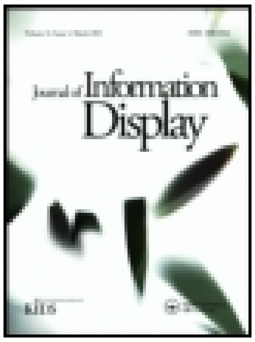

Journal of Information Display

ISSN: 1598-0316 (Print) 2158-1606 (Online) Journal homepage: http://www.tandfonline.com/loi/tjid20

Design of an achromatic wide-view circular polarizer using normal dispersion films

Seung-Won Oh, Sang-Hyeok Kim, Jong-Min Baek & Tae-Hoon Yoon

To cite this article: Seung-Won Oh, Sang-Hyeok Kim, Jong-Min Baek & Tae-Hoon Yoon (2018): Design of an achromatic wide-view circular polarizer using normal dispersion films, Journal of Information Display, DOI: 10.1080/15980316.2018.1538907

To link to this article: https://doi.org/10.1080/15980316.2018.1538907

Published online: 29 Oct 2018.

JOURNAL OF INFORMATION DISPLAY
https://doi.org/10.1080/15980316.2018.1538907

Design of an achromatic wide-view circular polarizer using normal dispersion films

Seung-Won Oh, Sang-Hyeok Kim, Jong-Min Baek and Tae-Hoon Yoon

Department of Electronics Engineering, Pusan National University, Busan, Republic of Korea

ABSTRACT

Proposed herein is an achromatic wide-view circular polarizer (CP) using normal dispersion films, which can suppress the light reflection over all the polar and azimuth angles. For normal incidence, the proposed CP with +A/−A/+C plates shows almost zero light reflection over all the wavelengths. For oblique incidence, the maximum reflected light of the proposed CP with +A/−A/+C plates is approximately 68 times lower than that of a CP with a single quarter-wave plate. Moreover, because all the films that were used had normal wavelength dispersion, they could be easily fabricated at a relatively low manufacturing cost.

ARTICLE HISTORY
Received 12 August 2018
Accepted 9 October 2018

KEYWORDS
Optical compensation; antireflection; circular polarizer; wide-view

1. Introduction

Organic light-emitting diode displays (OLEDs) are emerging as a promising technology for smartphones and televisions [1–4]. OLEDs exhibit advantages like a true black state, vivid colors, good flexibility, and a fast response time. In spite of all these advantages, the sunlight readability of OLEDs is still quite limited because of the strong reflection of the ambient light by the inner metallic electrodes. A circular polarizer (CP) has been commonly used in OLED display panels to suppress the reflection of the ambient light [5–11]. A circular polarizer consists of a linear polarizer and a quarter-wave plate (QWP). A linearly polarized light passed through a polarizer is transformed into a circularly polarized light state while passing through the QWP. Then the light reflected from the reflective electrode of an OLED passes through the QWP again and becomes a linearly polarized light whose polarization is orthogonal to the original input beam, resulting in the elimination of the reflected light.

Although the reflected light, however, can be suppressed at an optimized wavelength of 550 nm, the light reflection at other wavelengths (e.g. red and blue) remains very severe, as can be expected from Figure 1(a). The polarization state of light that has passed through the QWP depends on the wavelength because the phase retardation is inversely proportional to the wavelength of the incident light. Several approaches have been proposed to address this problem [5–15], and the so-called 'wide-band CP (WB-CP)' is widely used these days [6,7,11–13]. In a WB-CP, the optical axis of a half-wave plate (HWP) and a QWP are ±15 and ±75°, respectively. This optical structure suppresses the reflected light significantly because the polarization states are accumulated at the S_3 axis on the Poincaré sphere, as shown in Figure 1(b). Light reflection remains, however, at the edge regions (red and blue) of the visible range.

Moreover, a substantial amount of incident light is reflected for oblique incidence, although this method suppresses light reflection only for normal incidence [8–13]. Replacing the uniaxial QWP with a biaxial QWP will only slightly improve the acceptance angle [12,13]. The optimization of both HWP and QWP by combining the uniaxial A and C plates will significantly widen the acceptance angle [8–10], but their device configurations are quite complicated.

