Optimization of the display viewing angle for automotive application

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ABSTRACT

We studied the optimization of viewing angle properties of the in-plane switching (IPS) liquid crystal display (LCD) for automotive applications. We studied the optical properties inside the automotive viewing zone (AVZ) with narrow vertical and wide horizontal viewing angle range defined in German OEM specifications. The average dark state transmittance (TRd) and contrast ratio (CR) of the IPS-LCD compensated with a + A and a + C plate could be enhanced by 2.5% and 0.8%, respectively, in the AVZ by inserting an additional - C plate. The uniformity of TRd and CR in the AVZ zone also improved by 39.3% and 24.9%, respectively. Enhancement of optical properties by the additional - C plate was also observed in the IPS-LCD compensated with a Z plate. On the other hand, the optical properties of the IPS-LCD compensated with a - B and a + C plate were optimal when Rth of the existing + C plate is optimized for automotive displays.

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1. Introduction

The use of display devices is becoming more and more widespread in our daily lives. One of the rapidly growing applications of this display type is its use in automotive displays. For example, automotive displays are used in the electronic instrument cluster (EIC) that displays car information such as speed and engine status, or as a center information display (CID) that controls functions such as air-conditioning, navigation, and audio systems. The viewing angles of automotive displays are limited depending on the seat position. The vertical viewing angle of automotive displays is narrow compared to general display applications (i.e. monitor, TV, mobile). On the other hand, automotive displays require a relatively wide horizontal viewing angle to provide clear images for everyone (drivers and passengers) [Figure 1(a)]. This specific viewing angle condition is quantitatively managed by checking the contrast ratio in the rectangle zone in Figure 1(b). This zone is called the automotive viewing zone (AVZ) defined in the German original equipment manufacturer (OEM) specification. AVZ is composed of A+, A, and B area whose horizontal (H) and vertical (V) viewing angle of A+, A, and B area correspond to (H: ±10°, V: +8°/-4°), (H: ±40°, V: +20°/-10°), and (H: ±50°, V: +20°/-10°), respectively [1].

Automotive displays require thermal and mechanical reliability as well as a long life span. The in-plane switching (IPS) liquid crystal display (LCD) is widely used as in automotive displays because of its wide viewing angle, high reliability, low power consumption, and cost-effectiveness. Optical compensation is the key technique in achieving the wide viewing angle of IPS-LCD. There have been studies to optimize conventional optical compensation for automotive displays [2]. Conventional optical compensations are generally designed to provide low light leakage in the overall viewing angle. Therefore, the dependence of the viewing angle along the horizontal and vertical directions has a symmetrical distribution [3–7]. The viewing angle dependence of AVZ is asymmetric along with the horizontal and the vertical directions. The vertical viewing angle of the AVZ is relatively narrow compared to the horizontal viewing angle [Figure 1(a)]. In addition, the viewing angles away from the AVZ are less important. The light angular distribution of LCD is focused into the AVZ by the directional backlight unit (BLU), which enhances the efficiency and prevents reflections on the windshield [8]. Therefore, a new concept of optical compensation needs to be developed for automotive applications.
In this paper, we studied the optimization of the viewing angle properties using the in-plane switching (IPS) liquid crystal display (LCD). Various optical compensation methods for the IPS-LCDs have been proposed [9–15]. For example, the combination of + A plate and + C plate was reported as an approach to eliminating light leakage at the oblique viewing angle [16,17]. Another combination of + A plate and - A plate also gives a similar compensation effect [18,19]. In addition, one or two biaxial-plate can improve the viewing angle property [20–22]. In this paper, we introduced an additional C plate to the optically compensated IPS-LCDs above. We varied the out-of-plane retardation $R_{th}$ of the C plate and investigated its effect on the viewing angle property. Here, the $R_{th}$ is given by $R_{th} = [(n_x+n_y)/2-n_z]d$, where $n_x$, $n_y$, $n_z$ are refractive indices along the $x$-, $y$-, and $z$-axis, respectively, and $d$ is the thickness of retarder. It was found that the transmittance at dark state (TRd) and contrast ratio (CR) in AVZ could be improved by adjusting the $R_{th}$ of the additional C plate.

