Evaluation of Phase Retardation of Curved Thin Polycarbonate Substrates for Wide-viewing Angle Flexible Liquid Crystal Displays

Shuichi HONDA†(a), Takahiro ISHINABE†, Members, Yosei SHIBATA†, Nonmember, and Hideo FUJIKAKE†, Fellow

SUMMARY We investigated the effects of a bending stress on the change in phase retardation of curved polycarbonate substrates and optical characteristics of flexible liquid crystal displays (LCDs). We clarified that the change in phase retardation was extremely small even for the substrates with a small radius of curvature, because bending stresses occurred in the inner and upper surfaces are canceled each other out. We compensated for the phase retardation of polycarbonate substrates by a positive C-plate and successfully suppressed light leakage in both non-curved and curved states. These results indicate the feasibility of high-quality flexible LCDs using polycarbonate substrates even in curved states.

key words: liquid crystal display, flexible display, polycarbonate substrate, optical compensation, bending stress

1. Introduction

In recent years, flexible displays using plastic substrates have attracted much attention due to various advantages including their thinness, light weight, and shock resistance compared with glass substrates. Flexible displays can provide information anywhere and contribute to creating new viewing styles and excellent human interfaces [1]–[4]. Therefore, the development of flexible displays has long been awaited as the next-generation display technology.

Recently, the realization of flexible liquid crystal displays (LCDs) has been expected because of its advantages of high resolution and high reliability for smart phones and automotive applications. High-quality flexible LCDs require that high-contrast images are maintained in both curved and non-curved states [5]–[7], however, the contrast ratio and viewing angle range of flexible LCDs are limited due to light leakage caused by the optical anisotropy of plastic substrates.

In order to solve this problem, we previously reported a design method of optical compensation films to compensate for the phase retardation of polycarbonate substrates. We compensated for the phase retardation by using a positive-C plate and vertically aligned (VA) mode LC; a high contrast ratio of over 1000 : 1 was achieved in the non-curved state [8]. We also reported that a change in phase retardation by the bending stress of polycarbonate substrates was small in the case of a large radius of curvature (> 50 mm) and it increased in the case of a smaller radius of curvature, because of the tensile stress on the plastic substrates.

However, in general, a compressive stress also occurs in the inner surface of plastic substrates in a curved state. Therefore, there is a possibility that the influence of compressive stress becomes large in the case of a smaller radius of curvature, and the optical compensation condition for non-curved state could be changed due to a deformation of substrates. However, it has not been studied that the mechanism of the change in phase retardation caused by the bending stress and the lower limits of the radius of curvature of plastic substrates. Moreover, it has not been clarified how much the optical compensation films designed for the non-curved state could suppress light leakage in curved states.

Thus, in order to achieve high-quality flexible LCDs even in curved states, it is important to analyze the detail relationship of the bending stress between inner and upper surfaces in curved states. In this paper, we newly calculated the bending stress in each surfaces by using the simulation software based on the finite element method. As these results, we clarified that the change in phase retardation is extremely small even in a smaller radius of curvature because the tensile and compressive stresses are canceled each other out. In addition, we investigated an optical compensation technique of plastic substrates in curved states.

2. Change in Phase Retardation of Polycarbonate Substrates by The Bending Stress

The plastic substrates used in flexible LCDs are constructed from a polymer material. The refractive indices of a polymer depend on the change in polarizability when its molecular chains are stretched or compressed by bending strain [9]–[12]. Generally, when a plastic substrate is in a curved state, the inner surface of the substrate has compressive stress, and the upper surface has tensile stress. These bending stresses depend on the distance from the neutral plane $T_i$ and the radius of curvature $R$ (Fig. 1). The bending stress $\sigma_i$ can be calculated by the following equation [13], [14].
HONDA et al.: EVALUATION OF PHASE RETARDATION OF CURVED THIN POLYCARBONATE SUBSTRATES

Fig. 1 Deformation of plastic substrate in the curved state.

\[ \sigma_i = \frac{E \cdot T_i}{R} \]  
(1)

Where \( E \) is Young’s modulus of the substrate.

The change in refractive indices depend on the bending stress in curved plastic substrates and the stress optical coefficient (SOC). The amount of change in optical phase retardation \( \delta \) of the plastic substrate can be calculated by following equation [15], [16],

\[ \delta = SOC \cdot \Delta \sigma \cdot t \]  
(2)

Where \( \Delta \sigma \) is the difference between the bending stress in the inner and upper surfaces [Eq. (3)], and \( t \) is the thickness of the substrate,

\[ \Delta \sigma = \sigma_1 - \sigma_2 \]  
(3)

where \( \sigma_1 \) and \( \sigma_2 \) are compressive and tensile stresses at the inner and upper surfaces of plastic substrates respectively. However, it has not been clearly indicated the amount of change in phase retardation caused by the bending stress in curved states and how much the change in phase retardation increases when the plastic substrates are bent to a smaller radius of curvature. To resolve this problem, we calculated bending stresses in the inner and upper surfaces of the plastic substrate in curved states and evaluated the effects of the bending stresses on the change in the in-plane phase retardation by using simulation software based on the finite element method (ANSYS workbench, ANSYS Inc.). We used polycarbonate (supplied by Teijin) as the plastic substrate because polycarbonate substrates have low in-plane phase retardation (Re = 3.75 nm) and high glass-transition temperature (\( T_g \): 215 °C). The in-plane phase retardation (Re) is the phase retardation for the normal incidence light.

