

# Wideband antireflective circular polarizer exhibiting a perfect dark state in organic light-emitting-diode display

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**Abstract:** We proposed wideband antireflective circular polarizer for realizing a true black state in all viewing directions in organic light-emitting-diode displays (OLEDs). Present commercialized wideband circular polarizer consisted of a half wave and a quarter wave plates having the refractive index parameter ( $N_z$ ) of 1.5 in both films exhibits light leakage in the oblique viewing directions, deteriorating image quality of a black state. We evaluated  $N_z$ s of both films and proposed a new wideband antireflective circular polarizer with a perfect dark state in all viewing directions with  $N_z = 0.5$  in both plates, which will greatly improve image quality of OLEDs.

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**OCIS codes:** (230.2090) Electro-optical devices; (160.1190) Anisotropic optical materials; (230.3670) Light-emitting diodes.

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## 1. Introduction

Organic light-emitting-diode displays (OLEDs) are emerging as a promising technology for smart phones and televisions because they are self emitting displays with vivid color and have advantageous characteristics in thinness, lightweight and flexible display form factor [1–6]. Nevertheless, the emission efficiency of the OLEDs are still not maximized so that OLEDs with top emission method which uses a metal electrode with high reflectivity as an anode is used to increase emission efficiency [7–11]. Such approaches drop a contrast ratio of the display sharply with strong ambient light because the high reflectivity of the display reflects strongly an incident light to the display. As a solution to reduce the reflectivity of the display, a circular polarizer consisting of a polarizer and a quarter wave refractive plates have to be used to prevent the reflected light [12, 13]. A polarizing principle of antireflection film is that the linearly polarized light through polarizer transformed to a circularly polarized light state through the quarter-wave ( $\lambda/4$ ) film. Then, the reflected light from the reflective electrode of OLED passes through quarter-wave film again and then becomes linearly polarized light of which the polarizing direction is opposite to the original input beam, resulting in a dark state due to blocking of polarizer. However, conventional quarter-wave film with normal wavelength dispersion had caused a light leakage in normal direction as well as oblique direction because all visible wavelengths are not changed to circular polarized light and retardation is higher than  $\lambda/4$  in oblique direction. To solve this problem, several researches are suggested such as a quarter wave film with reverse wavelength dispersion [14, 15], a photochromic circular polarizer [16], and wideband quarter wave film [17, 18]. These methods improved a dark state only in normal direction, but substantially diminished a contrast ratio in oblique viewing directions. Recently, a new achromatic quarter-wave film with multiple layers consisted of half wave plate (HWP) made of discotic liquid crystal material and a quarter wave plate (QWP) made of rod-like liquid crystal material is developed by FUJIFILM [19]. In optical films, optimizing the refractive index parameter  $N_z$  which is defined as  $N_z = n_x n_z / n_y n_z$  (here, the  $n_x$ ,  $n_y$ , and  $n_z$  are the refractive index in the x, y, and z directions) [20] is very important. In their works, the maximal light leakage in reflectivity exhibits over 3% in oblique direction because  $N_z$  values of the HWP and QWP are 0 and 1, respectively. In addition, since reactive mesogen is used for both layers, the fabrication process requires uniform coating of the RM and then ultraviolet curing process for polymerization of the RM.

In this paper, we proposed a novel circular polarizer which exhibits a perfect dark state in all viewing directions for OLEDs, in which the polarizer is consisted of a HWP and a QWP and its  $N_z$  is controlled purely by mechanical stretching and contraction of the film.

