Ultra-wide-view patterned polarizer type stereoscopic LCDs using patterned alignment

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Abstract: The proposed patterned polarizer rather than the conventional ±λ/4 polarizer can further reduce the crosstalk through its corresponding glass for stereoscopic LCDs and can be fabricated by using the same patterned alignment technique. The patterned polarizer comprises a linear polarizer, a patterned retarder and a biaxial film. The maximum crosstalk ratio of the optimal design is reduced from 0.1 (for the conventional circular polarizer using ±λ/4 retarder and positive C film) to 0.016 (for the proposed structure) at ±60° viewing cone for the light obliquely passing through both the glasses and the LCD at the same angle. As to the light normally passing through both the LCD and glasses, the maximum crosstalk ratio can be reduced from 0.0167 to 0.0126 with rotated glasses.

References and links

1. C. H. Tsai, K. C. Huang, K. J. Lee, and W. J. Hsueh, “Fabricating microretarders by CO2 laser heating process technology,” Opt. Eng. 40(11), 2577–2581 (2001).
2. Y. J. Wu, Y. S. Jeng, P. C. Yeh, C. J. Hu, and W. M. Huang, “Stereoscopic 3D Display using Patterned Retarder,” SID Int. Symp. Digest Tech. Papers 39(1), 260–263 (2008).
3. J. Harrold, A. Jacobs, G. Woodgate, and D. Ezra, “3D Display Systems Hardware Research at Sharp Laboratories of Europe: an update,” Sharp Tech. J. 74, 24–30 (1999).
4. C. T. Lee, C. H. Tsai, and H. Y. Lin, “The Improvement of In-Cell Microretarder for Stereoscopic LCD Fabrication,” SID Int. Symp. Digest Tech. Papers 39(1), 448–451 (2008).
5. J. H. Oh, W. H. Park, B. S. Oh, D. H. Kang, H. J. Kim, S. M. Hong, J. H. Hur, J. Jang, S. J. Lee, M. J. Kim, K. H. Lee, and K. H. Park, “Stereoscopic TFT-LCD with Wire Grid Polarizer and Retarder,” SID Int. Symp. Digest Tech. Papers 39(1), 444–447 (2008).
6. C. T. Lee, C. H. Tsai, W. C. Liu, and H. Y. Lin, “Fabrication of In-Cell Microretarder & In-cell Polarizer for Stereoscopic LCD by Solution Process,” Proc. Int. Display Manufacturing Conference, pp. 2–16 (2009).
7. C. T. Lee, H. Y. Lin, and C. H. Tsai, “Designs of broadband and wide-view patterned polarizers for stereoscopic 3D displays,” Opt. Express 18(26), 27079–27094 (2010).
8. Y. Yoshihara, H. Ujike, and T. Tanabe, “3D Crosstalk of Stereoscopic (3D) Display using Patterned Retarder and Corresponding Glasses,” Proc. Int. Display Workshops, 3DP-5 (2008).
9. E. J. Acosta, E. J. Beynon, A. M. S. Jacobs, M. G. Robinson, K. A. Saynor, M. D. Tillin, M. J. Towler, and H. G. Walton, “Broadband optical retardation device,” US Patent 6735017 (2004).
10. H. Kang, S. D. Roh, I. S. Baik, H. J. Jung, W. N. Jeong, J. K. Shin, and J. J. Chung, “A Novel Polarizer Glasses-type 3D Displays with a Patterned Retarder,” SID Int. Symp. Digest Tech. Papers 41(1), 1–4 (2010).
11. Q. Hong, T. X. Wu, X. Zhu, R. Lu, and S. T. Wu, “Designs of wide-view and broadband circular polarizers,” Opt. Express 13(20), 8318–8331 (2005).
12. T. Ishinabe, T. Miyashita, and T. Uchida, “Wide-viewing-angle polarizer with a large wavelength range,” Jpn. J. Appl. Phys. 41(Part 1, No. 7A), 4553–4558 (2002).
13. Q. Hong, T. X. Wu, R. Lu, and S. T. Wu, “Wide-view circular polarizer consisting of a linear polarizer and two biaxial films,” Opt. Express 13(26), 10777–10783 (2005).
14. Y. C. Yang and D. K. Yang, “Analytic expressions of optical retardation of biaxial compensation films for liquid crystal displays,” J. Opt. A, Pure Appl. Opt. 11(10), 105502 (2009).
15. D. K. Yang and S. T. Wu, Fundamentals of Liquid Crystal Devices (Wiley, 2006).
16. P. Yeh and C. Gu, Optics of Liquid Crystal Displays (Wiley, 1999).

