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Dependence of viewing angle characteristics on pretilt angle in the in-plane switching mode

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Viewing angle characteristics were systematically obtained when using in-plane switching (IPS) of liquid crystals. Although the IPS mode originally shows stable electro-optical performance regardless of viewing directions, the viewing angle characteristics are found to be strongly dependent on pretilt angle (slant angle of the liquid crystals from the substrate). Experimentally, the smaller the pretilt angle of the liquid crystal, the much wider the viewing angle characteristics, while larger pretilt angles of liquid crystals cause the characteristics to deteriorate. This deterioration occurs in a particular viewing direction, i.e. at right angles to the initial orientation direction of the liquid crystal when there is no in-plane electric field. The experimentally observed behaviour of the viewing angle dependence on the pretilt angle was also confirmed by computer simulations. Calculated iso-contrast contour lines, as a function of the pretilt angles, nearly coincide with the experimentally obtained viewing angle characteristics of the contrast ratio.

1. Introduction

Although liquid crystal displays (LCDs) have made great progress in their quality, it is well known that twisted nematic (TN) LCDs, which are now the type most commonly used, have narrow and non-uniform viewing angle characteristics. The electro-optical characteristics of conventional TN-LCDs are strongly dependent on the viewing angle direction and this provides a serious inconvenience for good grey scale operation. These drawbacks concerning the viewing angle characteristics originate from the fact that liquid crystal molecules behave as a uniaxial medium and have a birefringence effect. In order to overcome them, a number of techniques have been developed [1–16]. One solution to the viewing angle problem is to average the electro-optical performance, which is strongly dependent on the viewing angle direction, by employing optical compensation. Division of the liquid crystal alignment in each pixel into sub-pixels, known as a multi-domain mode, in such a way that the birefringence is compensated by each domain, is one possibility [1–9]. Another solution is an electrically controllable bend alignment structure of the liquid crystal known as the OCB mode [10, 11]. Furthermore, birefringence films which compensate the birefringence effect in an oblique viewing direction are also noteworthy [12–16]. These three solutions are categorized as optical compensation of the birefringence. However, the multi-domain mode presents problems at the manufacturing stage and it is difficult to maintain a stable control of the liquid crystal by a bias voltage in the OCB mode.

We have reported a novel technology to offer an extremely wide viewing angle characteristic, which combines an actively addressed driving technique and an in-plane switching (IPS) mode, in which the liquid crystals are driven and switched while retaining the plane of the substrates by the in-plane electric field applied parallel to the substrates [17–20]. So far we have realized the switching physical principle, i.e. electro-optical effects, threshold behaviour and dynamical response mechanism of the liquid crystals, governed by the in-plane electric field [21–23]. A simplified expression describing the threshold behaviour of the liquid crystals, which was derived with the assumption that a uniform in-plane electric field was applied along the direction perpendicular to the director and parallel to the homogeneously aligned nematic slab, was confirmed to be sufficiently helpful to explain the experimentally obtained results. First, a critical field at which the liquid crystals just began to twist, was found to be proportional to the reciprocal of the cell gap. Second, it was the electric field and not the voltage that drove the liquid crystals. This relationship was due to the independence of the electric field to the liquid crystal layer normal

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direction. Hence, the threshold voltage in the IPS mode was strongly dependent on the variation of the cell gap. The switching on and off processes of the liquid crystals were analysed quantitatively to get the dynamical response mechanism of the liquid crystals to the in-plane electric field. The relaxation time of the liquid crystals when removing the electric field could be described as a proportional relationship to the square of the cell gap. A narrower cell gap also proved to be effective in obtaining a faster response time in the IPS mode. By contrast, the switching on time when applying the in-plane electric field was inversely proportional to the difference between the square of the electric field strength and the square of the critical electric field strength at which the liquid crystals began to deform.

To obtain a better understanding of the IPS operation, analysis of the IPS mode by computer simulations have been gradually introduced [24, 25]. Simulations are helpful in understanding the inhomogeneous electric field between the upper and lower substrates and the distribution of the liquid crystal directors between the interdigital electrodes, although it is possible to analyse the physical switching principle with an assumption of a uniform in-plane electric field between the substrates. Computer simulations will be indispensable for detailed design work on the IPS mode.

In this paper, we analyse the viewing angle characteristics in detail and investigate the effect of the pretilt angles on the viewing angle characteristics in the IPS mode. A simple comparison of the viewing angle characteristics between smaller and larger pretilt angles was carried out [26]. However, detailed analyses regarding the viewing angle characteristics have not been made, beyond noting the facts that the IPS mode provides extremely wide viewing angle characteristics and smaller pretilt angle is more effective for good viewing angle characteristics than larger pretilt angle. It is important to understand how good viewing angle characteristics can be obtained by using the IPS mode and to identify what parameters are related to them. From the viewpoint of the electro-optical performance in the IPS mode, the pretilt angle is not needed for switching the liquid crystals uniformly. However, our interest centres on the relationship between the viewing angle characteristic and the pretilt angle because it is one of the important parameters which give all the details of the viewing angle characteristics. We define the pretilt angle as the averaged inclined angle of the liquid crystal directors from the substrates. The pretilt angle is directly related to the orientation of the liquid crystals and the inclination of the liquid crystals from the substrates seems to affect the optical condition even in the IPS mode. First, we mention the reason for the good viewing angle characteristic of the IPS mode. We then describe experiments on the pretilt angle dependent viewing angle characteristics. Finally, we apply computer simulations to confirm the experimental viewing angle characteristics and to analyse how the pretilt angle affects them.

