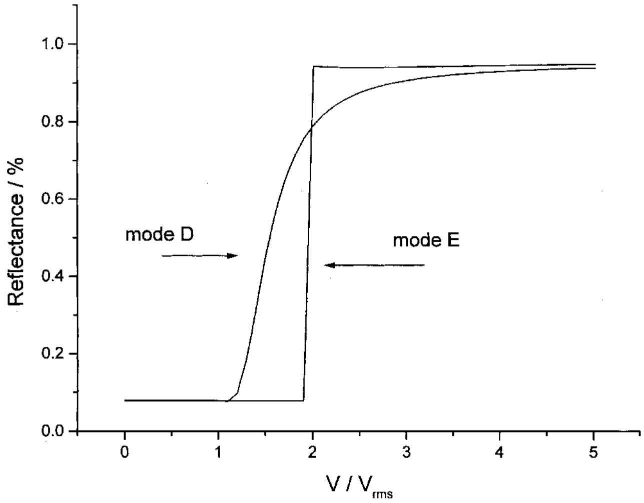

Figure 9. Electro-optical response for the normally black mode.

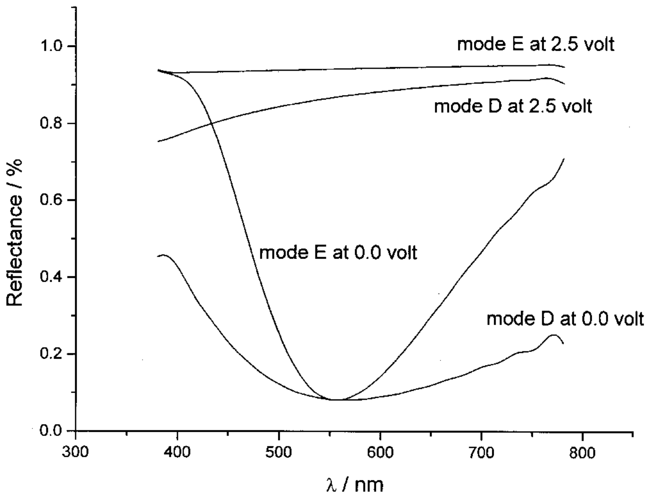

Figure 10. Reflectance spectra for modes D and E.

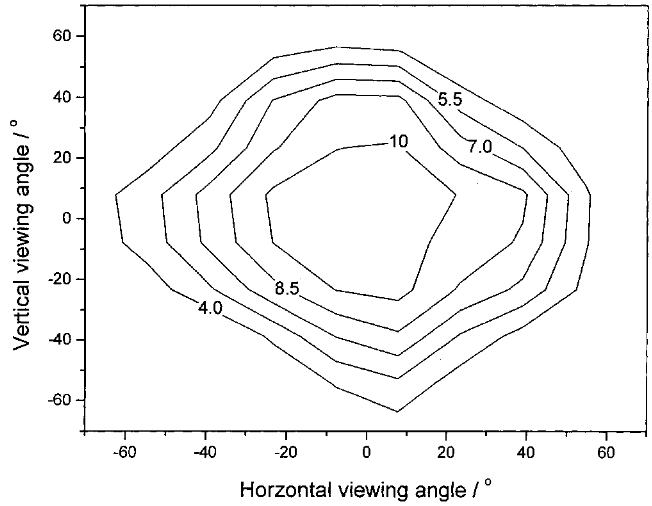

Figure 11. Viewing angle dependence of contrast ratio for mode D.

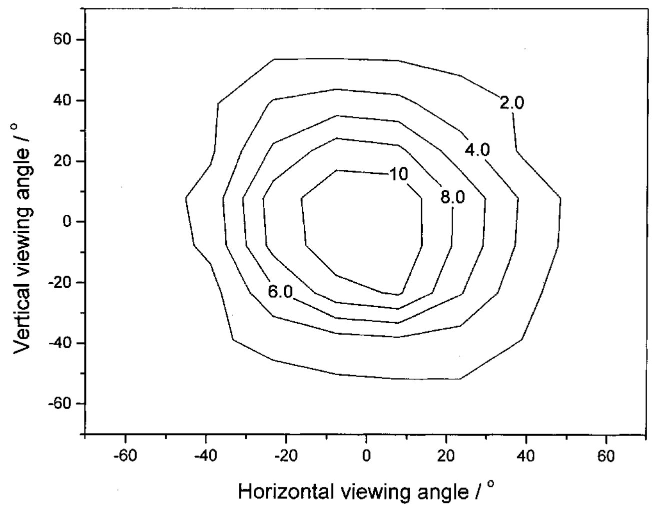

Figure 12. Viewing angle dependence of contrast ratio for mode E.

the mirror reflector could be placed inside the liquid crystal cell, so parallax could be removed. Only mode A at ($\phi = 90°$, $d\Delta n = 0.25\,\mu m$) was found for the normally white mode. Mode A has good electro-optical response and dispersion properties; for the normally black mode, mode D at ($\phi = 60°$, $d\Delta n = 0.20\,\mu m$) has a good dispersion property. The dispersion is better than for a reflective display device without a compensation film [1]. The viewing angle characteristic was calculated for these two optimum modes, they have a wide and symmetric viewing angle; mode D has the broadest viewing angle.

We also tried to optimize the polarizer angle β; there was no improvement of electro-optical response or dispersion on changing polarizer angle β. The simple configuration of parallel polarizer and input director, and 45° or 0° quarter wave plate, for the front film compensated reflective devices, gives very good operation modes for both normally white and normally black operation.

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