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# Analysis of operation mode of reflective liquid crystal display devices

HONGFEI CHENG* HONGJIN GAO and FUSHAN ZHOU
Center of Liquid Crystal Technology, Department of Chemistry, Tsinghua University, Beijing 100084, PR China

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The reflective liquid crystal display device having one polarizer was studied with the dynamic parameter space method. Device operation mode was analysed for both normally black and normally white operation conditions. The electro-optical responses and reflectance spectra were also studied for different operation modes. It was found that the optimized normally white modes for twist angles 180° and 220° of the reflective liquid crystal device have satisfactory contrast ratios and dispersion properties. For these twist angles, two equivalent normally white modes exist. The polarizer angles $\beta_1$ of the first mode and $\beta_2$ of the second mode have the simple relation $\beta_2 = 90° + \beta_1$.



## 1. Introduction

Liquid crystal display devices can be classified into two categories: transmissive or reflective. Transmissive devices usually require backlighting which is a main source of power consumption. Nowadays most widely used reflective liquid crystal devices use two polarizers and one diffuse reflector. This type of reflective liquid crystal device has very low light efficiency, since light travels four times through the polarizers. An optically ideal reflective liquid crystal device is of the structure as illustrated in figure 1, having one front polarizer and one reflector placed inside the cell. The liquid crystal is sandwiched between two glass plates coated with indium tin oxide (ITO) which act 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 passes the front polarizer twice. This type of reflective device has a brighter 'bright' state than a conventional two polarizers reflective device. In the conventional reflective device, the reflector is placed on the back of a substrate glass of the liquid crystal cell, the thickness of substrate glass in front of the reflector could cause parallax. By placing the reflector inside the cell, parallax could be removed.

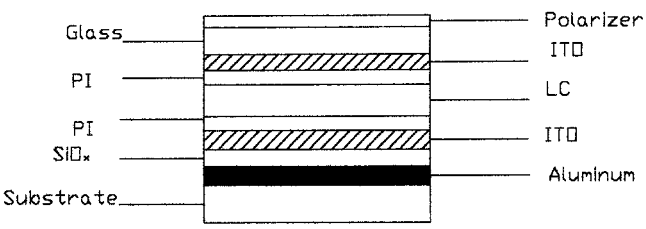


Figure 1. Illustration of the structure of the reflective LCD with one polarizer.

*Author for correspondence.

The reflective liquid crystal device with one polarizer has been discussed by several authors [1–3]. In this paper a systematic treatment of this structure will be given in terms of the dynamic parameter space method [4]. The parameters defining the parameters space are the thickness and birefringence product $d\Delta n$, the liquid crystal twist angle $\phi$ and the angle between polarizer and input director $\beta$. 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 parameter fixed while varying voltage is applied. This method is based upon very efficient programming for the calculation of director profile by variation technique [5]; Berreman's $4\times 4$ matrix method is used to calculate optical properties [6]. Two types of contour plot 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 distribution in the liquid crystal cell is calculated for the entire range of twist angle $\phi$ 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.

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## 2. Normally black mode

A simple geometry for the reflective device was assumed, for study of the normally black mode. The input director and the polarizer are 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 is 2°; cell thickness $d$ is 5.0 μm. Pitch $p$ varies with twist angle and is equal to $2\pi d/\phi$. The director profile was calculated for each twist angle from 0° to 360°, its optical properties were calculated by Berreman's $4 \times 4$ matrix method.

Figures 2 and 3 show reflectance contour plots of this reflective device at the 'off' state and the 'on' state, respectively. The voltages applied at 'off' and 'on' are 0.0 and 3.0 V respectively. The reflectance was normalized to the reflectance of an aluminum mirror and the front polarizer was attached to the aluminum mirror by itself. The reflectance was normalized in the same way throughout. Figure 4 shows the contrast ratio contour plot ($R_{\mathrm{on}}/R_{\mathrm{off}}$). The wavelength used in all calculations was 550 nm.