2. Experiment and calculation

To evaluate the viewing angle characteristics, we prepared samples by sandwiching the liquid crystal between two rubbed polyimide layers coated on substrates. In order to apply the in-plane electric field to the liquid crystals, interdigital electrodes made of chromium were formed on one substrate and no electrodes were prepared on the other substrate. The two substrates were set in the same rubbing direction to obtain homogeneously aligned liquid crystals. Polymer bead spacers were scattered over one substrate to provide a uniform cell gap. The liquid crystal materials, ZLI-2806 and ZLI-4535 (Merck KGaA, Darmstadt), which show the nematic phase at room temperature, were used. Their properties are as follows: ZLI-2806, (nematic–isotropic temperature T_{NI}: 100°C, birefringence Δn: 0·0437 (20°C), dielectric anisotropy $\Delta\varepsilon$: $-4{\cdot}8$ (20°C, 1 kHz), viscosity η: 57 cp (20°C)) and ZLI-4535, (nematic–isotropic temperature T_{NI}: 63°C, birefringence Δn: 0·0865 (20°C), dielectric anisotropy $\Delta\varepsilon$: 14·8 (20°C, 1 kHz), viscosity η: 26 cp (20°C)). To obtain a wide range of pretilt angles, the combination of the alignment layers, composed of polyimides with negative (N_n) and positive (N_p) dielectrio-anisotropic liquid crystals, was changed.

The measurements of the viewing angle characteristic were performed by using a spatial photometer (ELDIM EZContrast 120D). Figure 1 (*a*) defines the viewing angle directions, i.e. incident angle θ and azimuthal angle ϕ and figure 1 (*b*) shows the configuration of the liquid crystal director in the circular coordinate system used to evaluate the viewing angle characteristics. The rubbing direction was set at 165° for both N_n and N_p liquid crystals. Therefore the in-plane electric field applied to the liquid crystals differed by the right angle between the N_n and N_p liquid crystals in the circular coordinate system. Grey scales were determined as the voltages at which the transmittances were 100, 85·5, 57·0, 35·1, 20·7, 11·2, 4·6 and 1·0 per cent from the front view, assuming the maximum transmittance was 100 per cent. The pretilt angle was measured by the conventional crystal-rotation method [27].

For computer simulations of the viewing angle characteristics, the liquid crystal orientation achieved by the electric field was calculated by minimising the free energy per unit volume of a deformed liquid crystal: i.e. Frank's elastic energy and interaction energy with the electric field. The calculation of the liquid crystal orientation was carried out one dimensionally in the direction normal to the liquid crystal layer. The optical viewing