1. Introduction

Patterned polarizer is the key technology for spatial-multiplexed stereoscopic 3D display [1–5]. An in-cell polarizer and an in-cell patterned retarder were embedded inside the LCD panel,
for reducing the gap between LCD pixels and patterned retarder stripes to achieve a wider view angle for vertical direction [3–6]. It is easy for LCD makers to create patterned retarders using two-step polymerization [2]. A quarter-wave plate (QWP) cooperating with a patterned half-wave plate aligned by PI rubbing was used in [6], to achieve ±λ/4 phase difference. A broadband and wide-view patterned polarizer has been studied based on PI rubbing alignment [7], but the fabrication process is complex since it requires two layers of in-cell retarder. An alternative way is using the patterned alignment technique, so the retarder layer can be aligned as patterned ±λ/4 film [8]. A similar fabrication method is proposed to achieve the broadband patterned retarder by a λ/2 film with ±22.5° slow axes and λ/4 film with 90° slow axis [9]. On the other hand, the technique of patterned retarder can also be used for in-cell black stripes controlling by LCD pixels to achieve wider vertical viewing angle [10].

To design a wide-view patterned circular polarizer and its corresponding polarizers on glasses, the conventional way is applying a positive C plate to compensate ±λ/4 in-cell patterned retarder for the off-axis light [11]. Since the biaxial film provides an extra degree of freedom, the off-axis performance can be further enhanced [12, 13]. The design and simulation of retarders and biaxial layers is based on the analytical expressions of Muller matrix and extended Jones matrix described in [14–16]. The simulation models compiled by the Matlab codes have been proven to be consistent with the ones from 1Dimos software. Because 1Dimos cannot completely simulate the 3D performance, we use the self-developed Matlab codes and introduce the genetic algorithm (GA) for optimization in this study. Genetic algorithm is a well developed method to solve optimization problems by using such concepts as population, chromosome, and crossover inspired by natural evolution. We employed an improved version called differential evolution by using Optimus® from Noesis Solutions.

In this paper, white LED spectrum as the backlight system and RGB-color filters are simulated to calculate the crosstalk ratios. We assumed both left-eye and right-eye images have the same white light intensity and spectrum profile to exclude the crosstalk caused by the differences of 3D image content. The in-cell patterned retarder is made of Merck RMS-001 reactive liquid crystal and the biaxial retardation waveplate is made of PC (polycarbonate) film. At 550 nm wavelength, \( n_x = 1.6, n_y = n_z = 1.5 \) are assumed for the reactive LC; whereas \( n_x = 1.59, n_y = 1.58 \) for PC film. The refractive index \( n_\text{r} \) for biaxial PC film is determined by its \( N_z \) factor, where \( N_z = (n_y - n_z) / (n_x - n_z) \). The other LCD components including glass substrate, are all assumed with the refractive index \( n = 1.5 \). And for the air, refractive index is \( n = 1 \). The width of each patterned polarizer stripe is 60 μm and equal to the LCD pixel size.

2. Design and optimization of the proposed structure for oblique incidence

To optimize the proposed structure for oblique incidence, we first analyze the crosstalk ratio of the oblique view, there are two simulation models used in this study as shown in Figs. 1(a) and 1(b). Figure 1(a) illustrates the light obliquely passing through the patterned polarizer on LCD (polar angle \( \theta_1 \neq 0° \)), but normally passing through the left-eye and right-eye glasses (incident angle to the glasses \( \theta_2 = 0° \)), and is regarded as “oblique case A”. Figure 1(b) shows the light obliquely passing through both the patterned polarizer on LCD and glasses (polar angle \( \theta_1 = \theta_2 \neq 0° \)), and is regarded as “oblique case B”. We fix the angle at \( \varphi = 0° \) for both (a) and (b) cases for convenience. So the change of crosstalk ratio only depends on the polar angle \( \theta_1 \) and azimuthal angle \( \varphi \). And \( \mathbf{k} \) is the propagation vector of the light. The crosstalk ratio is defined as:

\[
\text{Crosstalk Ratio} = \frac{\text{Luminance of Unwanted Image}}{\text{Luminance of Correct Image}}.
\]