First, in order to examine the correlation between the thickness of the substrate and the change in the in-plane phase retardation, we calculated the bending stress in the inner and upper surfaces for substrate thicknesses of 40, 80, 200, and 400 \( \mu \)m, based on Eqs. (1) and (2). For comparison, we also calculated the change in phase retardation of conventional non-alkali LCD glass (EAGLE XG Corning Inc.) as the glass substrate [17], [18]. The parameters of each substrates used in the calculations are listed in Table 1. In this calculation, the radius of curvature was set to 13 mm assuming an application of a wearable device wound around a person’s arm. In addition, we fixed the left edge of the substrate and the right edge is only free to move in the \( x \)-direction.

The simulated bending strain distribution of the curved polycarbonate substrate is shown in Fig. 2; the deformation of the substrate in a curved state was larger at the center of the substrate. In this simulation result, we found that there are locally large deformation points at either end (Fig. 2). The both edges with large tensile strain are stretched easier to the curving direction (\( x \)-direction) than the center of the substrate because these edges are not subjected to constraining force from the orthogonal direction to the curving direction (\( y \)-direction). This locally large deformation points occurred only edges of the substrate, therefore, we used a value of bending strain at the center of substrate to evaluate the amount of change in the in-plane phase retardation.

Figure 3 (a) shows the difference of bending stresses between the inner and upper surfaces with different thicknesses; the compressive stress in the inner surface was larger than the tensile stress in the upper surface, and \( \Delta \sigma \) of the polycarbonate substrate was smaller than that of the glass substrate. From these results, we considered that the compressive stress in the inner surface increased due to the movement of the neutral plane to the outside; additionally \( \Delta \sigma \) of curved polycarbonate substrates becomes small because they have a low Young’s modulus in comparison with the glass substrates. Moreover, in the case of thin substrates, the compressive and tensile stresses could be canceled each other out, because the movement of the neutral plane was quite small. Figure 3 (b) shows the in-plane phase retarda-

Table 1  Parameters of polycarbonate and glass substrates.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Polycarbonate</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>40 × 40 mm</td>
<td></td>
</tr>
<tr>
<td>Thickness</td>
<td>40, 80, 200, 400 ( \mu )m</td>
<td></td>
</tr>
<tr>
<td>Radius of curvature</td>
<td>13 mm</td>
<td></td>
</tr>
<tr>
<td>Young’s modulus</td>
<td>2.5 GPa</td>
<td>73.6 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.39</td>
<td>0.23</td>
</tr>
<tr>
<td>Stress optical coefficient</td>
<td>( 45 \times 10^{-3} ) GPa^{-1}</td>
<td>( 3.31 \times 10^{-3} ) GPa^{-1}</td>
</tr>
</tbody>
</table>

Fig. 2 Simulation result of distribution of bending strain of polycarbonate substrate in the curved state.
tion change of polycarbonate and glass substrates. From Eq. (2), we calculated the change of phase retardation by multiplying $\Delta \sigma$ by $SOC$ and $r$. We found that the amount of change in the in-plane phase retardation decreased with substrate thickness. Based on these results, we clarified that the change in the in-plane phase retardation of the polycarbonate substrate became extremely small when the substrate was sufficiently thin, because $\Delta \sigma$ was small although polycarbonate substrates have the large $SOC$.

Next, in order to confirm how much the change in phase retardation increases when the polycarbonate substrates are bent to a smaller radius of curvature, we calculated the change in the in-plane phase retardation with different radius of curvature variation (13, 8, 4.3 and 2.5 mm). The thickness of the substrate was kept constant at 80 $\mu$m. The results are presented in Fig. 4. We confirmed that the amount of change in the in-plane phase retardation was extremely small, even with a smaller radius of curvature.

3. Measurement of Phase Retardation of Curved Polycarbonate Substrates

We measured the phase retardation of curved polycarbonate substrates using a stereoscopic ellipsometer (M-2000, J.A. Woolam) to confirm the validity of the simulation results. The measurement system used to maintain the polycarbonate substrate in curved state is shown in Fig. 5. We measured the amount of change in the in-plane phase retardation of the curved and non-curved states for different substrate thicknesses (80, 160 and 240 $\mu$m). The radius of curvature of the polycarbonate substrate was kept at 13 mm. When the bending direction is parallel to the slow axis direction of the polycarbonate substrate, the molecular chains are stretched in the optical slow axis direction, and the refractive indices in the slow axis direction become larger than those in the non-curved state. Conversely, when the bending direction is perpendicular to the slow axis direction, the molecular chains are stretched in the optical fast axis direction. Thus, the mutual relationship between the refractive index of the fast and slow axis directions changes, and the in-plane phase retardation decreases. When compressive stress is applied to the polycarbonate substrate, the in-plane phase retardation increases when the direction of the slow axis and compressive stress are perpendicular, and decreases when they are parallel. For these reasons, we examined the effect of the curved stresses of substrates on the change in phase retardation. The relationship between the amount of phase retardation change and the slow axis direction was evaluated, given that because the compressive and tensile stresses occur in the inner and upper surfaces at the same time.