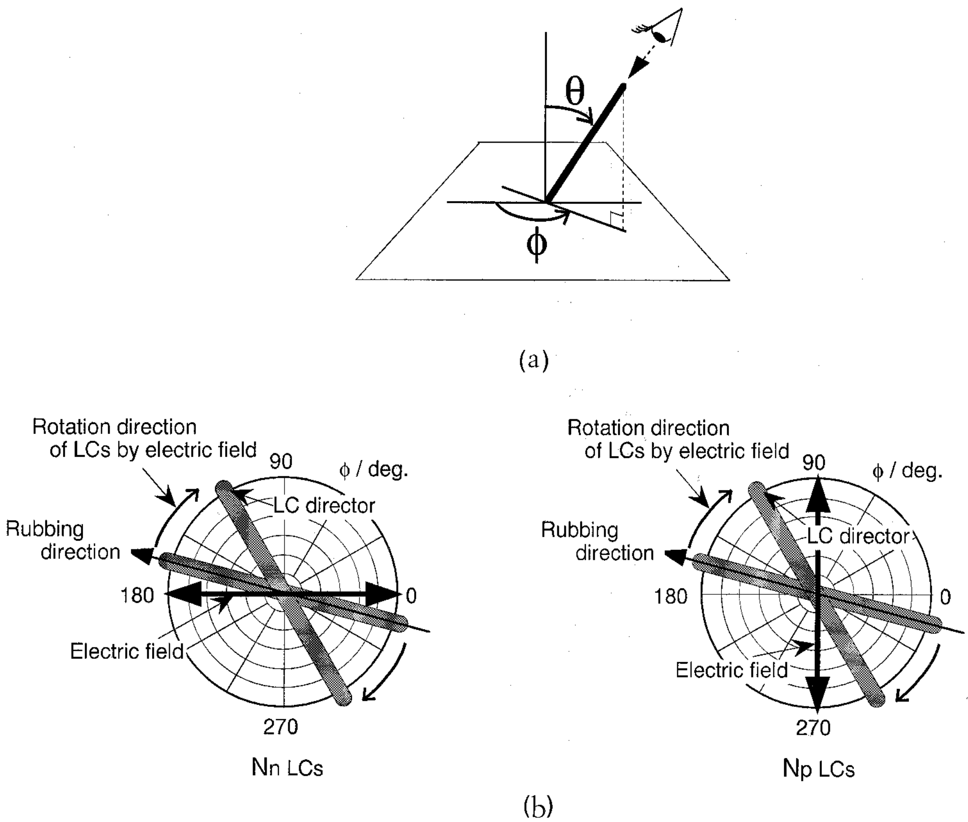


Figure 1. (*a*) Definition of viewing angle directions and (*b*) a circular coordinate system showing the LC configurations when evaluating the viewing angle characteristics of the IPS mode.

angle characteristics were calculated using the extended Jones matrix method developed by Lien [28]. The parameters used in the calculation are listed in the table.

3. Results and discussion

The fact that the IPS mode has a better viewing angle characteristic in comparison to the TN mode, originates from the difference in how a dark state is generated. First we need to consider briefly why the TN mode shows a limited and asymmetric viewing angle characteristic. The combination of the TN configuration and the electric field applied perpendicularly to the substrates causes switching of the optical function between the rotatory power effect at a lower voltage and the birefringence effect due to the uniaxial medium at a higher voltage. When a higher voltage is applied to the liquid crystals, the orientation of the longitudinal axes becomes nearly perpendicular to the substrates. This corresponds to the fact that there is only one direction, which is nearly perpendicular to the substrates, at which the optical difference due to the liquid crystals equals zero. In other words, this means a completely dark state can only be obtained when the viewing angle direction is perpendicular to the substrates when the polarisers are set at right angles to each other.

In the IPS mode, however, the dark state is generated

Table. Parameters used in the calculation of the viewing angle characteristics.

	N_n LC for IPS	N_p LC for IPS	N_p LC for TN
Model LC	ZLI-2806	ZLI-4535	MLC-2027
Birefringence Δn	0·0437	0·0865	0·0932
Dielectric constants			
longitudinal $\varepsilon_{\parallel}$	3·3	20·6	14·0
transverse $\varepsilon_{\perp}$	8·1	5·8	4·4
Elastic constants			
splay K_1 [pN]	14·9	9·3	10·4
twist K_2 [pN]	7·9	5·9	4·8
bend K_3 [pN]	15·2	11·8	16·2
Cell gap d [μm]	6·0	4·0	5·0
Pretilt angle [deg]	1·5, 4·0, 8·0	1·5, 20·0	8·0

in an entirely different way from the above. The transmittance of light passing through the uniaxial medium is represented as follows:

$$T/T_0 = \sin^2(2\chi)\cdot\sin^2\left(\frac{\delta}{2}\right) = \sin^2(2\chi)\cdot\sin^2\left(\frac{\pi d\cdot\Delta n(\phi,\theta)}{\lambda}\right) \quad (1)$$

where χ is the angle between the direction of the incident polarised light and the optical axis of the uniaxial media, $\Delta n(\phi, \theta)$ symbolises the birefringence of the uniaxial medium which is dependent on the aximuthal and incident angles of the viewing direction with respect to the substrate normal direction, and λ is the wavelength of the light. With equation (1), for the IPS mode with birefringence mode, switching from the dark to the bright state or from the bright to the dark state is achieved by changing the first sin term, i.e. changing the angle between the direction of the polarised incident light and the optical axis of the liquid crystals by the in-plane electric field. Therefore the viewing angle characteristics of the dark state reflect those which are generated by the crossed polarisers and the dark state in the IPS mode can be maintained even when the viewing direction is inclined. Figure 2 compares the viewing angle characteristics between the TN and the IPS modes in terms of the iso-contrast and the iso-brightness in the bright and dark states. As expected, the difference of the viewing angle characteristic was related to how the dark state generated the least light leakage for obliquely incident light over a wide range of angles.