## 2. Light leakage of the conventional wideband antireflective film in oblique viewing directions

In the conventional wideband antireflective film, the film is consisted of a polarizer, HWP, and QWP. Here, two wave plates are made of cyclo-olefin copolymer (COP). When the COP film is stretched, its refractive index becomes so high along the stretching direction while it becomes so small in other directions, especially small value in thickness direction. As a result,  $N_z$  value of both HWP and QWP result in close to 1.5, inevitably. Figure 1 shows optical configuration and iso-luminance of the film in reflectivity for the OLED that was applied to Galaxy S5 (Samsung Electronics Co., Korea). The slow axes of a HWP and a QWP are  $15^\circ$  and  $75^\circ$  with respect to transmittance axis of the polarizer, respectively. With the present configuration of the film, the linearly polarized light through the polarizer moves to another linearly polarized light state with a  $30^\circ$  rotation through HWP and becomes circularly polarized after passing QWP. After reflection by metal electrode of OLED, the circularly polarized light passes through QWP again and becomes linearly polarized with a  $120^\circ$  rotation. The linearly polarized light again passes through HWP, resulting in linearly polarized state opposite to the original input beam. This results in a dark state due to blocking of polarizer. The approach exhibits an excellent dark state at normal direction, however, the light leakage starts to increase as the viewing direction increases over  $40^\circ$  of polar angle in most azimuthal directions and reaches up to 40% reflectivity in specific azimuthal angles as shown in Fig. 1(b). For calculations of the optical properties, a commercially available simulation tool "TechWiz LCD" (Sanayi-system, Korea) has been used and the OLED is replaced with reflector.

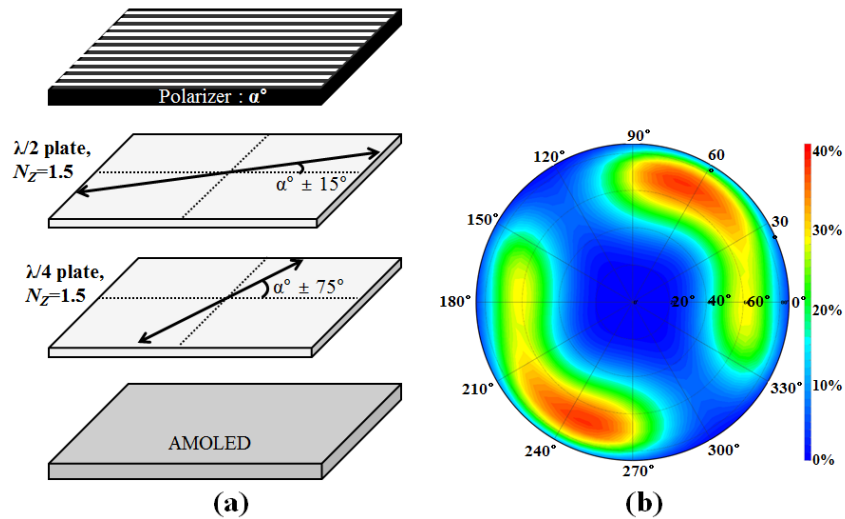


Fig. 1. (a) Device configuration and (b) iso-luminance contour in dark state of the wide view circular polarizers.

Figure 2 shows the changed polarization states of light in normal and oblique direction on Poincare sphere after passing through the wide-band antireflective film with  $N_z$  of 1.5 for OLED. The blue, green, and red colors express the polarization state of the light for blue (450nm), green (550nm), and red (650nm) wavelengths, respectively. As shown in Fig. 2(a), when an unpolarized incident light passes through polarizer, it becomes a linearly polarized light and its polarization state is located at point I on the S1 axis which is in the opposite direction of the absorption axis of polarizer. When this linearly polarized light propagates through the wideband quarter wave film, metal electrode of the OLED layer and then wideband quarter wave film again, the polarization state of the light moves along point 1 to 4 in the normal direction. Here, the green wavelength exactly reaches polarization position S1, which is equal to a horizontally linear polarization state, while, red and blue wavelengths

become slightly elliptical polarization states due to phase dispersion. Consequently, a good dark state is obtained because final polarization states of red and blue wavelengths are a little off from position S1 which is perpendicular to the transmission axis of polarizer. However, final polarization states of the all wavelengths in oblique directions are largely deviated from position O which is opposite to position I of the input light unlike that in normal direction, as shown in Fig. 2(b). In general, when the  $N_z$  of the wideband quarter wave film is greater than 1, the film becomes a negative biaxial plate which has two optic axes existing out of plane such that the retardation that an incident light experiences becomes so high in oblique direction, resulting in strong wavelength dispersion [21]. Therefore, a strong light leakage occurred in specific viewing angle directions, as shown in Fig. 1(b).