To obtain a better performance, we use the genetic algorithm to optimize the parameters of the patterned polarizer on LCD. In Fig. 2, the slow axis for each WP (waveplate) from #1 to #7 is defined as \( \psi_m \) with respect to the transmittance axis of in-cell polarizer, where \( d \) means film thickness and \( \Delta n \) means \( (n_x - n_y) \). The in-cell polarizer has a fixed transmitted axis at \( \psi_m = 0° \). The in-cell WPs #1 & #2 are made of reactive liquid crystal and hence have inherent \( N_z = 1 \), and their angles \( \psi_m \) of slow axes should be of different signs but the same magnitude. The
out-cell biaxial WP #3 is used to compensate the in-cell WPs #1 & #2 to maintain circular polarized light, and it is a uniform film with its $\psi_m$ being either 90° or 180°. Other parameters such as angles and retardation values are optimized results after GA process. The Muller matrix of a retarder or waveplate can be calculated by [14]

$$M_{wp}(\Gamma, \Phi) = \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & \cos^2 2\Phi + \sin^2 2\Phi \cos 2\Gamma & \sin 2\Phi \cos 2\Phi(1 - \cos \Gamma) & \sin 2\Phi \sin \Gamma \\
0 & \sin 2\Phi \cos 2\Phi & \sin^2 2\Phi & -\cos 2\Phi \sin 2\Phi \\
0 & -\sin 2\Phi \sin \Gamma & \cos 2\Phi \sin \Gamma & \cos \Gamma
\end{pmatrix}$$ (2)

And the angle $2\Phi$ in the Muller matrix representation is [7]:

$$2\Phi = -\arctan \left( \frac{\Delta n_k [\sin 2(\psi - \psi_m)] \cos \theta_0}{(1/2) \Delta n_k [\cos 2(\psi - \psi_m)] [1 + \cos^2 \theta_0] + \Delta n_s \sin^2 \theta_0} \right).$$ (3)

with $\Delta n_s = n_x - n_y$ and $\Delta n_k = n_z - (n_x + n_y)$. And the angle $\theta_0$ can be calculated by Snell’s law $1 \times \sin \theta \approx 1.5 \times \sin \theta_0$.

For the oblique incident light, the refractive index difference between the slow and fast axes can be derived by

$$n_s - n_y = \left| \frac{-\Delta n_k \sin 2(\psi - \psi_m) \cos \theta_0}{\sin 2\Phi} \right|.$$ (4)

Fig. 1. Two simulation models for oblique incidence. (a) Light obliquely passes through the patterned polarizer on LCD ($\theta_1 \neq 0^\circ$), but normally passes through the glasses ($\theta_2 = 0^\circ$). (b) Light obliquely passes through both the patterned polarizer on LCD and glasses ($\theta_2 = \theta_1 \neq 0^\circ$).

Fig. 2. Configuration of wide-view patterned polarizer for stereoscopic displays with corresponding polarizers on glasses.

Also for the oblique incident light, the refractive index difference between the slow and fast axes can be derived by
where $n_s$ and $n_f$ refer to the refractive indices of the slow and fast axes for the off-axis light, respectively. So the retardation value of the oblique incidence is given by

$$
\Gamma = \frac{2\pi (n_s - n_f) d}{\lambda \cos \theta}.
$$

(5)

where $\lambda$ is the wavelength and $d$ is the thickness of the waveplate. Thus we can use the abovementioned equations to optimize our structure.