Figure 3 shows the viewing angle characteristics when using the IPS mode with a variety of pretilt angle. To obtain a wide range of pretilt angle, the combination of the liquid crystals with the alignment layers was changed and both N_n type, i.e. ZLI-2806, and N_p type, i.e. ZLI-4535, liquid crystals were used. We had already confirmed that both N_p and N_n type liquid crystals exhibit good viewing angle characteristics when using the IPS mode. The circular coordinate system was set as the initial orientation direction of the liquid crystals, pointing in the same direction, regardless of whether N_n or N_p type liquid crystals were being considered. In terms of the grey scale reversal, almost the same characteristics were obtained regardless of having smaller or larger pretilt angles. The direction in which the reversal of grey scales was observed was found to coincide with the longitudinal axes direction of the liquid crystals in the bright state. Along the direction of the longitudinal axes of the liquid crystals, the viewed optical birefringence could be varied even for a small change of viewing direction. In addition, the birefringence when viewed along the longitudinal axes of the liquid crystals was smaller than that along the transverse axes. Figures 4 (*a*) and (*b*) show the brightness dependencies on the incident viewing angles in the sectional plane passing from 120° to 300° of the azimuthal direction and in the sectional plane passing from 30° to 210° of the azimuthal direction, respectively. The light leakage of the dark state in an oblique direction as shown in figure 3 could be due to the crossed polarisers' property because the viewing direction in these cases corresponded to just 45° from the crossed polarization axes. On the other hand, in the bright state and all grey scales of figure 4 (*a*), the brightness was decreased by following the inclined viewing direction. This could be caused by the apparent change of optical difference ($d\cdot\Delta n$) in quite an oblique direction because the viewed birefringence of the liquid crystals decreased when viewing them along the longitudinal axes direction. Therefore, we attributed the occurrence of the grey scale reversal to the combination of the light leakage in the dark state with the decrease of the brightness in other states. In the sectional plane passing from 30° to 210° of the azimuthal direction as shown in figure 4 (*b*), however, the brightness of the grey scales was only slightly increased and it levelled off accordingly as the viewing direction was inclined from the substrate normal direction. As a result, no grey scale reversal occurred. This behaviour could occur because there was no apparent change of the birefringence along the transverse axes direction. In addition, the optical difference of the liquid crystal layer was a little smaller than that which generated the maximum brightness due to the strong anchoring near the surface. Therefore, the brightness in the oblique direction would be insensitive to the incident angles in this case.

In contrast to the characteristics of the grey scale reversal, the iso-contrast contour lines were strongly dependent on the pretilt angle. With smaller pretilt angles, the viewing angle characteristics were extremely wide and excellent as we expected. The shape of the lines reflected the transmittance characteristics of the crossed polarisers. However, the increased pretilt angles caused deterioration of the viewing angle characteristics. The shape of the iso-contrast contour lines gradually narrowed when the pretilt angle was increased. The deterioration was found to occur in a particular direction and at the same time, the contrast was maintained in the direction which was at right angles to the deterioration direction. The direction of the most deterioration regarding the contrast ratio by the increased pretilt angle was the transverse axes direction of the liquid crystals in the dark state with no electric field, i.e. the direction passing from 75° to 255° of the azimuthal direction. By