In this paper, an achromatic wide-view circular polarizer using normal dispersion films is proposed to suppress light reflection over all the polar and azimuth angles. Three uniaxial films with different dispersion characteristics are used so that they can compensate for one another's limitations to achieve the desired achromatic effective phase retardation. The retardation values can be optimized with the aid of the Poincaré sphere. Zero or negative dispersion films are not used as they are incidentally difficult to fabricate and are very expensive for practical display applications.

CONTACT Tae-Hoon Yoon thyoon@pusan.ac.kr Department of Electronics Engineering, Pusan National University, Busan 46241, Republic of Korea

ISSN (print): 1598-0316; ISSN (online): 2158-1606

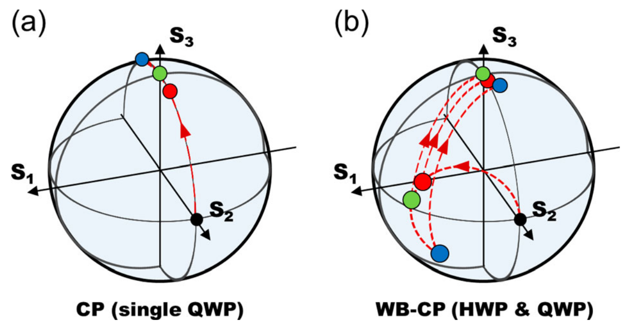

Figure 1. Polarization change on the Poincaré sphere of each color (450, 550, and 650 nm wavelengths) by the (a) CP and (b) WB-CP structures for normal incidence.

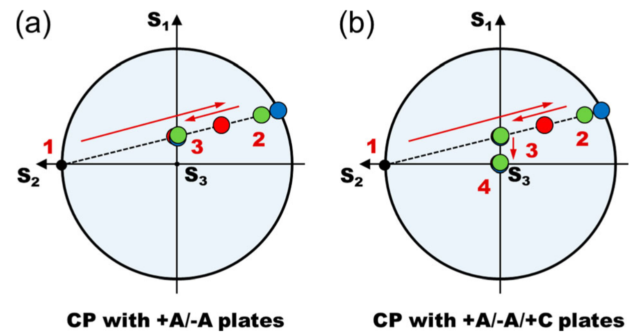

Figure 3. Polarization states of each color (450, 550, and 650 nm wavelengths) in the CPs with (a) +A/−A and (b) +A/−A/+C plates on the S_1–S_2 plane of the Poincaré sphere under oblique incidence ($\theta = 70°$, $\varphi = 0°$).

2. Optical design of an achromatic wide-view circular polarizer

A uniaxial film with normal dispersion commonly increases the light reflection [16–20]. In the proposed structure, however, the strong dispersion of uniaxial films makes the polarization states accumulate at S_3 on the Poincaré sphere so that it can be used in the opposite way to remove the light reflection. Figure 2(a) shows the proposed CP with a +A/−A/+C configuration using two A plates and a C plate. When unpolarized light traverses through the polarizer, it becomes linearly polarized (located at point 1), as shown in Figure 2(b). As the optic axes of the two A plates are the same but the sign of the phase retardations is opposite, the rotations of the polarization state caused by the A plates (on the Poincaré sphere) proceed in opposite directions. Thus, the wavelength dispersion is canceled by the two A plates. The dispersion can be effectively removed by setting the degree of dispersion of the plates so that the first A plate (which has a high retardation value) will have a weak dispersion while the second A plate (which has a low retardation value) will have a strong dispersion. Finally, the polarization states at all the visible wavelengths are effectively accumulated at the S_3 axis (point 3).

The polarization can be changed to circular polarization by using two designed A plates for normal incidence.

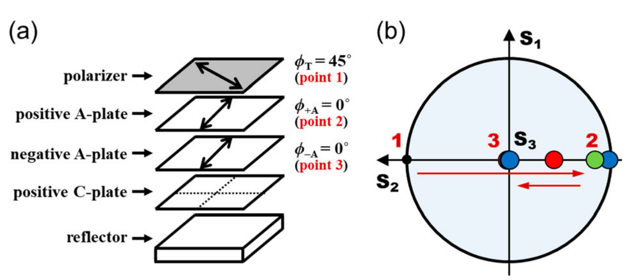

Figure 2. (a) Compensation scheme of the CP with +A/−A/+C plates. (b) Polarization change of each color (450, 550, and 650 nm wavelengths) on the Poincaré sphere for normal incidence.