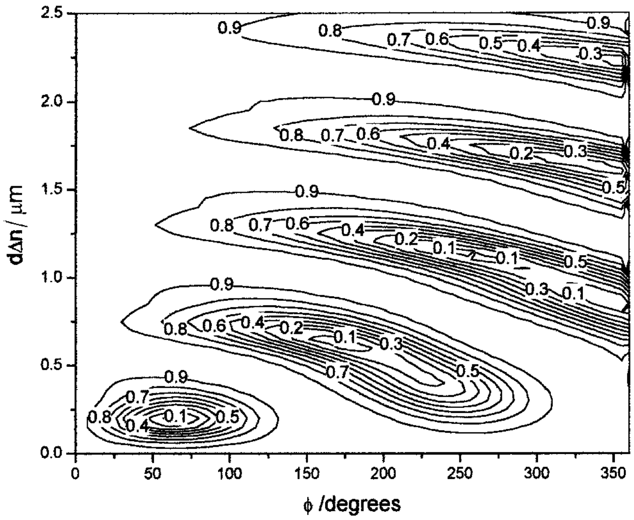


Figure 2. Reflectance contour plot at 'off' state for normally black mode.

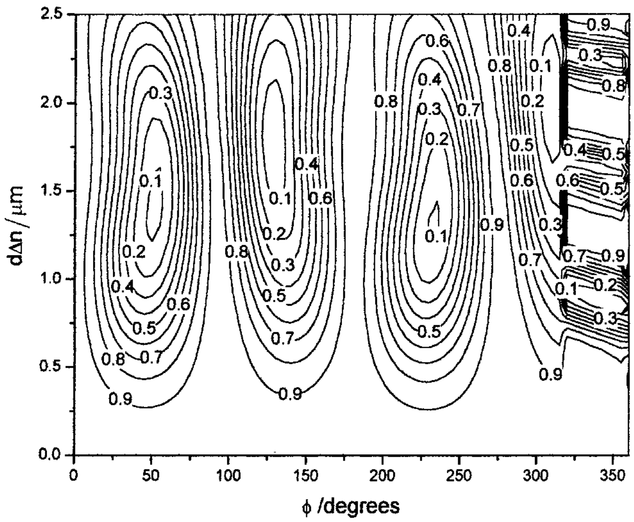


Figure 3. Reflectance contour plot at 'on' state for the normally black mode.

From figure 4 there are three possible operation modes, they are: mode A ($\phi = 65°$, $d\Delta n = 0.22$ μm), mode B ($\phi = 168°$, $d\Delta n = 0.65$ μm) and mode C ($\phi = 273°$, $d\Delta n = 1.15$ μm). Mode B has the highest contrast ratio of these three, and its requirement of $d\Delta n = 0.65$ μm can be easily met by available STN liquid crystal materials. The reflectance efficiency for these three modes are almost equally good. In general the reflective device has a lower contrast ratio compared with the transmissive device due to the reflection of the front polarizer surface. The contrast ratios of these three modes are listed in table 1. The contrast ratios in table 1 were calculated for a particular wavelength of light. In reality all the modes have a large colour separation.

The electro-optical responses for the three modes were also calculated as shown in figure 5. The dependence of the electro-optical response on the twist angle is similar to TN and STN devices. The electro-optical response becomes steeper when the twist angle increases. Mode B