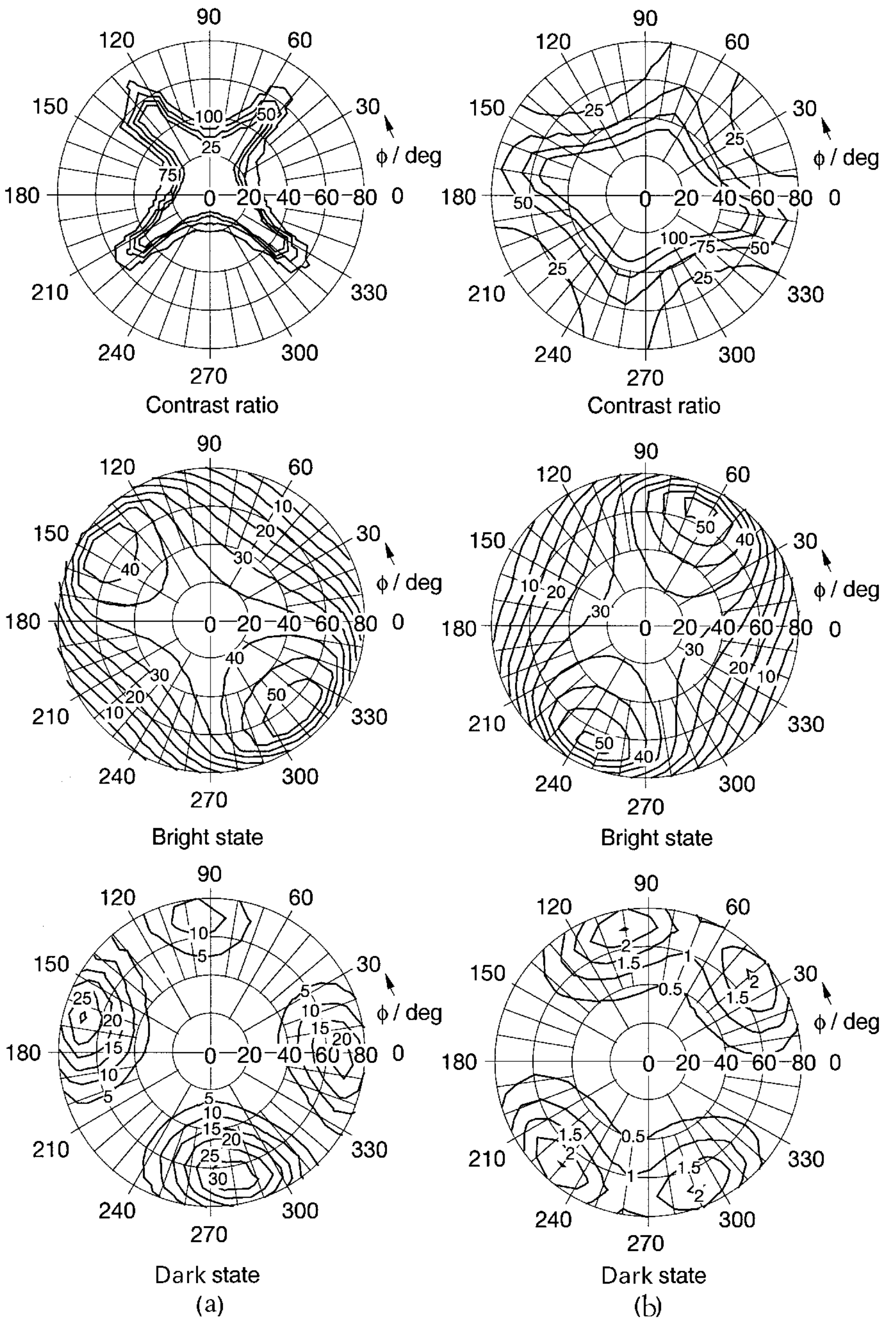


Figure 2. Comparison of the viewing angle characteristics in terms of the contrast ratio and the brightness in the bright and dark states between the TN and the IPS modes as obtained by computer simulations; (*a*) TN mode; (*b*) IPS mode. Pretilt angles in both modes were set to 8°.

contrast, in the direction passing from 165° to 345° of the azimuthal direction, the contrast ratio held regardless of the increased pretilt angle. The contrast ratio was determined by the transmittance of the bright state divided by that of the dark state. Therefore, the contrast ratio was strongly dependent on the light leakage of the dark state. Figures 5 (*a*) and (*b*) show the dependence of brightness in the dark state in the oblique viewing direction, which was affected by the pretilt angle, in the sectional plane passing from 165° to 345° of the azimuthal direction and in the sectional plane passing from 75° to 255° of the azimuthal direction, respectively. The brightness of the dark state was maintained when viewing in the sectional plane passing from 165° to 345° of the azimuthal direction, even if the pretilt angles were increased. However, the increase in the pretilt angle was confirmed to cause light leakage in the dark state in the direction, passing from 75° to 255° of the azimuthal