2. Optical simulation conditions

We considered the IPS-LCDs compensated with various combinations of retarders as shown in Figure 2. The liquid crystal (LC) molecules are aligned along the $x$-axis at zero field state. The LC layers are split into two domains whose optic axes are at $-45^\circ$ and $45^\circ$, respectively, in the presence of an electric field. The refractive indices of the retarders used in the calculation are summarized in Table 1. The in-plane retardation $R_{in}$ ($R_{in} = (n_x-n_y)d$) and the $R_{th}$ were 328.2 and 164.1 nm, respectively. The absorption axes of the polarizer and the analyzer of the IPS-LCDs were commonly along the $y$- and the $x$-axis, respectively. The refractive index of the polarizer is set to be 1.50. We inserted an additional C plate as a variable and calculated its effect on the optical properties in the A area. The $R_{th}$ of the C plate was varied from $-20$ to +20 nm. A commercial optical simulator TechWiz LCD 1D (Sanayi system) was used for the optical calculation based on the Extended Jones matrix method [23].

Figure 2(a) shows the IPS-LCD compensated with the + A plate and + C plate [16,17]. The + A plate and the + C plate are located between the polarizer and the LC. The $c$-axis of the + A plate is perpendicular to the absorption axis of the analyzer. The retarder films are used to compensate for the decrossing effect of the polarizer-analyzer at a large oblique viewing angle. The details of the compensation principle are comprehensively described in the literature [11, 24]. In this study, we inserted an additional C plate between the LC and the analyzer.

Figure 2(b) corresponds to the IPS-LCD compensated with a - B plate and a + C plate [12]. The retarders are located between the polarizer and the LC layer. The $x$-principal axis of the - B plate is perpendicular to the absorption axis of the analyzer. We inserted an additional C plate between the LC and the analyzer.

Figure 2(c) represents the IPS-LCD compensated with a Z plate [20, 21]. The $R_{in}$ of Z plate in Figure 2(c) varied from 255.0 ~ 295.0 nm, while its $R_{th}$ was 0 nm. A single Z plate is located between the polarizer and the LC layer. The principal-axis of the Z plate is perpendicular to the absorption axis of the polarizer. We inserted an additional C plate between the LC and the analyzer. Note that the optical properties are identical when the $R_{th}$ of the additional C plate is 0 nm and when there is no additional C plate.

3. Results and discussion

As the first step of this study, we investigated the optimal optical film conditions for general applications (i.e. monitor, TV, mobile). The IPS-LCD compensated with
optimal conditions is expected to have uniform viewing angle properties over the entire viewing angles exceeding AVZ. The average contrast ratio (CR\textsubscript{avg}) of IPS-LCDs at full viewing angles ($\phi = 0^\circ \sim 360^\circ$, $\theta = 0^\circ \sim 89^\circ$) was simulated with varying $R_{th}$ of the + C plate ($R_{th,+C}$) and $R_{in}$ of Z plate ($R_{in,Z}$) [Figure 3]. In the simulation results, CR\textsubscript{avg} of IPS-LCDs compensated with + A/+ C and - B/+ C was maximum when $R_{th,+C} = -98$, and 126 nm, respectively, while CR\textsubscript{avg} of the IPS-LCD compensated with Z plate was maximum when $R_{in}$ of Z plate was 275 nm.

The optimal conditions for automotive displays will be different from general applications because AVZ is asymmetric. The optical properties CR\textsubscript{avg} and CV\textsubscript{CR} of IPS-LCDs at area A were simulated with the various conditions of the optical films [Figure 4]. Three optimal conditions were chosen for different cases. First, the black dots represent the optimal conditions for general applications, as shown in Figure 3. Second, the red dots indicate the optimal conditions of conventional optical compensation for automotive displays without the additional C plate. Third, the blue dots correspond to the optimal conditions of optical conditions of compensated IPS-LCDs

![Figure 2](image_url)  
**Figure 2.** Schematic illustrations of the IPS-LCDs compensated with (a) + A plate and + C plate, (b) - B plate and + C plate, and (c) Z plate ($0-R_{th}$).