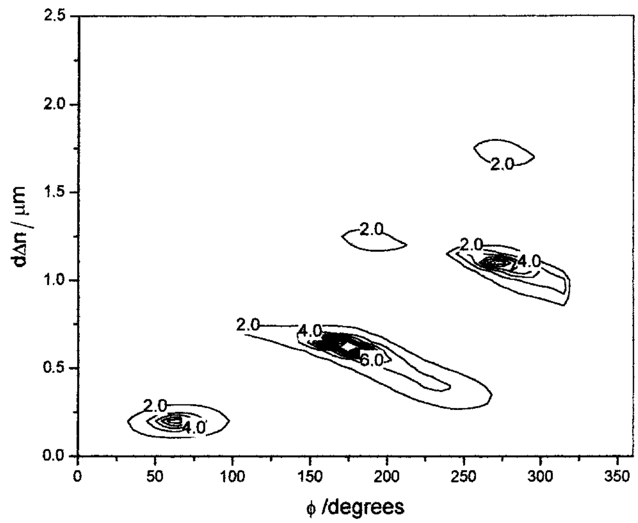


Figure 4. Contrast ratio contour plot ($R_{\mathrm{on}}/R_{\mathrm{off}}$) for the normally black mode.

Table 1. Contrast ratios for the normally black modes.

| Mode | Contrast ratio |
|---|---|
| A ($\phi = 65°$, $d\Delta n = 0.22$ μm) | 11.75 |
| B ($\phi = 168°$, $d\Delta n = 0.65$ μm) | 19.54 |
| C ($\phi = 273°$, $d\Delta n = 1.15$ μm) | 9.26 |

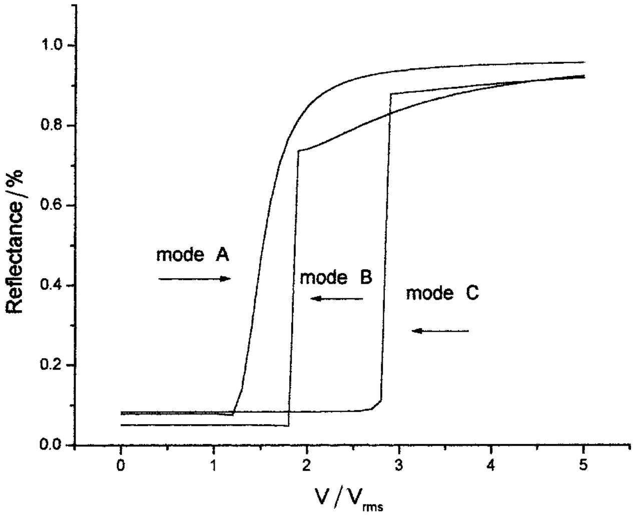


Figure 5. Electro-optical response for the normally black mode.

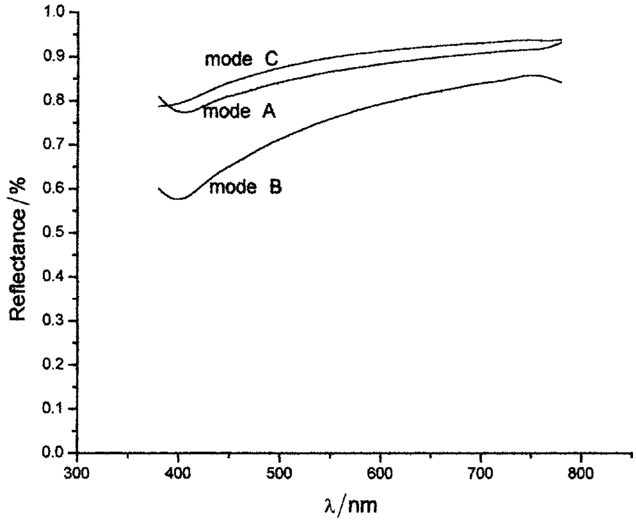


Figure 7. Reflectance spectra at 'on' state for the normally black mode.

has the lowest operation voltage of the three modes. Figure 6 shows the reflectance spectra for the three modes at 'off' states; figure 7 shows the reflectance spectra for the three modes at 'on' states. The voltages applied for modes A, B and C were 2.5, 2.0 and 3.0 V, respectively. The reflectance spectrum has a strong dependence on the wavelength for the negative modes (normally black modes) at the 'off' state.