Since the light emerged from the left-eye and right-eye polarizers on LCD generate similar loci but different orientations (left-hand and right-hand) on the Poincare sphere, we only illustrate the optimization of the right-eye polarizer on LCD in this study. The $COST$ function is introduced as:

$$
COST = \max \{S3 \mid \theta_l = 0^\circ \sim 60^\circ, \phi_r = 0^\circ \sim 360^\circ\},
$$

(6)

where $S3$ is the Stokes parameter of the light emerged from the right-eye polarizer on LCD. The $COST$ function equals to the maximum value of $S3$. The data of $S3$ are taken from polar angle $\theta_l = 0^\circ$ to $60^\circ$ and from azimuthal angle $\phi_r = 0^\circ$ to $360^\circ$, with $1^\circ$ interval, respectively. So totally there are 61 times 361 numbers of $S3$. In this case, the $S3$ should approach $-1$ to generate a right-hand circular polarized light and its spectrum should be centered at 550 nm wavelength because of human eye’s sensitivity. By minimizing the $COST$ function shown in Eq. (6), we can obtain the five optimal parameters, in-cell WP #2: $\psi_m = 58.8^\circ$, $\Delta n_d = 159.53$ nm; out-cell WP #3: $N_z = -1.045$, $\Delta n_d = 48.03$ nm and $\psi_m = 180^\circ$ to achieve minimum $S3$.

Figure 3(a) shows the Stokes parameters of the light normally emerged from the right-eye polarizer on LCD, it starts from $(S1, S2, S3) = (1, 0, 0)$, to $R = -0.9706$ ($S3$ of 650 nm in wavelength) $G = -1$ ($S3$ of 550 nm in wavelength) and $B = -0.9609$ ($S3$ of 450 nm in wavelength). At oblique incidence $\theta = 60^\circ$, the minimum $S3$ of the resulted Stokes parameters are $R = -0.9416$, $G = -0.9852$ and $B = -0.895$ as shown in Fig. 3(b). The results show the proposed structure can still maintain good circular polarization even at different wavelengths and of large incident angles. After optimization, the phase retardation of oblique incidence at 550 nm becomes closer to the normal one. And hence at 650 and 450 nm wavelengths, the retardation values also become closer to the normal ones.

Then we use the genetic algorithm to optimize the corresponding polarizers on glasses. To perform this optimization, white LED spectrum and human eye sensitivity function are considered to calculate the crosstalk ratios. We only need to optimize either the corresponding left- or right-eye polarizer on glasses. The corresponding left-eye polarizer on glasses is considered in this case. The transmitted axis of glasses polarizer is oriented at $90^\circ$ with respect to the one of in-cell polarizer. By minimizing the cost function defined as:

-1
-0.5
0
0.5
1
-1
-0.5
0
0.5
1
S1
S2
S3
In-cell retarder
Biaxial film
Final $S3$:
$R = -0.9706$
$G = -1$
$B = -0.9609$

Fig. 3. (a) Simulated loci of Stokes parameters at normal incidence for the light emerged from the right-eye polarizer on LCD in Fig. 2. (b) $S3$ of different wavelengths at $\theta = 60^\circ$ with varied azimuthal angles.

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and restricting the resulted crosstalk ratio $< 10^{-4}$ for $\theta_1 < 6^\circ$, we can obtain six optimal parameters of the corresponding left-eye polarizer on glasses depicted in Fig. 2, biaxial WP #4: $\Delta nd = 138.18$ nm, $\psi_m = -41.4^\circ$, $N_z = 0.674$; biaxial WP #6: $\Delta nd = 314.14$ nm, $\psi_m = -88.0^\circ$, $N_z = 0.575$.

Figure 4 shows the iso-crosstalk ratio contour for the conventional $\pm \lambda/4$ structure compensated by a positive C film and Fig. 5 shows that for the proposed structure. To clearly show the parameters of the conventional structure, we replace the WP #1, #2, #3, #4 and #6 in Fig. 2 as follows: WP #1: $\Delta nd = 137.5$ nm, $\psi_m = -45^\circ$, $N_z = 1$; WP #2: $\Delta nd = 137.5$ nm, $\psi_m = 45^\circ$, $N_z = 1$; WP #3 & #4: $(n_z - n_x)d = 59.9$ nm (positive C plate); WP #6: $\Delta nd = 137.5$ nm, $\psi_m = -45^\circ$, $N_z = 1$. Because the left-eye and right-eye systems have similar loci but different orientations of polarization states (one is left-hand and the other is right-hand) on the Poincare sphere, their crosstalk ratios have the same maximum value in each of the polar angle $\theta$. So we only consider the left-eye crosstalk in this case. Figure 4(a) describes the “oblique case A” and (b) describes the “oblique case B”, which refer to Figs. 1(a) and 1(b), respectively. At $\theta = 60^\circ$ cone, the maximum crosstalk ratios are less than 0.025 in (a) and 0.1 in (b).