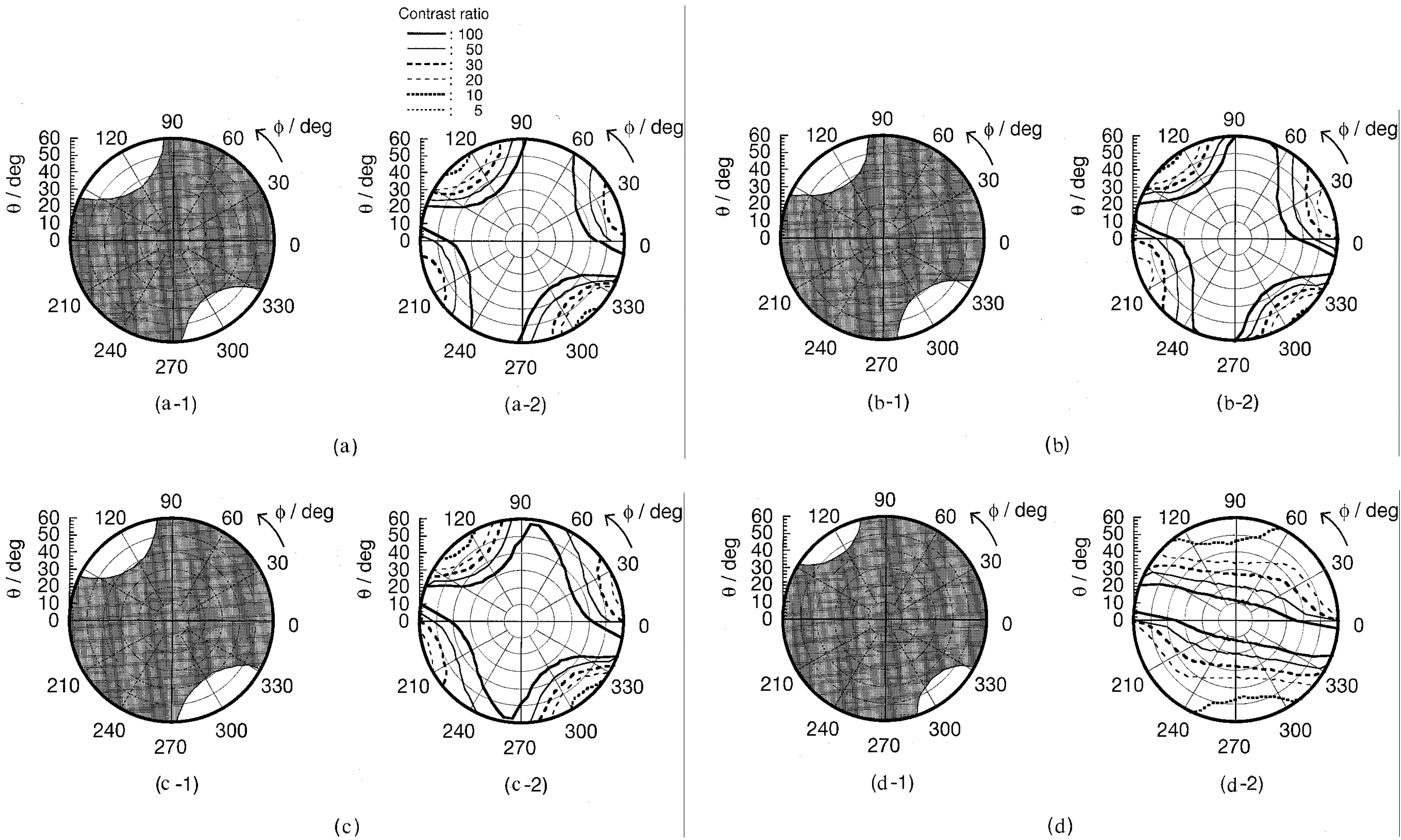


Figure 3. Experimentally obtained results of the viewing angle characteristics as a function of pretilt angle. Figures (*a*-1), (*b*-1), (*c*-1) and (*d*-1) display the non-reversal region of grey scales and figures (*a*-2), (*b*-2), (*c*-2) and (*d*-2) show the iso-contrast contour lines of the contrast ratio. (*a*) pretilt angle, 1·6°; LC, ZLI-2806; cell gap, 6·4 μm; (*b*) pretilt angle, 4·7°; LC, ZLI-2806; cell gap, 6·4 μm; (*c*) pretilt angle, 7·9°; LC, ZLI-2806; cell gap, 6·4 μm; (*d*) pretilt angle, >20°; LC, ZLI-4535; cell gap, 3·6 μm. Interdigital electrode width and electrode distance for all samples were 10 μm and 15 μm, respectively.

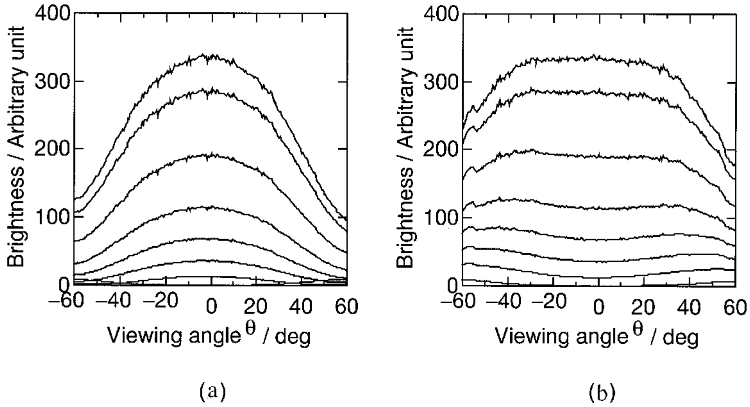


Figure 4. Incident viewing angle dependent brightness of eight grey scales (*a*) in the sectional plane passing from 120° to 300° of the azimuthal direction and (*b*) in the sectional plane passing from 30° to 210° of the azimuthal direction.