## 3. Normally white mode

In order to compare the one polarizer reflective liquid crystal display device with TN and STN display devices, twist angles 90°, 180°, 220° and 240° were chosen to study the normally white mode. The director profiles were solved for these four twist angles. The polarizer angle $\beta$ and $d\Delta n$ were determined by drawing reflectance contour plots in ($\beta$, $d\Delta n$) coordinates. The liquid crystal material parameters used in the calculation were the same as stated above. Pitch $p$ is equal to $2\pi d/\phi$; $\phi$ is the twist angle. The pretilt angles for twist angles 90°, 180°, 220° and 240° are 1°, 2°, 3° and 5° respectively. Assuming the reference direction is the same as the input director direction, positive $\phi$ means that the director twists in an anti-clockwise fashion beginning from the input director; positive $\beta$ means that the angle of the polarizer with reference to the input director is anti-clockwise.

The reflectance contour plot for twist angle 180° at the 'off' and 'on' states is shown in figures 8 and 9. The applied voltages at the 'off' and 'on' states are 0.0 and 2.5 V, respectively. The contrast ratio contour plot ($R_{off}/R_{on}$) is shown in figure 10. From this figure, two

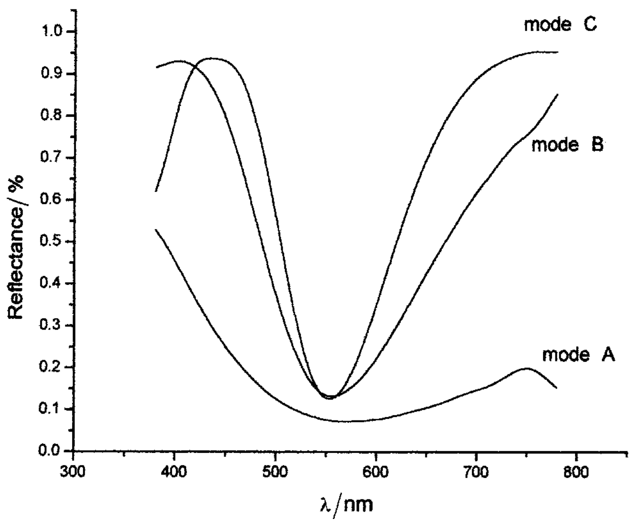


Figure 6. Reflectance spectra at 'off' state for the normally black mode.