As light reflection still exists for oblique incidence, however, a positive C plate was added to solve this problem. This positive C plate contributes phase retardation at oblique angles so that the produced polarization is closer to the ideal circular polarization while the performance for normal incidence remains the same. The wavelength dependence of the polarization change at $\theta = 70°$ in the proposed CP configurations is shown on the Poincaré sphere, as can be seen in Figure 3. Without a positive C plate, the polarization will become elliptical, resulting in light reflection. With a positive C plate, the polarization at all the visible wavelengths will be effectively accumulated and will remain at S_3 for oblique incidence.

To find the optimum Δnd of the positive C plate for minimum reflection over the ±85° viewing cone, the iso-luminance contours were plotted as the Δnd of the C plate gradually increased from 0 to 100 nm, as shown in Figure 4. Increasing the Δnd of the C plate reduced the off-axis reflection. When the Δnd of the C plate was 60 nm, the reflected light was suppressed over the entire ±85° viewing cone, as shown in Figure 4(d). The reflected light increased, however, as the Δnd of the C plate increased to higher than 60 nm because the polarization states, which are located at point 4 in Figure 3(c), deviated from S_3 on the Poincaré sphere. Therefore, the Δnd of the C plate was set to 60 nm.

The parameters of the films were set through computer simulation to confirm the performance of the proposed compensation scheme, as listed in Table 1. Three uniaxial films with different dispersion characteristics, which were reported in previous works [14,21,22], are used. The first positive A plate has a weak wavelength dispersion whereas the second negative A plate has a strong wavelength dispersion. The C plate has a weak wavelength dispersion. The conventional compensation schemes have poor characteristics when films with normal dispersion are used. In the proposed configuration,

