Technology of the GRP Formula for Wide-Viewing-Angle LCDs

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Abstract

This paper describes one of the wide-viewing-angle technologies for thin-film-transistor liquid-crystal-displays (TFT-LCDs), Gradual Refraction Polarizer (GRP) formula especially for a twisted nematic liquid crystal display (TN-LCD). This formula uses optical compensation films with an inclined optical indicatrix. The optical characteristics of the entire compensation film composed of a hybrid aligned discotic compound layer on a triacetylcellulose (TAC) substrate were identified as uniaxial negative birefringence whose optical axis was inclined from the normal direction. We determined that the optical parameters of combination of the discotic layer and the substrate as a whole govern the viewing characteristics of TN-LCDs using GRP films.

Introduction

As active-matrix LCDs (AM-LCDs) have dropped in price in recent years, they have moved beyond applications centered mainly on laptop and notebook PCs to encompass PC monitors, car navigation systems, camcorders, LCD TVs, PDAs, game devices, and mobile phones. However, in terms of viewing angle, the AM-LCDs used in these expanded applications suffer in comparison with CRTs (cathode ray tubes). Increasing the viewing angle of these LCDs has remained a nagging problem, and there is still room for improvement in this area. Several solutions to this problem have been reported, such as in-plane switching (IPS) mode1)2) and multi-domain vertical alignment (MVA) mode3). These display modes offer wider viewing angles, but there are problems with these approaches, such as front-surface brightness is sacrificed, the manufacturing process becomes complex, etc. The current situation is that twisted nematic (TN) mode LCDs having an optical compensation film with an inclined optical indicatrix predominates among the wide-viewing-angle LCDs offered by all manufacturers.

The use of optical compensation films having an inclined optical indicatrix to widen the viewing angles of TN-LCDs was first proposed by Yamahara, et al4). Later, Ito, et al5), proposed a method to obtain an optical compensation film with an inclined optical indicatrix by coating a discotic liquid crystal compound onto a transparent substrate such as triacetylcellulose (TAC), followed by cross-linking. Mori, et al, however, reported that the discotic compound layer of this film has a hybrid alignment, and thus, has no optical axis6). Triphenylene derivatives are used as the discotic liquid crystal compound in these films7)8). However, it has been reported that, in the N_D phase of discotic liquid crystals, the degree of orientation of triphenylene, which makes up the disc-like cores from which the term "discotic" is derived, is not especially high, and in addition, cross-linking reduces the degree of orientation9). Consequently, because the discotic compound layer of the optical compensation film comprising a discotic compound layer on a TAC substrate is cross-linked in the N_D phase7), it is quite unlikely that it is fixed into a hybrid alignment state. What's more, optical compensation expands the viewing angle by using optical compensation films to alter polarized light both before it enters the LCD cells and after it exits, and thus it is important to examine the optical properties of the compensation films from a broad perspective.

This paper describes the overall optical properties of compensation films formed from a discotic compound layer on a TAC substrate, and the TN-LCDs that employ them.

1. Optical Properties of Optical Compensation Films[10]

The optical compensation films employed in wide-viewing-angle technologies using the gradual refraction polarizer (GRP) system are WV (wide-view) films (manufactured by Fuji Photo Film Co., Ltd.). We used WV A02B film (from Fuji Photo Film) to characterize the properties of optical compensation films as a whole. As shown in **Fig. 1**, an inclined biaxial optical indicatrix can be defined for the entire compensation film and measured using a transmission ellipsometer (model M-220 manufactured by JASCO Corporation). We set the inclination direction of the optical indicatrix shown in **Fig. 1** to be normal to the rotational axis of the compensation film, and measured retardation with respect to the polar angle. The polar angle is equivalent to the angle of incidence of the light and the viewing angle. Thus, the optical indicatrix that most closely approximates the measured data can be calculated based on the measurement data. Accordingly, we derived the biaxial optical indicatrix shown in **Fig. 1**.