![Table 1](image_url)  
**Table 1.** Refractive indices and retardation of the LC and the retarders used in the simulation.

| Materials      | $R_{in}$ (nm) | $R_{th}$ (nm) |
|----------------|---------------|---------------|
| LC             | 328.2         | 164.1         |
| C plate        | 0.0           | -20.0 ~ 20.0  |
| + A plate      | 138.0         | 69.0          |
| + C plate      | 0.0           | -65.0 ~ 105.0 |
| - B plate      | 120.0         | 100.0         |
| + C plate      | 0.0           | -100.0 ~ 140.0|
| Z plate ($0-R_{th}$) | 255.0 ~ 295 | 0.0 |

![Figure 3](image_url)  
**Figure 3.** Simulated average contrast ratio (CR\textsubscript{avg}) as a function of $R_{in}$ of + C plate of the IPS-LCDs at entire viewing angles ($\phi = 0^\circ \sim 360^\circ$, $\theta = 0^\circ \sim 89^\circ$) and $R_{in}$ of Z plate compensated by (black) + A/+ C, (red) - B/+ C and (blue) $0-R_{th}$ films.
Figure 4. Simulated (a)-(c) CR avg and (d)-(f) CV CR of the IPS-LCDs at the A area where they are compensated with (a, d) +A/+C films, (b, e) +B/+C films, and (c, f) 0-Rth film as a function of Rth of the additional C plate (Rth,add), and Rth or Rin of the +C plate (Rth,C) and the Z plate (Rin,Z), respectively. Three points represent the optimum value of Rth or Rin for the (black) entire viewing angle and (red) the A area without additional C plate (Rth,C = 0 nm), and (blue) the A area with additional C plate.

for automotive displays with the additional C plate. Uniformity was quantitatively compared using the coefficient of the variant (CV) defined as \( \sigma/\text{avg} \), where \( \sigma \) and \( \text{avg} \) are the standard deviation and the average of the values, respectively.

Figure 4(a,d) are the simulated CR avg and CV CR of the IPS-LCD compensated +A/+C films with varying Rth of the +C plate and the additional C plate. The peak (maximum) of CR avg and the belly (minimum) of CV CR was located in the region where Rth of the additional C plate (Rth,add) is positive (-C plate). The optimal Rth,+C for general applications and automotive displays were \(-97.9\) nm and \(-93.3\) nm, respectively. CR avg of Rth,+C = \(-97.9\) nm, and \(-39.3\) nm were 12349.22 and 12445.10, respectively, and CV avg under those conditions were 0.06797 and 0.05547, respectively. Optimization of Rth,+C improved CR avg and CV CR by 1.2% and 35.6%, respectively. The CR avg and CV CR increased to 12514.53 and 0.04790, respectively, when Rth,+C = \(-126.2\) nm and Rth,add = \(-3.2\) nm.

The CR avg and CV CR of IPS-LCD compensated with Z plate were optimal when Rin,Z was 275.0 nm for both automotive displays and general applications [Figure 4(c,f)]. The peak of the CR avg was at Rth,add = 6.0 nm, while CV CR decreased as Rin,Z decreased at the positive Rth,add region. CR avg and the CV CR were 12469.99 and 0.05740, respectively, when Rin,Z = 275.0 nm. The additional C plate enhanced CR avg to 12499.45 (0.2%) and CV CR to 0.05080 (11.5%) when Rin,Z = 285.0 nm and Rth,add = 6.0 nm.