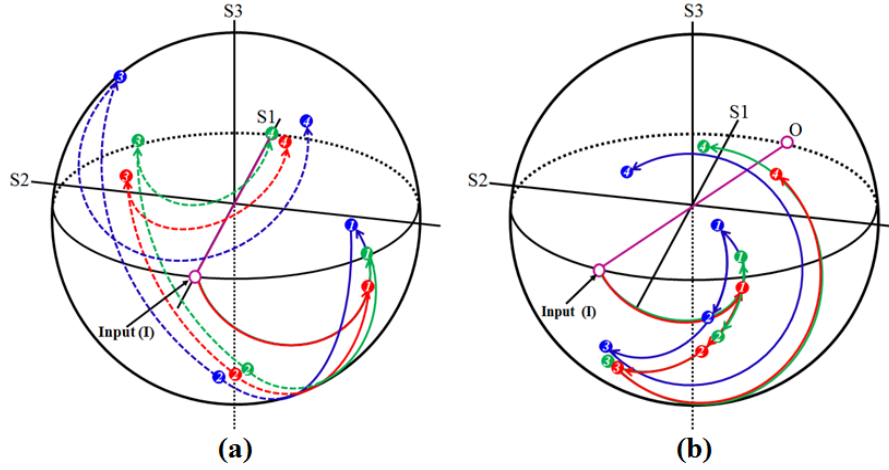


Fig. 2. States of polarization inside a wideband antireflective film with  $N_z = 1.5$  according to red, green, blue wavelengths on Poincaré sphere under (a) normal direction and (b) oblique direction (azimuthal angle =  $60^\circ$  and polar angle =  $70^\circ$ ).

### 3. Optical design of proposed wideband film and its optical characteristics

Figure 3 shows the calculated iso-luminance contour in a dark state of the OLED cell, using the wideband circular polarizer according to  $N_z$  values of the HWP and QWP films. All conditions are the same as those in Fig. 1(a). As clearly indicated in Fig. 3, when both  $N_z$  values of the HWP and QWP films are close to 0.5, the light leakage is minimal in the all viewing directions. In general, the HWP and QWP films with COP are stretched to oblique direction relative to machine direction in order to apply the roll-to-roll process, which renders them to have  $N_z$  close to 1.5. In such a fabrication process, the wave plates can be produced easily using the roll-to-roll process, but performance of antireflection is reduced as already abovementioned. To make a retardation film with  $N_z = 0.5$ , the film should be stretched to machine direction at first, and then shrunken to transverse direction. In order to shrink the film to transverse direction, a pair of films stretched to transverse direction is attached at both sides of a film stretched to the machine direction and then heats the set of the film, resulting in a shrinkage of the film to the transverse direction [21].

Figure 4(a) shows polarization states of the proposed antireflective film on the Poincaré sphere in the red, green, and blue wavelengths after the light passes through the HWP and QWP in the oblique direction. When the linearly polarized light passes through polarizer propagates through the wideband quarter wave film, metal electrode of the OLED layer, and then wideband quarter wave film again, the polarization state of the light moves along point 1 to 4 like in the normal direction. The dark state is good even in oblique directions because red, green and blue wavelengths become elliptical polarization states but their major axes are close to linear polarization states of the position O. Figure 4(b) shows light leakage along horizontal

direction of  $60^\circ$  in all wavelengths according to  $N_z$ . The calculated leakage of light in reflectivity is very low at  $N_z = 0.5$ , showing a perfect dark state even at a large polar angle. However, it increases with different  $N_z$  values and increasing a polar angle due to increase in effective retardation and deviation from optic axis of the film such that it increases to over 35% at a polar angle of  $70^\circ$  when either  $N_z = 1.5$  or  $-1.5$  in both HWP and QWP.