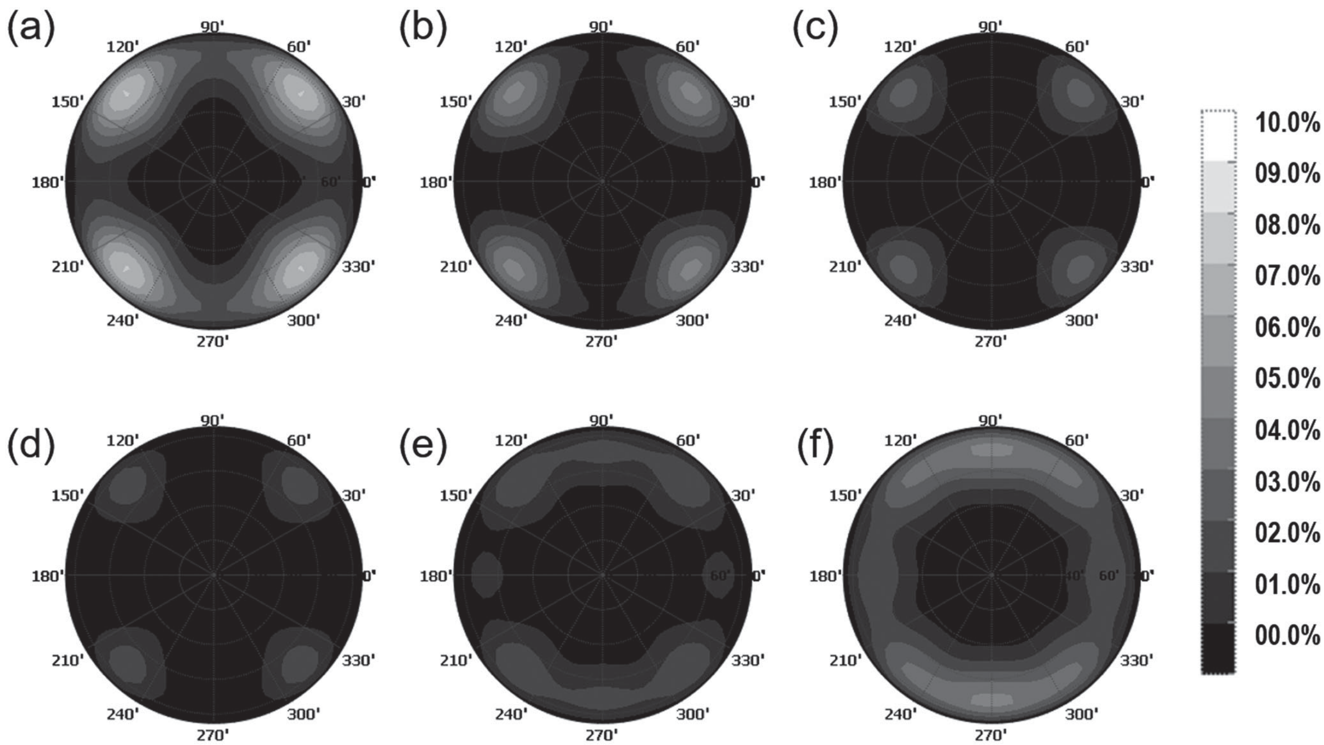

Figure 4. Calculated iso-luminance contours with the Δnd of the positive C plate as a parameter: (a) 0; (b) 20; (c) 40; (d) 60; (e) 80; and (f) 100 nm.

Table 1. Parameters of the uniaxial plates used for the proposed structure.

	Δn (n_e–n_o)			Δnd [nm]
Uniaxial plates	450 nm	550 nm	650 nm	at 550 nm
Positive A plate [Ref. 14]	0.0109	0.01	0.0094	287
Negative A plate [Ref. 21]	−0.0134	−0.01	−0.0072	−150
Positive C plate [Ref. 22]	0.0109	0.01	0.0095	60

however, uniaxial films with normal dispersion are used to remove the deviation in the polarization states over all the visible wavelengths. The retardation values and the degree of dispersion of the films can be freely changed and optimized under the condition mentioned above. Moreover, zero or negative dispersion films are not used as they are incidentally difficult to fabricate and are very expensive for practical display applications.

3. Numerical results and discussion

The reflected light was calculated using the simulation program 'TechWiz LCD 1D.' In this calculation, an ideal polarizer was assumed, but the tendency will not change with a real polarizer. A cold-cathode fluorescence lamp, a broadband light source with a continuous spectrum, was used as the light source.

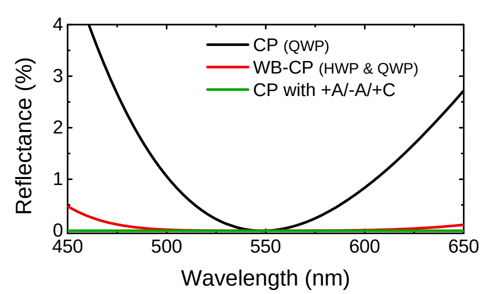

Figure 5. Reflection spectra of the CP, WB-CP, and CP with +A/−A/+C plates for normal incidence.

To investigate the dispersion characteristics of the optical configurations in the visible region, the reflection spectra were calculated for normal incidence, as shown in Figure 5. The WB-CP (red line) shows much lower reflectance than CP (black line), and it is quite insensitive to the 450–650 nm wavelengths. Although the WB-CP reasonably reduces the reflection compared to the CP, the reflected light remains, especially in the blue region. The green line represents the reflection of the CP with +A/−A/+C plates, which is shown as almost zero over all the wavelengths. The average reflections in the CP, uniaxial WB-CP, and biaxial WB-CP were 1.36, 0.0621, and 0.0003%, respectively.

To show the compensation performance, the reflectance over the entire range of polar angles at the

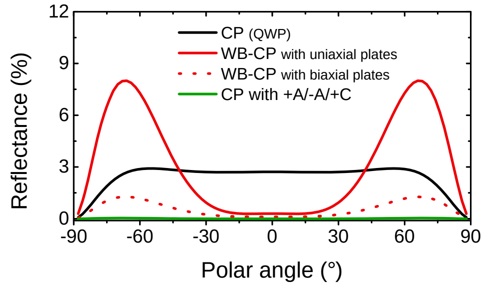

Figure 6. Reflectance of the CP, WB-CP, and CP with +A/−A/+C plates vs. the polar angle at the 0° azimuth angle.