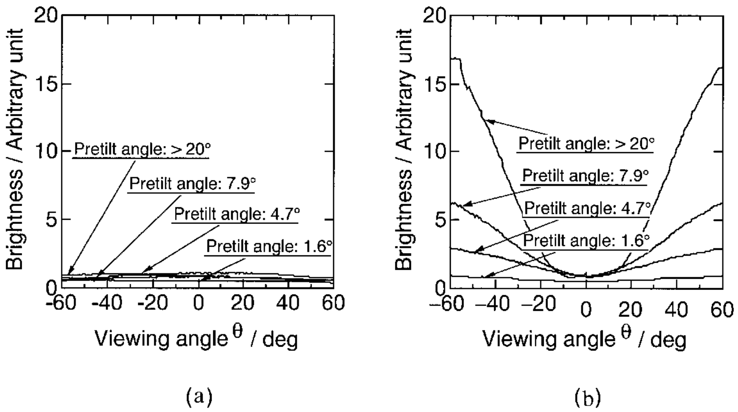


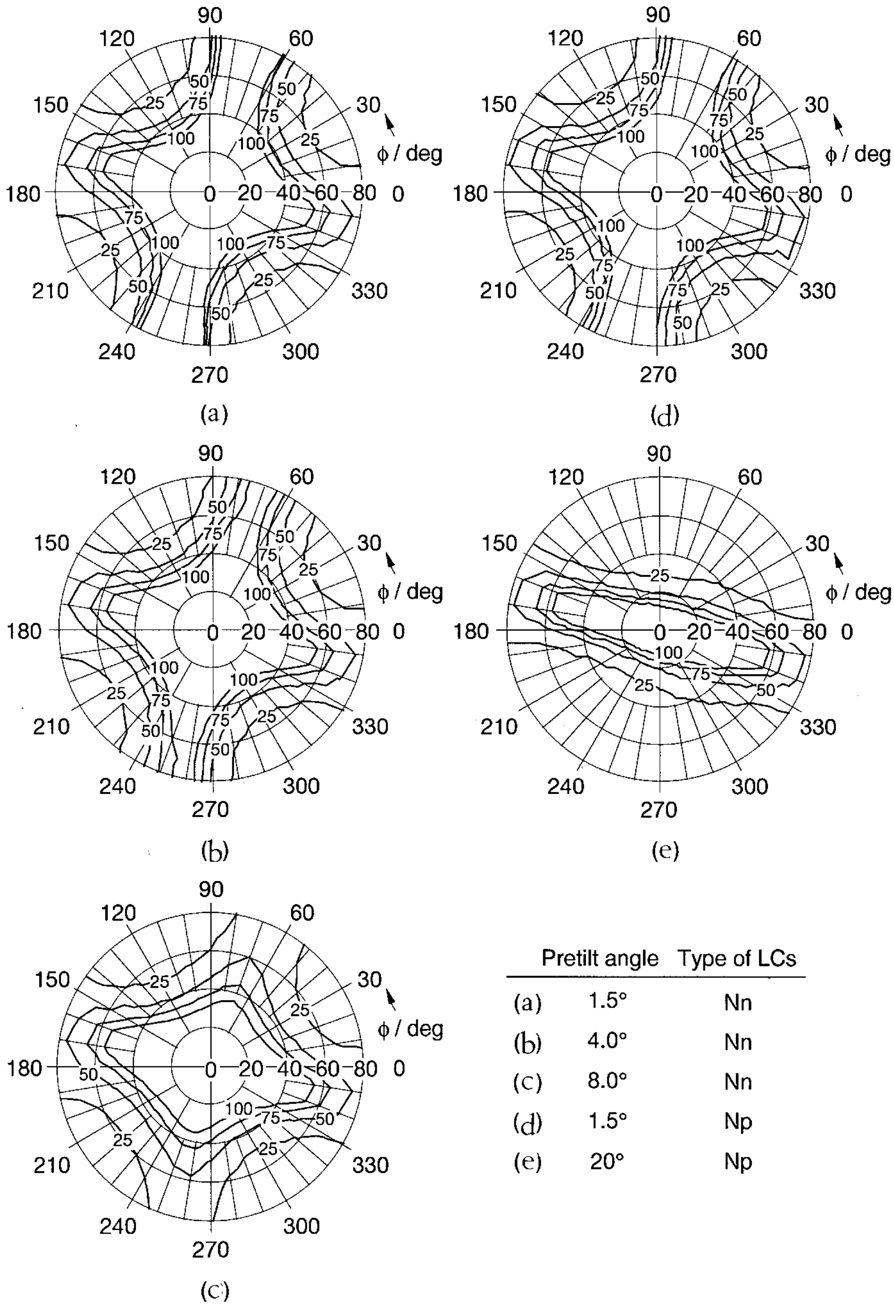
Figure 5. Incident viewing angle dependent brightness of the dark state as a function of pretilt angle (*a*) in the sectional plane passing from 165° to 345° of the azimuthal direction and (*b*) in the sectional plane passing from 75° to 255° of the azimuthal direction.

direction which was the same as the transverse axes direction of the liquid crystals in the dark state with no electric field, where the deterioration of the contrast ratio was observed. In this direction, the increased pretilt angle could cause the birefringence effect because the incident polarised light would pass through by crossing the optical axes of the liquid crystals. Therefore, light leakage at the higher pretilt angles could occur.

To confirm the viewing angle characteristics of the contrast ratio as a function of the pretilt angles, we carried out computer simulations of the iso-contrast contour lines. Figure 6 shows the calculated results of the iso-contrast contour lines as a function of the pretilt angles. The rubbing direction in the calculation was set to 165° in the azimuthal direction, which was the same coordinate system as in the experiments. First, as the experimental results indicated, the iso-contrast ratio contour characteristics were dependent on the pretilt angle and the larger pretilt angles deteriorated the contrast ratio in a particular viewing direction. Second, the particular direction was in good agreement with the transverse axes direction of the liquid crystals in the dark state when there was no electric field. This deterioration was caused by the increase in the brightness of the dark state. Figure 7 plots calculated viewing angle characteristics of brightness in the dark and bright states. The iso-brightness contour lines in the bright state were independent of the pretilt angle. In the dark state, however, the larger pretilt angle causes light leakage in the transverse axes direction of the liquid crystals, which was at right angles to the rubbing direction. Therefore, the computer simulations agreed well with the experimentally obtained results on the relationship between the viewing angle characteristics and the pretilt angle.