The optical properties of area A were simulated for further analysis [Figures 5–7]. The inset in Figures 5–7 illustrates the corresponding optical properties at large viewing angles (\( \phi = 0^\circ \sim 360^\circ \), \( \theta = 0^\circ \sim 89^\circ \)). The angular and radial axes represent the in-plane and polar viewing angles (\( \phi \) and \( \theta \)), respectively. The angular axis starts (\( \phi = 0^\circ \)) at 3 o'clock and increases in the counterclockwise (CCW) direction. The color scale of insets is the same, but differs with the color scale of the parent figure. Figure 5 represents the simulated transmittance at white state (TRw), TRd, and CR of the IPS-LCD.
compensated with $+A/+C$ plates. Whether optimizing the $R_{th}$ of the existing $+C$ plate or using the additional $C$ plate, the $TR_w$ was 29.17% for all conditions [Figure 5(a–c)]. The CV of $TR_w$ (CV$_w$) were 0.00806, 0.00811, and 0.00836 when the $+C$ plate is optimized for general applications ($R_{th,+C} = -97.9$ nm), automotive displays ($R_{th,+C} = -93.3$ nm) and with the additional $C$ plate ($R_{th,+C} = -85.6$ nm, $R_{th,add} = 7.6$ nm), respectively. The average $TR_d$ ($TR_{d,avg}$) was $2.40 \times 10^{-3}$%, $2.35 \times 10^{-3}$% and $2.34 \times 10^{-3}$% when the $R_{th,+C}$ and the $R_{th,add}$ pairs were ($-97.9$ nm, none), ($-93.3$ nm, none), and ($-85.6$, 7.6 nm), respectively, while corresponding CV of $TR_d$ (CV$_d$) was 0.09972, 0.07319 and 0.06050 [Figure 5(d–f)]. The CR profile of three optimal conditions chosen in Figure 4(a) are shown in Figure 5(g–i).

The optimization of compensation films has less impact on the $TR_w$. Optimization of the existing $+C$ plate decreases light leakage especially at the corners of area A, and further decreased by adding the $-C$ plate [Figure 5(d–f)]. The AVZ has the larger horizontal viewing angle compared to the vertical viewing angle [Figure 1]. Therefore, the enhancement of $TR_d$ in area A is closely related to the asymmetric viewing angle profile. The effects of the $R_{th,+C}$ and the $R_{th,add}$ on the viewing angle are clearly shown in large viewing angles [inset in Figure 5(d–f)]. The angular distribution of light leakage.

Figure 5. Simulation results of the optical properties of the IPS-LCD compensated with $+A/+C$ films at the A area. (a)-(c) are $TR_w$ when $R_{th}$ of $+C$ plate and additional $C$ plate are ($-97.9$ nm, none), ($-93.3$ nm, none), and ($-85.6$, 7.6 nm), respectively. (d)-(f) and (g)-(i) are $TR_d$ and CR with the corresponding conditions. The inset images present the corresponding optical properties at a large viewing angle ($\phi = 0^\circ \sim 360^\circ, \theta = 0^\circ \sim 89^\circ$).

Figure 6. Simulation results of the optical properties of the IPS-LCD compensated with $-B/+C$ films at the A area. (a)-(c) are $TR_w$ when $R_{th}$ of $+C$ plate and additional $C$ plate are ($-126.2$ nm, none), ($-121.8$ nm, none), and ($-126.2$ nm, $-3.2$ nm), respectively. (d)-(f) and (g)-(i) are $TR_d$ and CR with the corresponding conditions. The inset images present the corresponding optical properties at a large viewing angle ($\phi = 0^\circ \sim 360^\circ, \theta = 0^\circ \sim 89^\circ$).
Figure 7. Simulation results of the optical properties of the IPS-LCD compensated with 0°-Rth film at the A area. (a, b) are TRw when Rth of the Z plate and Rth of the additional C plate are (275.0 nm, none), and (285.0, 6.0 nm), respectively. (c, d) and (e, f) are TRd and CR with the corresponding conditions. The inset images present the corresponding optical properties at a large viewing angle ($\phi = 0° \sim 360°$, $\theta = 0° \sim 89°$).

is uniform in in-plane viewing angles when optical film conditions are maximized for general applications. After optimizing the Rth, +C for automotive displays, light leakage on the vertical axis became severe while light leakage on the horizontal axis was mitigated. Adding the -C plate made the distribution of light leakage on the vertical and horizontal axes more asymmetric, while light leakage at the corners of the A region decreased. As a result, the distribution of CR became asymmetric in large viewing angles. The use of an additional -C plate achieved a uniform distribution of CR in area A and improved by 11.6% in terms of CVCR compared to the case where only Rth, +C is optimized.