azimuth angle of 0° was plotted, as shown in Figure 6. The solid black and red lines represent the reflectance of the CP and WB-CP structures. Strong reflection was observed at any polar angle in both structures. When the uniaxial plates were replaced with biaxial plates in a WB-CP structure [12,13], the reflectance was much smaller than the uniaxial WB-CP structure, as shown by the dashed red line. The solid green line represents the reflectance of the proposed CP with a +A/−A/+C structure, which is shown as almost zero over the entire polar angle. The maximum reflectance values in the CP, WB-CP, biaxial WB-CP, and proposed CP with +A/−A/+C plates were 2.92, 8.00, 1.27, and 0.043%, respectively. The maximum reflectance in the proposed CP with +A/−A/+C plates is approximately 68 times lower than that in the CP structure. This will result in a low light reflection over the entire viewing cone for the white light.

To investigate the performance of the CP with +A/−A/+C plates, the reflectance of the CPs for antireflection of an OLED was calculated. Figure 7 shows the iso-luminance contours. The maximum reflectance values in the CP, WB-CP, and biaxial WB-CP were 7.27, 13.3, and 8.47%, respectively. The CP with +A/−A/+C plates showed the least viewing angle dependence, and the maximum reflectance was 1.45% [Figure 7(d)]. The reflectance in the CP with +A/−A/+C plates was even smaller than that in the WB-CP with biaxial plates (8.47%) [Figure 7(c)]. The better viewing angle property of the CP with +A/−A/+C plates can be explained by the polarization states on the Poincaré sphere in Figure 7(b).

4. Conclusions

Proposed herein is an achromatic wide-view circular polarizer (CP) using normal dispersion films to suppress the light reflection over all the polar and azimuth