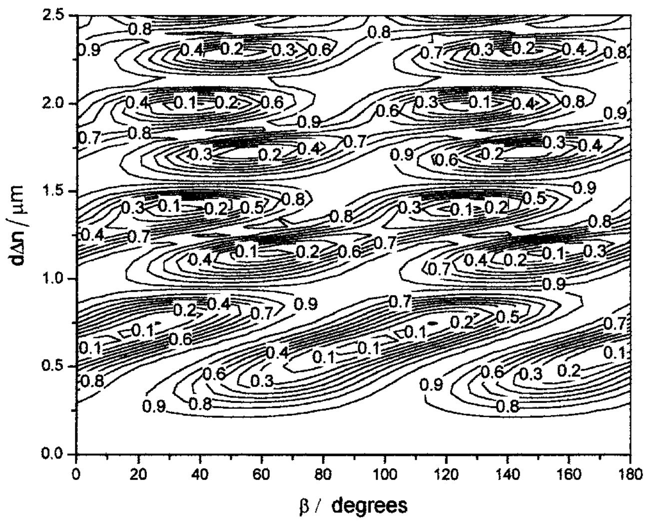


Figure 8. Reflectance contour plot at 'off' state for twist angle 180°

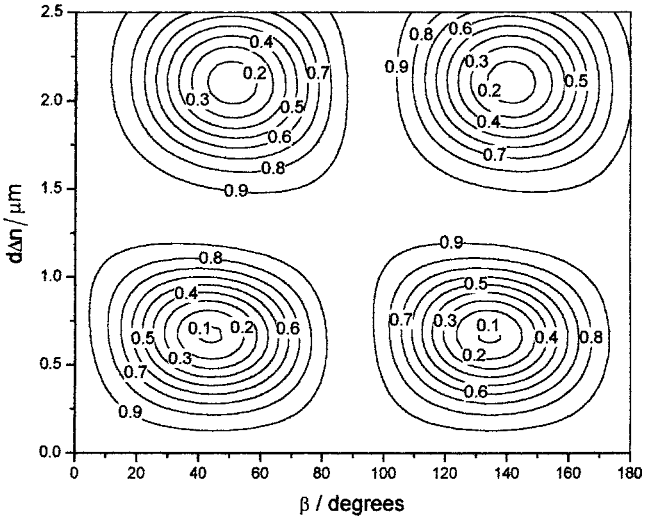


Figure 9. Reflectance contour plot at 'on' state for twist angle 180°

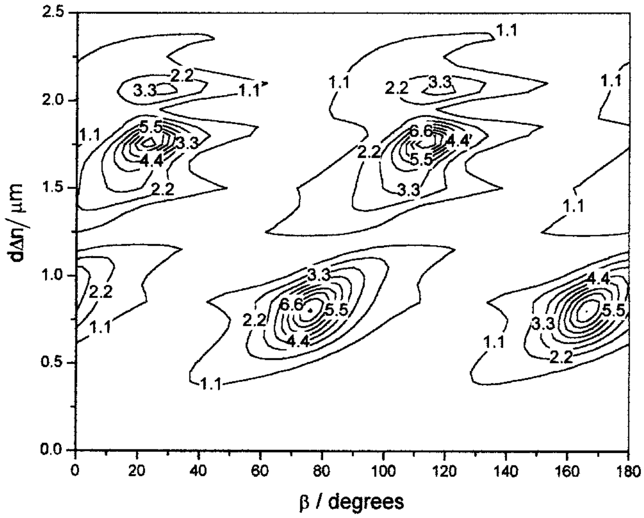


Figure 11. Contrast ratio contour plot ($R_{off}/R_{on}$) for twist angle 220°.

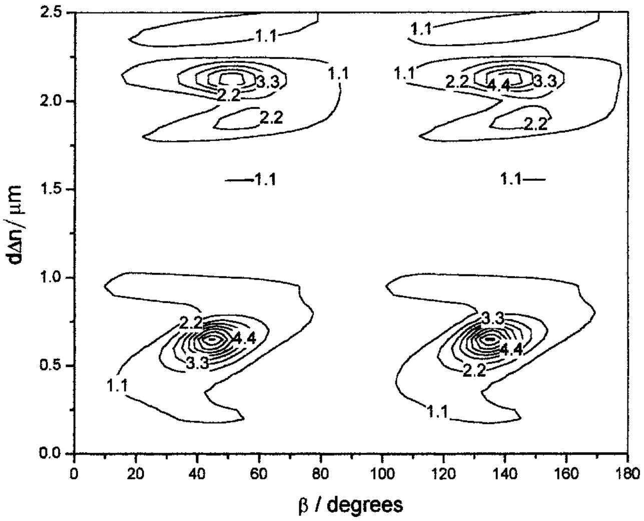


Figure 10. Contrast ratio contour plot ($R_{off}/R_{on}$) for twist angle 180°.

modes (at $\beta_1 = 45°$, $d\Delta n = 0.65\,\mu m$; and $\beta_2 = 135°$, $d\Delta n = 0.65\,\mu m$) have appropriate $d\Delta n$ value which can be easily realized by currently available liquid crystal materials. They are called mode D and E respectively. The contrast ratio contour plot ($R_{off}/R_{on}$) for the twist angle 220° is shown in figure 11. The applied voltages at 'off' and 'on' states are 0.0 and 2.5 V, respectively. Two modes exist (at $\beta_1 = 76°$, $d\Delta n = 0.80\,\mu m$; and $\beta_2 = 166°$, $d\Delta n = 0.80\,\mu m$). They are named mode F and G respectively. It is interesting to point out that polarizer angle $\beta_1$ of the first mode and polarizer angle $\beta_2$ of the second mode have a simple relation: $\beta_2 = 90° + \beta_1$ for both twist angles 180° and 220°. We also found that the first and second modes actually have same electro-optical response and reflectance spectra.