As shown in **Fig. 2**, for the S-wave of the light, Snell's Law is defined as follows:

$$n_S \sin\phi_S = \sin\phi_{air} \qquad (1)$$

where, n_S is the refractive index sensitive to S-wave light, ϕ_S is the angle of refraction of the S-wave light, and ϕ_{air} is the angle of incidence of the light. As shown in **Figs. 1** and **2**, nb is normally the refractive index sensitive to S waves, and the refractive index sensitive to S waves can be expressed by the following equation:

$n_s = nb$

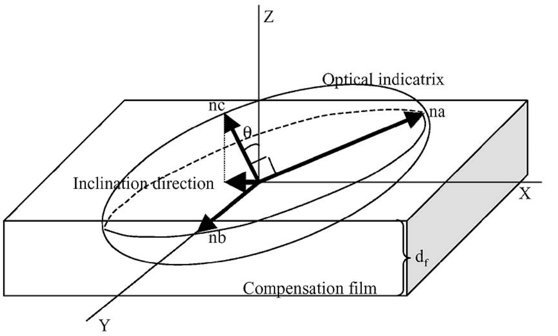


Fig. 1 Optical indicatrix of the entire compensation film

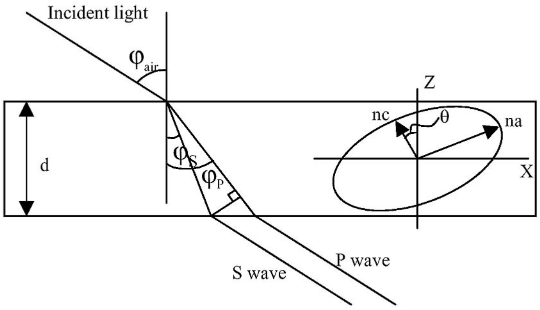


Fig. 2 Geometry of light transmission through the compensation film

For P-wave light, Snell's Law is defined similarly to S-wave light, and the refractive index sensitive to P-wave light is expressed as a function of the angle of refraction and the angle of inclination of the optical indicatrix.

$$n_P \sin\phi_P = \sin\phi_{air} \qquad (2)$$

$$\frac{1}{n_P{}^2} = \frac{\cos^2(\phi_P+\theta)}{na^2} + \frac{\sin^2(\phi_P+\theta)}{nc^2} \qquad (3)$$

where, n_P is the refractive index sensitive to P-wave light, ψ_P is the angle of refraction of P-wave light, and θ is the angle of inclination of the optical indicatrix. The system of simultaneous equations (1), (2) and (3) were solved accordingly. Here, we used the method that separates the S-wave and P-wave light in the calculations.

Refractive index sensitive to S-wave light : $n_s = nb$

Refractive index sensitive to P-wave light :

$$n_P = na \cdot nc \sqrt{\frac{1+\tan^2(\psi_P+\theta)}{nc^2+na^2\tan^2(\psi_P+\theta)}} \qquad \text{(from Equation (3))}$$

Refractive angle : $\psi_S = \arcsin \dfrac{\sin\psi_{air}}{nb}$

$$\psi_P = \arcsin \frac{2AB+C^2-\sqrt{4ABC^2+C^4+4B^2C^2}}{2A^2+2C^2}$$

where, $A = \dfrac{1}{\sin^2\psi_{air}} - \cos 2\theta \left(\dfrac{1}{nc^2} - \dfrac{1}{na^2}\right)$

$$B = \frac{\cos^2\theta}{na^2} + \frac{\sin^2\theta}{nc^2}$$

$$C = \sin 2\theta \left(\frac{1}{nc^2} - \frac{1}{na^2}\right)$$

Retardation : $Re = Res - Rep = n_S \cdot \dfrac{d}{\cos\psi_s}$

$$- n_P \left\{\frac{d}{\cos\psi_P} - d\cdot\sin\psi_P(\tan\psi_P - \tan\psi_s)\right\}$$

From these equations, we did a curve fit of the retardation values versus the polar angle of the biaxial optical indicatrix that most closely approximated the measured data, and were able to estimate the main refractive indices na, nb and nc, as well as angle of inclination θ. When this retardation versus polar angle curve deviates from the curve for measured data, it means that no model for the optical indicatrix is defined for this compensation film. **Fig. 3** shows experimental findings and the calculation results. Curve fitting based on the model in which the optical indicatrix is inclined for the optical compensation film as a whole (**Fig. 1**) coincides with actual measurements (calculated curve 1 in **Fig. 3**), but in doing the calculations in a similar manner based on a model in which the discotic layer is separated from the TAC substrate (calculated curve 2 in **Fig. 3**), curve fitting did not coincide with actual measurements. Consequently, the fact that the entire compensation film comprising a discotic layer and a TAC substrate has optical properties of a biaxial inclined optical indicatrix was confirmed.