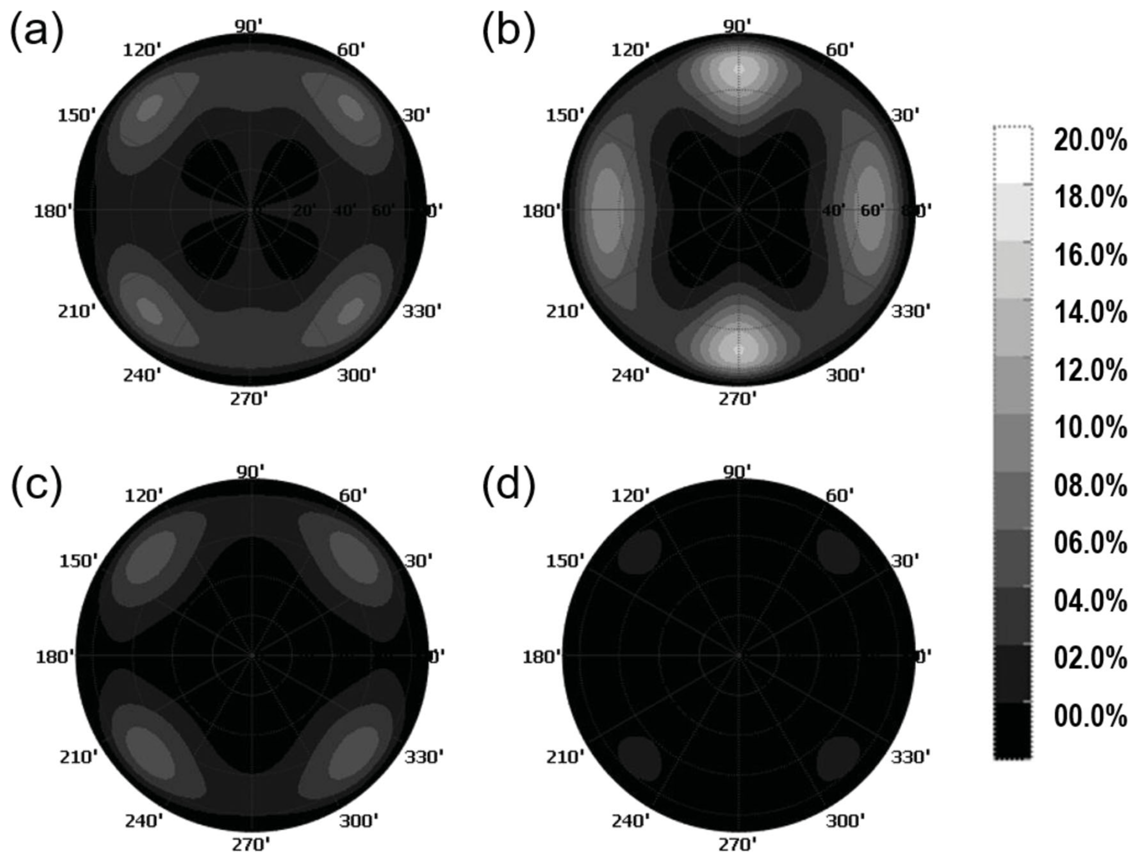

Figure 7. Calculated iso-luminance contours of the (a) CP, (b) WB-CP with uniaxial plates, (c) WB-CP with biaxial plates, and (d) CP with +A/−A/+C plates.

angles. For normal incidence, the proposed CP with +A/−A/+C plates shows almost zero light reflection over all the wavelengths by canceling the wavelength dispersion. For oblique incidence, the maximum reflectance in the proposed CP with +A/−A/+C plates is approximately 68 times lower than that in the CP structure. This will result in low light reflection over the entire viewing cone for the white light. Moreover, all the films that were used had normal wavelength dispersion and could be easily fabricated at a relatively low manufacturing cost.

Funding

This work was supported by National Research Foundation of Korea: [Grant Number 2017R1A2A1A05001067].

Notes on contributors

Seung-Won Oh received his B.S. and Ph.D. Electronics Engineering degrees from Pusan National University, Busan, South Korea in 2013 and 2018, respectively. He is currently a postdoctoral associate in the same institute. His research interest is the self-shading window for energy saving.

Sang-Hyeok Kim received his B.S. Electronics Engineering degree from Pusan National University in 2017. He is currently working towards an M.S. Electronics Engineering degree in the same university. His research interests are the liquid crystal light shutter and self-shading window.

Jong-Min Baek received his B.S. and M.S. Electronics Engineering degrees from Pusan National University in 2015 and 2017, respectively. He is currently a research engineer at LG Display, South Korea.

Tae-Hoon Yoon received his B.S. Electronics Engineering degree from Seoul National University in 1979, and his M.S. and Ph.D. Electrical Engineering degrees from Korea Advanced Institute of Science and Technology (KAIST) in 1982 and 1986, respectively.

Since 1986, he has been with the Department of Electronics Engineering of Pusan National University, where he is currently a professor. In 1990, he worked as a research scientist at the Optical Sciences Center, University of Arizona. In 1997, he worked as a visiting scholar at the Department of Electrical and Computer Engineering, University of California, Santa Barbara. From 2001 to 2003, he served full-time as the Program Director for the Information & Electronics Program at the Korea Institute of S & T Evaluation and Planning. He has authored and co-authored 241 international journal papers, and has 90 issued and pending patents. His current research interests include the liquid crystal light shutter and the fast switching of liquid crystals.

Dr. Yoon chaired the Program Committee of IMID (International Meeting on Information Display) 2010 as well as the Executive Committee of IMID 2011. In 2012, he served as the president of the Optical Society of Korea. He also served as the chair of the Organizing Committee of ACLC (Asian Conference on Liquid Crystals) 2015. From 2014 to 2016, he was the editor-in-chief of the Journal of Information Display.

ORCID

Seung-Won Oh http://orcid.org/0000-0001-7596-948X
Tae-Hoon Yoon http://orcid.org/0000-0002-9047-8002