The simulated optical properties of the IPS-LCD compensated with -B/+C plates are shown in Figure 6. For Rth, +C and the Rth,add pairs (−126.2 nm, none), (−121.8 nm, none) and (−126.2 nm, 3.2 nm), the TRw were equal to 29.17% and CVw were 0.00806, 0.00817 and 0.00806, respectively [Figure 6(a–c)]. The TRd,avg were 2.40×10^{-3}%, 2.35×10^{-3}% when Rth, +C = −126.2 nm and −121.8 nm, and 2.34×10^{-3}% when Rth, +C = −126.2 nm, and Rth,add = 3.2 nm, respectively. The corresponding CVd of each condition was 0.10998, 0.05133 and 0.05734, respectively [Figure 6(d–f)]. The viewing angle profile of CR is shown in Figure 6(g–i). The optimization of Rth, +C decreased the TRd in area A and increased the asymmetricity of the viewing angle profile as shown in Figure 6(d,e). Unlike the other two cases, the additional C plate increases the CRavg when Rth is negative (+C plate) [Figure 4(b)]. The asymmetric viewing angle properties of TRd and CR are weakened after adding the +C plate [Figure 6(f,i)]. Less asymmetricity means more light leakage along the horizontal axis and worse distribution of TRd and CR in area A.

The optical properties of IPS-LCD compensated with a Z plate were simulated and the results are shown in Figure 7. Note that optimal Rin,Z for the general applications and automotive displays is equal to 275.0 nm. The TRw with or without the additional C plate was 29.18% in both cases [Figure 7(a,b)]. The CVw was 0.00816 and 0.00834 without the additional C plate (Rin,Z = 275.0 nm) and with C plate (Rin,Z = 285.0 nm, Rth,add = 6.0 nm). TRd was 2.36×10^{-3}% and 2.35×10^{-3}%, and CVd was 0.07617 and 0.06314 when Rin,Z = 275.0 nm and Rin,Z = 285.0 nm with additional -C plate (Rth,add = 6.0 nm), respectively [Figure 7(c,d)]. The viewing angle profile of the CR is shown in Figure 7(e,f). Light leakage at the top corners in area A is decreased by the additional -C plate. In large viewing angles, the additional -C plate made the viewing angle profile asymmetric. The simulation results are summarized in Table 2.
Table 2. The average and CV values of TRw, TRd and CR of the IPS-LCDs compensated with various methods having different Rth of +C and additional C plates and Rth of Z plate.

| Retardation (nm) | TRw Average (%) | CV | TRd Average (10^-3%) | CV | CR Average (a.u.) | CV |
|------------------|-----------------|----|---------------------|----|-------------------|----|
| +C plate         |                 |    |                     |    |                   |    |
| −97.9            | 29.17           | 0.00806 | 2.38              | 0.09972 | 12393.97 | 0.06529 |
| −93.3            | 29.17           | 0.00811 | 2.36              | 0.07319 | 12445.10 | 0.05547 |
| −95.6            | 7.6             | 0.00836 | 2.35              | 0.0605  | 12495.74 | 0.04903 |
| −B/C plate       |                 |    |                     |    |                   |    |
| −126.2           | 29.17           | 0.00806 | 2.40              | 0.10998 | 12349.22 | 0.06797 |
| −121.8           | 29.17           | 0.00817 | 2.35              | 0.05133 | 12497.09 | 0.04374 |
| −126.2           | −3.2            | 29.17 | 0.00806 | 2.34 | 0.05734 | 12514.53 | 0.04790 |
| Z plate           |                 |    |                     |    |                   |    |
| 275.0            | 29.18           | 0.00816 | 2.36              | 0.07617 | 12469.99 | 0.05740 |
| 285.0            | 6.0             | 0.00834 | 2.35              | 0.06314 | 12499.45 | 0.05080 |

Figure 8 shows the polarization state of light passing through the dark state IPS-LCDs at the top-right corner (φ = 44.7°, θ = 26.5°) of area A on the 2ψ-2χ plane of the Poincare sphere. Here, 2ψ and 2χ are azimuthal and polar angles in spherical coordinates of the Poincare sphere, respectively, where ψ and χ are power split ratio and ellipticity in radians [24]. The C plate shifts the polarization state toward up (positive) or down (negative) in 2χ axis depend on the sign of Rth. After passing through the LC, the light polarization state rotates in CCW as much as in the phase retardation of LC.