Figure 5 describes the left-eye crosstalk of the proposed structure. In Fig. 5(a), the crosstalk ratio of oblique case A is less than 0.025 at $\theta = 60^\circ$ cone. In Fig. 5(b), the crosstalk ratio of oblique case B is 0.016 at $\theta = 60^\circ$ cone. Although, the crosstalk ratio increases from $10^{-7}$ to $1.4 \times 10^{-5}$ at polar angle within $0^\circ$~$3^\circ$ range, it is negligible for 3D crosstalk discussion.

\[ COST = \max \left\{ \text{Crosstalk Ratio} \mid \begin{array}{l}
\theta_1 = 0^\circ \sim 30^\circ, \psi = 0^\circ \sim 360^\circ \\
\theta_2 = 0^\circ \& \theta_1
\end{array} \right\}. \] (7)

Fig. 4. Simulated iso-crosstalk ratio contour of left-eye crosstalk by conventional circular polarizer consisting of an in-cell QWP and a positive C plate. (a) Oblique case A and (b) Oblique case B.

Fig. 5. Simulated iso-crosstalk ratio contour of left-eye crosstalk by proposed circular polarizer consisting of an in-cell WP and a biaxial plate. (a) Oblique case A and (b) Oblique case B.
3. Comparison of the “normal view” of 3D display

Figure 6(a) illustrates the change of crosstalk ratio due to the glasses rotated with the varied angle of $\phi$. The light normally passes through both the patterned polarizer on LCD and the glasses ($\theta_1 = \theta_2 = 0^\circ$). In this situation, the crosstalk ratio depends on the angle of $\phi$ with respect to x axis, and $\phi = 0^\circ$ means the viewer is completely at correct and suitable position while watching LCD screen, and the crosstalk ratio is therefore almost equal to zero. When $\phi$ is increased or decreased from 0, the polarizers on LCD and glasses are no longer orthogonal. In our design, the left and right eyes have the same crosstalk ratio for each different $\phi$ angle.

Then we compared the “normal view performance of 3D display” for the proposed and conventional systems. As shown in Fig. 6(b), the conventional patterned polarizer made of a $\pm \lambda/4$ retarder and a positive C plate has larger crosstalk ratios for each of the $\phi$ angle, the maximum crosstalk ratio is 0.0168 at $\phi = \pm 90^\circ$. Furthermore, the proposed patterned polarizer with the optimized corresponding polarizers on glasses in Fig. 1 shows the maximum value of 0.0126 at $\phi = \pm 90^\circ$.

![Fig. 6.](image)

4. Conclusion

This work presents a new methodology to design patterned circular polarizer consisting of a linear polarizer, an in-cell patterned retarder and a biaxial film for stereoscopic LCDs. Genetic algorithm is utilized to optimize the parameters of the patterned polarizer on LCD to preserve circular polarization state at large incident angles. In addition to the optimization of the Stokes parameters $S_3$, GA is also applied to optimize the parameters of the corresponding polarizers on glasses and hence the crosstalk ratio can be reduced further. Compared to the conventional patterned $\lambda/4$ polarizer compensated by positive C film, the maximum crosstalk ratio of the optimal structure reduced from 0.025 to 0.018 over 60° viewing cone for the “oblique case A” and from 0.1 to 0.016 over 60° viewing cone for the “oblique case B”. As to “normal view performance”, the maximum crosstalk ratio of the proposed structure is reduced from 0.0168 to 0.0126 at $\phi = \pm 90^\circ$ as compared to the conventional one. In conclusion, we design a wide-view patterned polarizer and its corresponding polarizers on glasses for 3D displays based on the existing fabrication techniques and, it obviously enhances the viewing freedom of stereoscopic 3D LCDs.

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