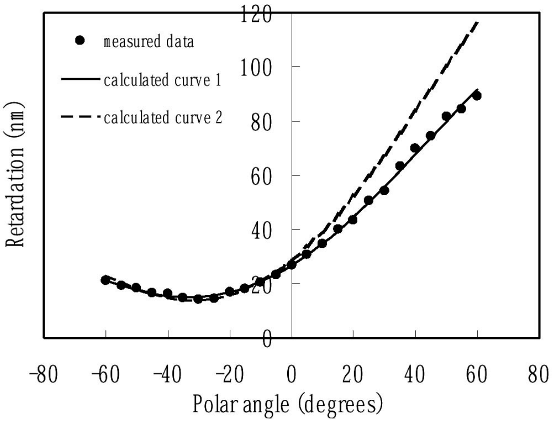


Fig. 3 Retardation vs. polar angle curves for the entire compensation film

Fig. 4 shows the curve fit and measurement results of changes in retardation versus polar angle for a non-stretchable TAC film (manufactured by Fuji Photo Film) similarly to the WV film. This non-stretchable TAC film is commercially available as an optical compensation film having a uniaxial non-inclined negative optical indicatrix. **Fig. 4** confirms the fact that the measured values and fitting curves are in good agreement.

Accordingly, we compared na-nb in relation to the principal refractive indices of the WV film and non-stretchable TAC film. The na-nb of the WV film and the non-stretchable TAC film were nearly identical at 0.00010 and 0.00008, respectively. Consequently, the fact that an optical compensation film comprising a discotic compound layer and a TAC substrate has uniaxial inclined negative optical indicatrix was confirmed. We also defined Rin, the parameter indicating the retardation of the uniaxial medium, to be:

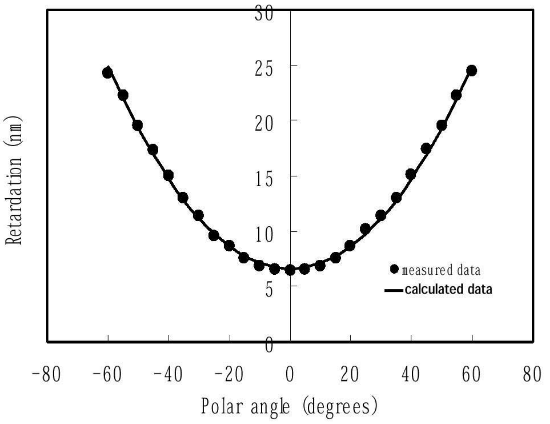


Fig. 4 Retardation vs. polar angle curves for the non-stretchable TAC film

$$Rin = \Delta n_f \cdot d = \{(na + nb)/2 - nc\} \cdot d_f$$

For the WV A02B film, the inclination angle θ was 21.4°, and the retardation Rin 103 nm.

2. Viewing Angle Characteristics of Wide-Viewing-Angle TN-LCDs Using the GRP System

2.1 Actual Measurements and Simulations[10)]

A comparison of iso-contrast ratio curves using actual measurements and computer simulations was used to characterize the viewing angle characteristics of a GRP wide-viewing-angle TN-LCD. A block diagram of the GRP wide-viewing-angle TN-LCD is shown in **Fig. 5**. We used a model CV-1000 manufactured by Minolta to make the contrast ratio measurements. For the computer simulations, we used Oseen-Frank continuum theory[11)12)] for the liquid crystal molecule director calculations, and the Berreman 4x4 matrix[13)] method to calculate light propagation. In addition, based on the results of ellipsometry measurements, a retardation Rin of 103 nm and an inclination angle θ of 21.4° for the uniaxial negative birefringence optical compensation film were used as inputs for the optical parameters of the compensation films. **Fig. 6** shows the iso-contrast ratio curves for (a) the computer simulations and (b) actual measurements. We confirmed the fact that the simulation results and the actual measurements are in good agreement, and from the viewing angle characteristics, we also identified the fact that an optical compensation film comprising a discotic layer and a TAC substrate as having the optical characteristics of a uniaxial inclined negative optical indicatrix.