The electro-optical responses are given in figure 12. The curve labelled 180° represents both the first and second modes of twist angle 180°. The curve labelled 220° represents both the first and second mode of twist angle 220°. By comparing figures 5 and 12, the electro-optical response of normally black modes are seen to be steeper than those of normally white modes at comparable twist angles. The multiplex property of the normally black mode is better than the normally white mode. The reflectance spectra at both 'on' and 'off' are shown in figure 13. The voltages applied at 'off' and 'on' were 0.0 and 2.5 V for both twist angles 180° and 220°. The dispersion property is much improved for the normally white modes as compared with the normally

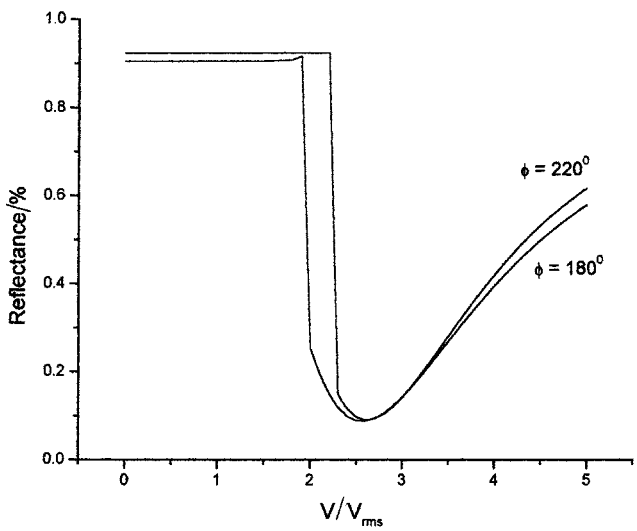


Figure 12. Electro-optical response for the normally white mode.

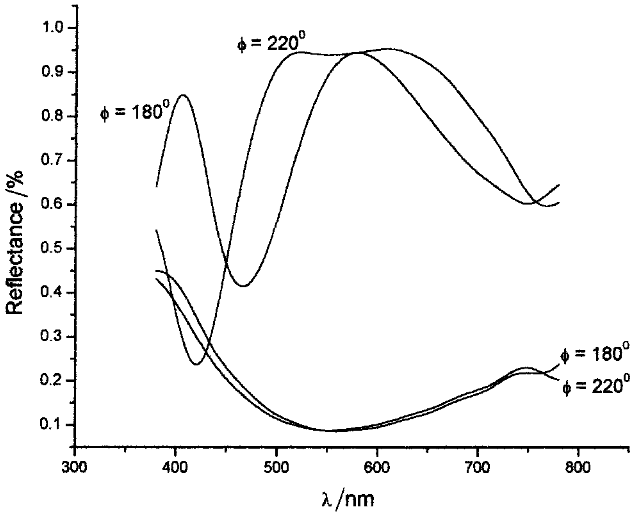


Figure 13. Reflectance spectra for the normally white mode.

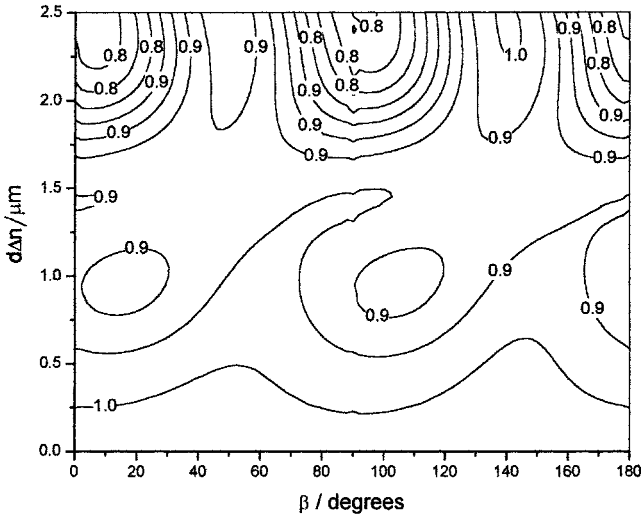


Figure 15. Reflectance contour plot at 'on' state for twist angle 90°.

black modes. The contrast ratios of mode D of twist angle 180° and mode F of twist angle 220° are listed in table 2.