Therefore, we measured the in-plane phase retardation when the curvature direction and slow axis direction of the
plastic substrate were parallel and perpendicular. The results of this measurement are shown in Fig. 6. We confirmed that the in-plane phase retardation in the parallel state decreases with substrate thickness. This is attributable to the fact that the neutral plane moved to the outside of the substrate because the stress value of the inner surface was larger than that of the upper surface. As a result, we clarified that the amount of change in phase retardation depends on the relationship between the curvature direction of the inner surface and slow axis directions.

Next, we measured the phase retardation when the radiiuses of curvature were 13, 8, and 4.3 mm (thickness: 80 μm) to confirm the value of $R_e$ with a small radius of curvature. In the curved state, the incident angle dependence of phase retardation could change because of the deformation of the refractive index ellipsoid. Therefore, in order to achieve optical compensation for polycarbonate substrates in the curved state, it is important to measure the phase retardation for the in-plane and the oblique incident light. Figure 7 shows the results of the angle of incidence dependence of phase retardation of the polycarbonate substrate in curved and non-curved states. We confirmed that the change in phase retardation of the curved polycarbonate substrate was extremely small even with a small radius of curvature. Figure 8 shows that the polycarbonate substrates were curved with a smaller radius of curvature in a cross-Nicol arrangement (radius of curvature: 4.3, 2.5, and 1.5 mm). We confirmed that light leakage caused by bending stress does not occur at the center of the substrates. These results indicate that the change in optical anisotropy caused by the deformation of the substrate is extremely small and that the optical compensation designed for the non-curved state is applicable even in curved states.

4. Optical Compensation of The Polycarbonate Substrate with a Positive C-Plate

From these results, we confirmed that the change in phase retardation was extremely small when the thickness of the substrates was sufficiently small. Therefore, we considered that it was possible to achieve a high contrast ratio and wide viewing angle range for flexible LCDs using a polycarbonate substrate in curved states by using optical compensation films [19], [20]. In order to compensate for the in-plane phase retardation of polycarbonate substrates, we laminated two substrates with their slow axis direction orthogonal. This laminating method keeps the in-plane phase retardation at zero by cancelling the anisotropy of the refractive indices of both substrates. Figure 9 shows the measurement result. We confirmed that the in-plane phase retardation of polycarbonate substrates was almost zero by laminating their slow axis direction in an orthogonal configuration.
We calculated the phase retardation in the thickness direction $R_{th}$ from the result of the incident angle dependence of phase retardation with compensation in Fig. 9. $R_{th}$ is defined as [21],

$$R_{th} = \left( \frac{n_x + n_y}{2} - n_z \right) \cdot d$$  \hspace{1cm} (4)

where $n_x$, $n_y$, and $n_z$ are the refractive indices along the in-plane slow axis, the in-plane fast axis, and thickness directions, and $d$ is the thickness of the sample. $R_{th}$ was $95.64$ nm. Therefore, we found that $R_{th}$ of the compensation film was $-95.64$ nm to suppress the phase retardation without depending on the incident angle. Polycarbonate substrates have a negative optical anisotropy film ($n_x = n_c < n_z$), therefore, we used a positive C-plate ($n_x = n_f > n_c$) (KX416, supplied by DENKA) as a compensation film for the polycarbonate substrates. Figure 10 shows the results of the angle of incidence dependence of phase retardation of a positive C-plate as a dashed line and that of the polycarbonate substrate with compensation in the non-curved state. We measured the angle of incidence dependence of phase retardation of curved states and confirmed that the dependence could be compensated without depending on the angle (Fig. 10). Thus, we can compensate for the dependence of the phase retardation angle of incidence of the polycarbonate substrate in curved states as well as the non-curved state. Pictures of the curved polycarbonate substrates in the cross-Nicol state are shown in Fig. 11 (radius of curvature: 13 mm). Based on the measurements, we clarified that we could compensate for the phase retardation of the polycarbonate substrate even in the curved and non-curved states by using a positive C-plate.

5. Conclusion

We evaluated the phase retardation of polycarbonate substrates in curved states to investigate the mechanism of the change in phase retardation. Our results showed that the amount of change in phase retardation by the bending stress was extremely small because the neutral plane does not move and the compressive and tensile stresses canceled each other out. Based on these results, we compensated for the phase retardation of polycarbonate substrates by using a positive C-plate and successfully suppressed light leakage in curved and non-curved states. These results indicate the feasibility of fabricating a high contrast ratio and wide viewing angle for flexible LCDs using plastic substrates, even for substrates with a small radius of curvature.

References


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