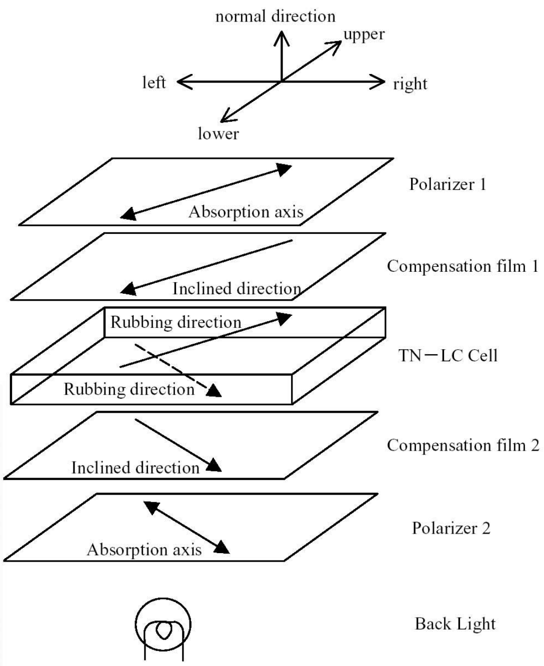
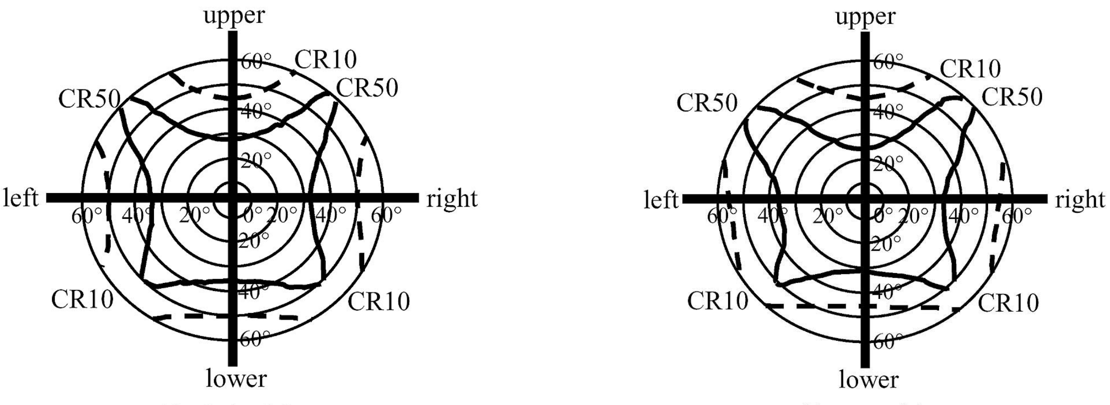


Fig. 5 Configuration of TN-LCD with the optical compensation film



(a) calculated data

(b) measured data

Fig. 6 Iso-contrast ratio curves for TN-LCDs with the compensation film:
(a) calculated results, and (b) measured results

2.2 Influence of Optical Parameters of Compensation Films on Viewing Angle Characteristics[10)14)]

For the viewing angle characteristics, given the fact that the simulation results and actual measurements coincide, we used computer simulation to examine the influence of the optical parameters of the compensation film on the viewing angle. **Fig. 7** shows the dependency of the angle of inclination θ on the viewing angle at a contrast ratio of 10:1. For the compensation film's optical parameters, we held retardation Rin constant at 100 nm and varied the angle of inclination θ over the range from 0° to 25°. The upper (positive vertical) viewing angle increases monotonically but the viewing angle to the right (positive horizontal) viewing angle has a local minima at approximately 15°.