The polarization states of light passing through the IPS-LCD compensated with +A/+C films are shown in Figure 8(a). The polarization state deviated from the equator when Rth,+C is optimized for general applications [black squares in Figure 8(a)]. Optimization for automotive displays reduces the Rth,+C and moves the polarization state closer to the equator [red circles in Figure 8(a)]. The closer the polarization state to the equator is after passing through the +C plate, the closer the polarization state shifts after passing through the LC. Consequently, light leakage at the corner of area A decreases after optimizing the Rth,+C for automotive displays. The Rth,+C can be reduced further by using the additional -C plate [blue triangles in Figure 8(a)]. The polarization state after passing through +C plate deviated in the positive direction of the 2χ axis at the equator. The reduced Rth,+C resulting in the polarization state deviates from the equator in the negative direction of the 2χ axis, after passing through the LC. The additional -C plate compensates for the deviation of the polarization state and moves it closer to the point of the analyzer compared to the other cases. Thus, light leakage is minimized when the additional -C plate is used.

The polarization states of light passing through the IPS-LCD compensated with -B/+C films are shown in Figure 8(b). After passing through the +C plate, the polarization states deviated from the equator in the following order: when Rth,+C is optimized for general applications (black squares), the additional -C plate is used (blue triangles), and Rth,+C is optimized for automotive displays (red circles) [Figure 8(b)]. The polarization states after passing through LC have deviated from the analyzer point in the same order. The deviation of the polarization states after passing through the +C plate appears to have a close relationship with CV. This is because the CV of IPS-LCDs decreased with smaller Rth,+C when optimized. The final polarization states with

Figure 8. Projection of the polarization states of light passing through the IPS-LCD on the 2ψ-2χ plane of the Poincare sphere at the dark state. The viewing angle was φ = 44.7°, θ = 26.5°. The IPS-LCD was compensated with (a) +A/+C, (b) -B/+C, and (c) 0-Rth films.
and without the additional + C plate did not deviate from the analyzer point as much as the IPS-LCD compensated with + A/+C films did. Therefore, light leakage is similar in both cases when $R_{th,+C}$ is optimized for automotive displays and when the additional -C plate is used.

Figure 8(c) represented the polarization states of light after passing through the IPS-LCD compensated with Z plate. The polarization state is very close to the equator when $R_{in,2}$ is optimized for the general applications [black square in Figure 8(c)]. The small deviation of the polarization state from the equator appears to account for the optimal $R_{in,2}$ value for automotive displays of 275.0 nm, which is the same as for the general applications. The $R_{in,2}$ is reduced when the additional -C plate is used. Consequently, the polarization state deviates from the equator in both cases after passing through the Z plate and LC. The additional -C plate compensated for the deviation and the polarization state became closer to the analyzer point. The light leakage at area A decreased and uniformity enhanced with smaller $R_{in,2}$.

4. Conclusion

In this paper, we studied the optimization of the viewing angle property of various IPS-LCDs for automotive applications. We introduced an additional C plate to the IPS-LCDs compensated with + A/+C, -B/+C, or 0-$R_{th}$ films. The optimal optical film conditions for automotive displays differed from those for general applications (i.e. monitor, TV, mobile). In addition, the viewing angle property in AVZ could be improved further by inserting the additional C plate. The additional -C plate decreased light leakage at the horizontal viewing angle. Thus, the uniformity (CV) of TRd and CR could be enhanced up to 39.3% and 24.9% in AVZ, respectively, compared to when optical films condition is optimized for general applications. The additional -C plate is preferred with better uniformity for IPS-LCD compensated with + A/+C and 0-$R_{th}$ films. Optimizing the $R_{th}$ of the existing + C plate shows the best performance for IPS-LCD compensated with -B/+C films. The overall viewing angle properties were optimal when the additional C plate was absent, even though the optical properties outside of AVZ are negligible in automotive applications [1, 8]. We believe that our suggested method will be helpful in the development of automotive optimized displays.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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