Figures 14 and 15 show the reflectance contour plots for twist angle 240° and 90° at 'on' states. The voltage applied was 2.5 V. The minimum points in the reflectance contour of twist angle 240° have a higher $d\Delta n$ value than is practicable. For the twist angle 90°, no minimum points of reflectance exist. Thus, normally white modes could not be found for twist angles 240° and 90°.

Table 2. Contrast ratios for the normally white modes.

| Mode | Contrast ratio |
|---|---|
| D ($\beta$= 45°, $d\Delta n$ = 0.65 μm) | 10.02 |
| F ($\beta$= 76°, $d\Delta n$ = 0.80 μm) | 10.01 |

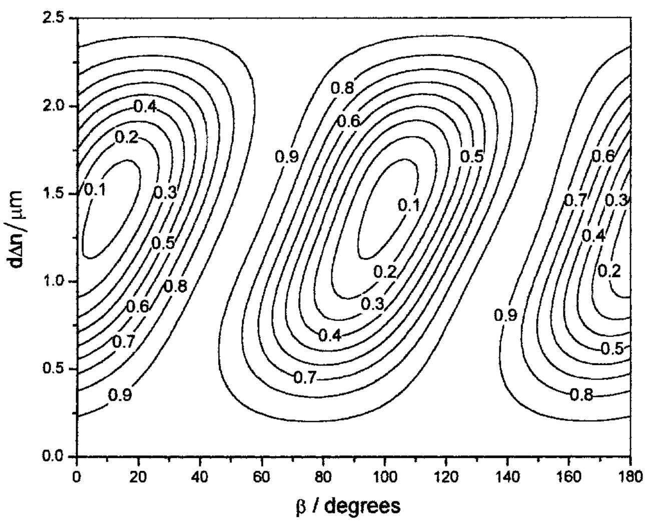


Figure 14. Reflectance contour plot at 'on' state for twist angle 240°.

## 4. Conclusions

The reflective liquid crystal device with one polarizer was studied in terms of the dynamic parameter space method. Both normally black modes and normally white modes were investigated. For the normally black modes, mode B at ($\phi$ = 168°, $d\Delta n$ = 0.65 μm) shows good contrast and has a reasonable $d\Delta n$ value. But the reflectance spectrum has serious dispersion at the 'off' state for the normally black modes. The dispersion could be improved by using a compensation film in MTN mode [7]. For the normally white modes, we have found that two modes exist for twist angle 180° or 220°. Mode D at ($\beta_1$ = 45°, $d\Delta n$ = 0.65 μm) and mode E at ($\beta_2$ = 135°, $d\Delta n$ = 0.65 μm) are for the twist angle 180°. Mode F at ($\beta_1$ = 76°, $d\Delta n$ = 0.80 μm) and mode G at ($\beta_2$ = 166°, $d\Delta n$ = 0.80 μm) are for the twist angle 220°. It is shown for the first time that the polarizer angle $\beta_1$ of first mode and the polarizer angle $\beta_2$ of second mode, for twist angle 180° or 220°, have the simple relation $\beta_2 = 90° + \beta_1$. The first and second modes are actually equivalent in terms of electro-optical response and reflectance spectra. The normally white modes have satisfactory dispersion properties and contrast ratios and could be readily realized by current STN technology. The relatively low contrast ratio of the reflective liquid crystal display device is caused by the surface reflection of the front polarizer. The contrast ratio can be much improved by using an antireflection polarizing film instead. The surface reflection is around 4% for the conventional polarizer while that of antireflection polarizing film is around 0.3% in most of the visible light region.

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