Fig. 8 shows the dependency of retardation Rin on the viewing angle at a contrast of 10:1. The angle of inclination θ for the compensation film was held constant at 20° while retardation Rin was varied over the range from 50 to 200 nm. The upper viewing angle has a local maximum at approximately 130 nm while the viewing angle to the right begins to decline at approximately 120 nm. Based on these calculations, we designed a compensation film that achieves even wider viewing angles.

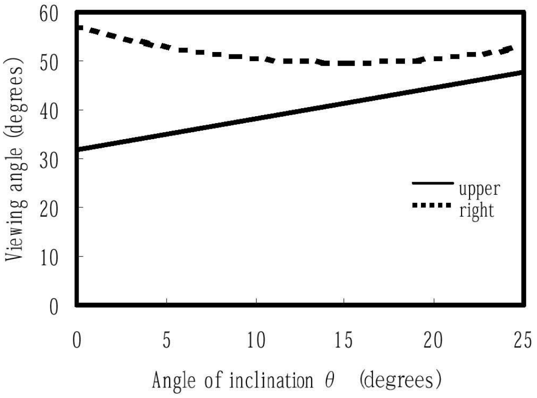


Fig. 7 Influence of the angle of inclination on the viewing angle of contrast ratio 10:1

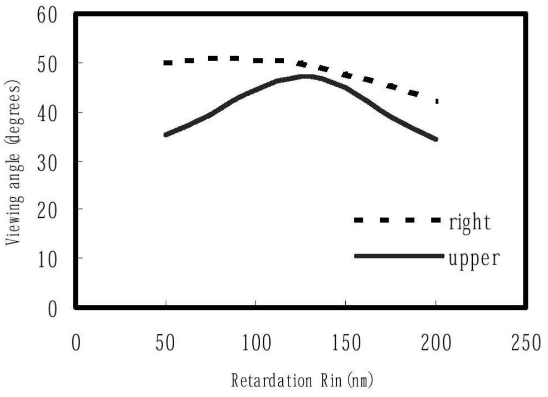


Fig. 8 Influence of the retardation on the viewing angle of contrast ratio 10:1

3 Design of the Optical Compensation Film[14)]

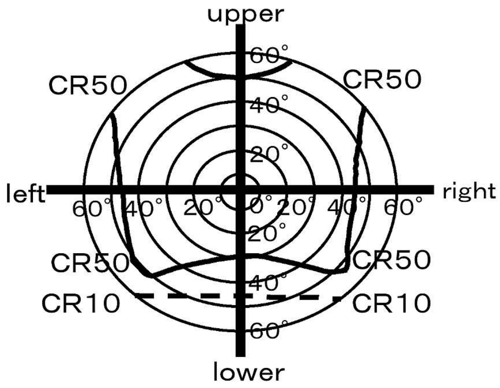


Fig. 9 Measured iso-contrast ratio curves of the TN-LCD with the optimized optical compensation film

As shown in **Fig. 6(b)**, the viewing angle of a GRP wide-viewing-angle TN-LCD using the WV A02B film in the upper direction is about 10° narrower than in the side-to-side (transverse) direction. Consequently, we studied various designs, focusing on increasing the upper viewing angle. For the upward direction, we set the retardation value at 130 nm and expanded the viewing angle by increasing the angle of inclination θ. Using retardation of 130 nm, the viewing angle is slightly narrower in the side-to-side direction, but by increasing the angle of inclination θ to 25° in this direction, we assumed that the viewing angle would increase by the same amount or more, and we prepared a compensation film, focusing our efforts on making the value for retardation Rin be 130 nm and the angle of inclination θ be 25°. **Fig. 9** shows the iso-contrast ratio curve using a compensation film with retardation Rin at 132 nm and the angle of inclination at 25.6°. **Fig. 9** confirms that our assumptions and actual measured values coincide. Consequently, GRP wide-viewing-angle TN-LCD was designed based on the fact that the optical parameters of the entire compensation film govern the viewing angle.

Conclusion

An optical compensation film comprising a discotic compound layer and a TAC substrate has optical properties of a uniaxial inclined negative optical indicatrix. Thus, the optical parameters of the entire compensation film govern the viewing angle properties of GRP wide-viewing-angle TN-LCDs. As a result, the optical properties of the compensation films of a GRP wide-viewing-angle TN-LCD can be designed based on the overall optical parameters of the film.

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