4. Conclusions

The relationship between the viewing angle characteristics and the pretilt angle in the IPS mode was analysed. Almost the same region was obtained as non-grey scale reversal, irrespective of the pretilt angle. The direction in which the grey scale reversal was observed coincided with the longitudinal axes direction of the liquid crystal directors in the bright state when the electric field was applied. The occurrence of the grey scale reversal was related to both the increase in the brightness of the dark state which was the crossed polarisers' property, and the



	Pretilt angle	Type of LCs
(a)	1.5°	Nn
(b)	4.0°	Nn
(c)	8.0°	Nn
(d)	1.5°	Np
(e)	20°	Np

Figure 6. Calculated iso-contrast contour lines as a function of pretilt angle. (*a*) pretilt angle, 1·5°; LC, N_n; (*b*) pretilt angle, 4·0°; LC, N_n; (*c*) pretilt angle, 8·0°; LC, N_n; (*d*) pretilt angle, 1·5°; LC, N_p; (*e*) pretilt angle, >20°; LC, N_p.

decrease in the brightness of other grey scales which was due to the decrease in the birefringence of the liquid crystals. On the other hand, smaller pretilt angles provided an extremely wide region of high contrast ratio, while larger pretilt angles caused deterioration of the contrast ratio in a particular viewing direction which was at right angles to the initial orientation direction of the liquid crystal directors when there was no electric field. Larger pretilt angles caused light leakage in the dark state because the incident polarised light passed through by crossing the optical axes of the liquid crystals. Finally, the results of the computer simulations for the viewing angle characteristics were in good agreement with the experimentally obtained results.

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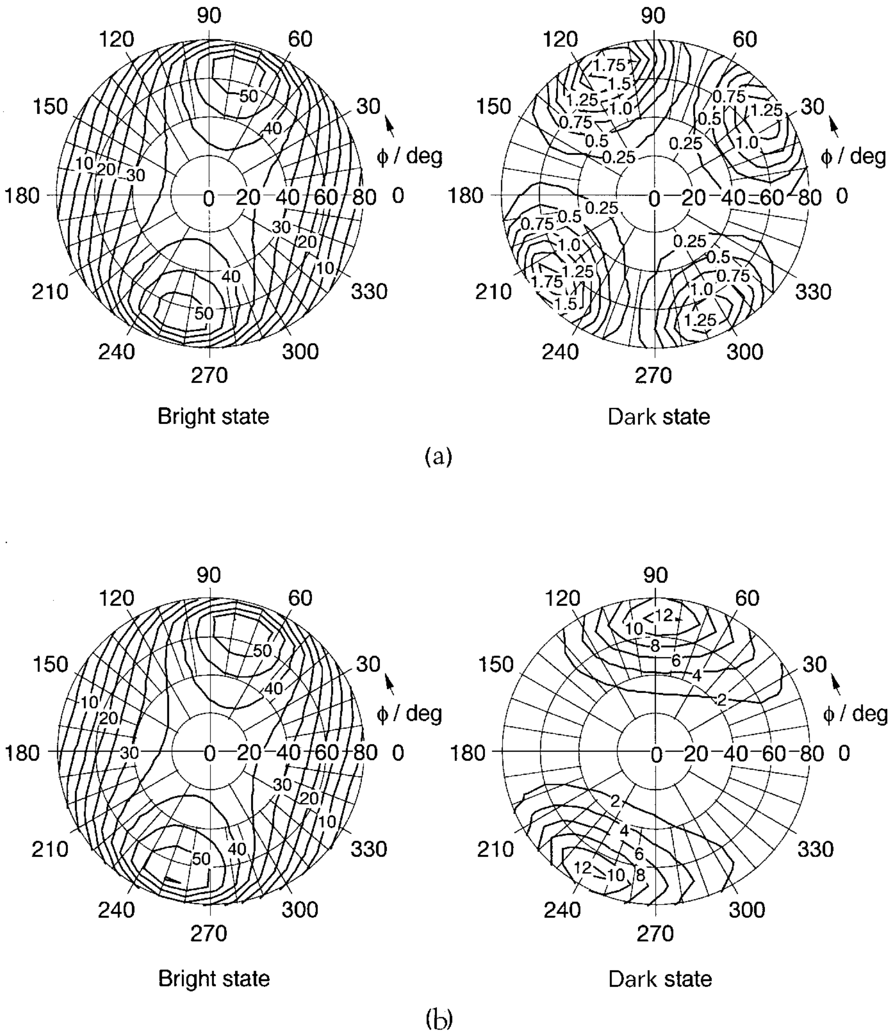

Figure 7. Calculated iso-brightness contour lines in the bright and black states (*a*) when the pretilt angle was set to 1·5° and (*b*) when the pretilt angle was set to 20°.

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