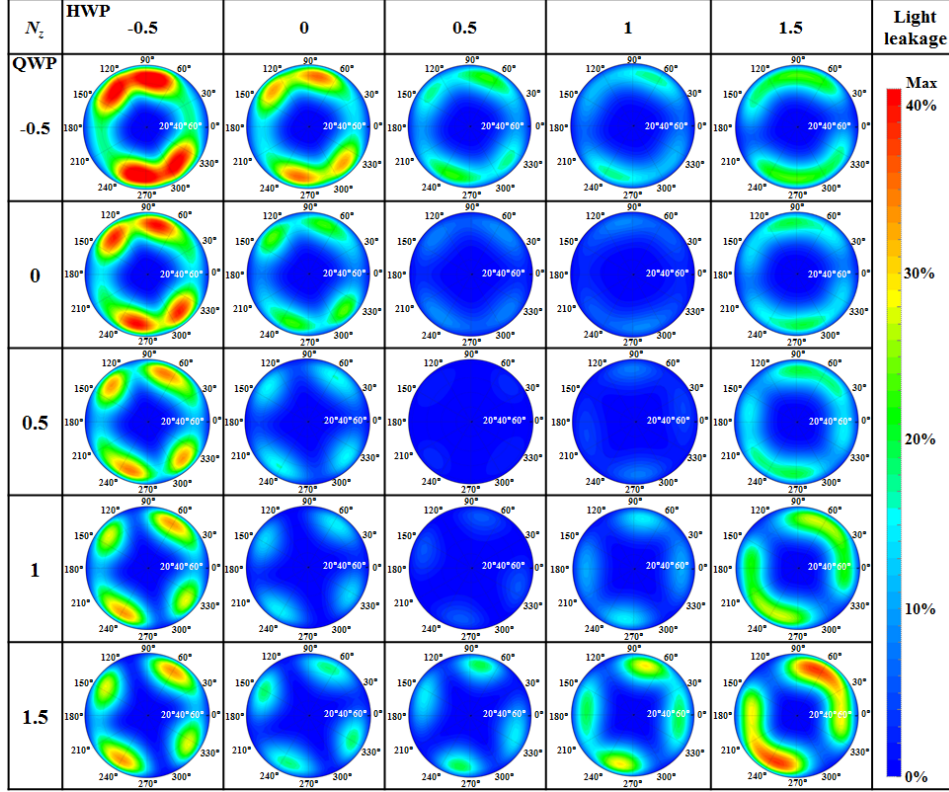


Fig. 3. Calculated iso-luminance contour in a dark state according to  $N_z$  of the wideband antireflective film.

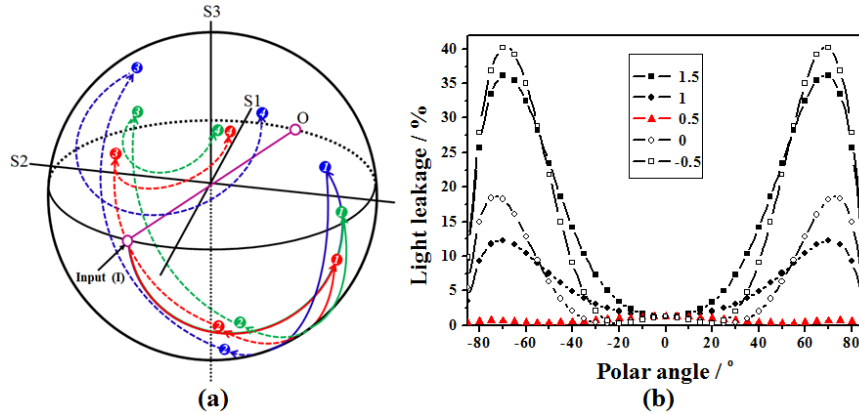


Fig. 4. (a) States of polarization inside a wideband antireflective film with  $N_z = 0.5$  according to red, green, blue wavelengths on Poincaré sphere under oblique direction (azimuthal angle =  $60^\circ$  and polar angle =  $70^\circ$ ) and (b) calculated leakage of light along horizontal direction up to  $\pm 80^\circ$  of a polar angle according to  $N_z$ .

#### **4. Summary**

We have developed a wideband antireflective circular polarizer for achieving a perfect dark state in OLEDs. The light leakage is generated at off normal axis when using the conventional wideband antireflective film with  $N_z = 1.5$  due to its optical characteristics such as increased retardation to the machine direction and the deviation of its optic axis from absorption axis of polarizer in the oblique direction. We tested the retardation of HWP and QWP films and analyzed the polarization states of the light passing through wideband antireflective film in all viewing directions. Then, we found out optimal optical parameters,  $N_z$  values of 0.5 for both HWP and QWP, that gives rise to true black state in all viewing directions, because when the film is with  $N_z = 0.5$ , the retardation in normal direction remains about the same even in off normal axis. We believe that the proposed wideband antireflective circular polarizer will greatly improve the image quality and viewing angle of OLEDs in both indoors and outdoors.

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