References

[1] C.W. Tang and S.A. Vanslyke, Organic electroluminescent diodes, Appl. Phys. Lett. **51**, 913 (1987).
[2] M.A. Baldo, D.F. O'Brien, Y. You, A. Shoustikov, S. Sibley, M.E. Thompson, and S. R. Forrest, Highly efficient phosphorescent emission from organic electroluminescent devices, Nature **395**, 151 (1998).
[3] Y.-C. Kim, S.-H. Cho, Y.-W. Song, Y.-J. Lee, Y.-H. Lee, and Y.R. Do, Planarized SiNx/spin-on-glass photonic crystal organic light-emitting diodes, Appl. Phys. Lett. **89**, 173502 (2006).
[4] S. Hofmann, M. Thomschke, B. Lössem, and K. Leo, Top-emitting organic light-emitting diodes, Opt. Express 19, A1250 (2011).
[5] M. Okamoto, K. Minoura, and S. Mitsui, Optical design of the LC layer on reflective LCDs with a single polarizer, in Proceedings of the 7th International Display Workshop, Society for Information Display, 1999, pp. 49–52.
[6] T.-H. Yoon, G.-D. Lee, and J.C. Kim, Nontwist quarter-wave liquid-crystal cell for a high-contrast reflective display, Opt. Lett. **25**, 1547 (2000).
[7] A. Uchiyama and T. Yatabe, P-5: Characteristics and applications of new wide-band retardation films, SID Symposium Digest of Technical Papers **32**, 566–569 (2001).
[8] Q. Hong, T.X. Wu, X. Zhu, R. Lu, and S.-T. Wu, Designs of wide-view and broadband circular polarizers, Opt. Express **13**, 8318–8331 (2005).
[9] Z. Ge, M. Jiao, R. Lu, T. X. Wu, S.-T. Wu, W.-Y. Li, and C.-K. Wei, Wide-view and broadband circular polarizers for transflective liquid crystal displays, J. Disp. Technol. **4**, 129 (2008).
[10] Z. Ge, R. Lu, T. X. Wu, S.-T. Wu, C.-L. Lin, N.-C. Hsu, W.-Y. Li, and C.-K. Wei, Extraordinarily wide-view circular polarizers for liquid crystal displays, Opt. Express **16**, 3120 (2008).
[11] J. S. Gwag, Optical fine-tuning for improving the dark level of a reflective liquid crystal display, Appl. Opt. **56**, 1893 (2017).
[12] T. Takahashi, Y. Furuki, S. Yoshida, T. Otani, M. Muto, Y. Suga, and Y. Ito, 29.1: A new achromatic quarter-wave film using liquid-crystal materials for anti-reflection of OLEDs, SID Symposium Digest of Technical Papers **45**, 381–384 (2014).

[13] B. C. Kim, Y. J. Lim, J. H. Song, J. H. Lee, K.-U. Jeong, J. H. Lee, G.-D. Lee, and S.-H. Lee, Wideband antireflective circular polarizer exhibiting a perfect dark state in organic light-emitting-diode display, Opt. Express 22, A1725 (2014).

[14] S. Yang, H. Lee, J.-H. Lee, Negative dispersion retarder with a wide viewing angle made by stacking reactive mesogen on a polymethylmethacrylate film, Opt. Eng. **55**, 027106 (2016).

[15] J. Hwang, S. Yang, Y.-J. Choi, Y. Lee, K.-U. Jeong, and J.-H. Lee, Single layer retarder with negative dispersion of birefringence and wide field-of-view, Opt. Express **24**, 19934 (2016).

[16] S.-W. Oh, B. W. Park, J.-H. Lee, and T.-H. Yoon, Achromatic optical compensation using dispersion of uniaxial films for elimination of off-axis light leakage in a liquid crystal cell, Appl. Opt. **52**, 7785 (2013).

[17] S.-W. Oh and T.-H. Yoon, Elimination of light leakage over the entire viewing cone in a homogeneously-aligned liquid crystal cell, Opt. Express **22**, 5808 (2014).

[18] S.-W. Oh and T.-H. Yoon, Achromatic wide-view circular polarizers for a high-transmittance vertically-aligned liquid crystal cell, Opt. Lett. **39**, 4683 (2014).

[19] S.-W. Oh, A.-K. Kim, B.W. Park, and T.-H. Yoon, Optical compensation methods for the elimination of off-axis light leakage in an in-plane-switching liquid crystal display, J. Inf. Disp. **16**, 1 (2015).

[20] S.-W. Oh and T.-H. Yoon, Optical compensation for elimination of off-axis light leakage in a homogeneously-aligned liquid crystal cell, Mol. Cryst. Liq. Cryst. **613**, 181 (2015).

[21] A. Uchiyama, Y. Ono, Y. Ikeda, H. Shuto, and K. Yahata, Copolycarbonate optical films developed using birefringence dispersion control, Polym. J. **44**, 995 (2012).

[22] 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**, 105502 (2009).