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Qi Hong
University of Central Florida

Thomas X. Wu
University of Central Florida

Ruibo Lu
University of Central Florida

Shin-Tson Wu
University of Central Florida

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Wide-view circular polarizer consisting of a linear polarizer and two biaxial films

Qi Hong and Thomas X. Wu
School of Electrical Engineering and Computer Science, University of Central Florida, Orlando, Florida 32816
Ruibo Lu and Shin-Tson Wu
College of Optics and Photonics, University of Central Florida, Orlando, Florida 32816
swu@mail.ucf.edu

Abstract: A simple wide-view circular polarizer comprising of a linear polarizer and two biaxial films is proposed. Over the ±85° viewing cone, the produced polarization is almost circular and the light leakage from the crossed circular polarizers is calculated to be less than 8.23×10⁻⁵, provided that the air-interface surface reflections are ignored. The design tolerance within ±5% of the optimal parameters is analyzed.

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OCIS codes: (230.3720) Liquid crystal devices; (260.5430) Polarization; (999.9999) Circular polarizer

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1. Introduction

Circular polarizer is an important component for optical communications, optical remote sensing, and liquid crystal displays (LCDs) [1-5]. Various multi-domain approaches have been proposed to widen the viewing angle and reduce the color shift of LCDs [6]. However, the LC directors twist continuously from domain to domain so that the boundary areas are formed between domains [7-11]. These boundary areas appear dark under crossed linear polarizers and the pixel’s transmittance is reduced. One way to remove the dark zones and boost light transmittance is to use a pair of crossed circular polarizers [2-5]. Nevertheless, a conventional circular polarizer consisting of a linear polarizer and a uniaxial quarter-wave plate produces circular polarization only at normal incidence [2-5]. Replacing the uniaxial quarter-wave plate with a biaxial quarter-wave plate only slightly improves the acceptance angle [2-5]. A wide-view circular polarizer using the combinations of optimally designed uniaxial A-plates and C-plates significantly widens the acceptance angle, but its device configuration is too sophisticated [5]. As a result, it is difficult to fabricate and the cost is high. There is an urgent need to develop a simple and low cost wide-view circular polarizer.

Comparing to a uniaxial retardation film, the biaxial film provides an extra degree of freedom so that the device configuration of the wide-view circular polarizer can be simplified [11]. In this paper, we propose a wide-view circular polarizer consisting of a linear polarizer and two biaxial films. The produced states of polarization are very close to the ideal circular polarization over a wide range of incident angles. Over the entire ±85º viewing cone, the light leakage of the crossed circular polarizers is less than 8.23x10^{-5}, provided that the air-interface surface reflections are ignored.

To design a wide-view circular polarizer, we represent the state of polarization with Stokes parameters ($S_1$, $S_2$, and $S_3$) and portray on Poincaré sphere after the orthogonal components of the electric field are solved using the 4-by-4 matrix method [12-14]. If the state of polarization is represented by vector $\mathbf{P} = (S_1, S_2, S_3)$, then the polarization difference between an arbitrary polarization $\mathbf{P}(X) = (S_{1,X}, S_{2,X}, S_{3,X})$ and the right-handed circular polarization $\mathbf{P}_{\text{RCP}} = (0, 0, -1)$ can be described by [5, 12-13]:

$$\Delta \mathbf{P}_{\text{X,RCP}} = \mathbf{P}(X) - \mathbf{P}_{\text{RCP}} = \sqrt{(S_{1,X} - 0)^2 + (S_{2,X} - 0)^2 + (S_{3,X} - (-1))^2}$$

$$= \sqrt{2(S_{3,X} + 1)}.$$  

As shown in Eq. (1), once $S_{3,X}$ descends to $-1$, $\Delta \mathbf{P}_{\text{X,RCP}}$ approaches zero and the polarization $\mathbf{P}(X)$ becomes the right-handed circular polarization $\mathbf{P}_{\text{RCP}}$.

In this paper, the absorptive linear polarizer is modeled as a lossy uniaxial material. We assume the refractive indices of the linear polarizer and the biaxial retardation films are as follows: $n_{z,\text{pol}} = 1.5 + i\times3.251\times10^{-3}$, $n_{y,\text{pol}} = 1.5 + i\times2.86\times10^{-5}$, $n_{x,\text{pol}} = 1.5 + i\times2.86\times10^{-5}$, $n_{z,\text{film}} = 1.5124$, $n_{x,\text{film}} = 1.5089$. The refractive index $n_{z,\text{film}}$ of each biaxial film is determined by its NZ factor, where $NZ = (n_z - n_y)/(n_x - n_y)$ [15]. The linear polarizer has a thickness of 210 µm and its absorption axis is oriented along 0º. The design wavelength is $\lambda=550$ nm.

On both sides of the absorptive polarizer, the protective Tri-Acetyl-Cellulose (TAC) films exhibit a small birefringence and act as negative birefringence C-plates. The phase change due to the TAC film can be minimized if we laminate a positive birefringence C-plate to the exit protective film. The phase retardation of this C-plate compensates for the adjacent protective film so that the C-plate effect of the linear polarizer is negligible.

2. Design of wide-view circular polarizer

A circular state of polarization is achieved when a quarter-wave plate is illuminated by a linearly polarized light vibrating at 45º with respect to its slow axis [12-13]. If this light is
produced by a linear polarizer, the quarter-wave plate together with the linear polarizer forms a conventional circular polarizer. At normal incidence, when the linearly polarized light passes through the quarter-wave plate, the light sustains \(\pi/2\) phase change while the magnitudes of its orthogonal components remain equal so that the light becomes circularly polarized. However, at oblique angles the quarter-wave plate contributes other than \(\pi/2\) phase change [2-5] and the slow axis is not at 45° with respect to the incoming linear polarization. As a result, the produced polarization state becomes elliptical and a relatively large amount of light leaks through the crossed circular polarizers. Replacing the uniaxial quarter-wave plate with a biaxial quarter-wave plate reduces the variation in the \(\pi/2\) phase change at oblique incident angles. However, the 45° angle between the light’s vibration direction and the biaxial film’s slow axis is not maintained at oblique incidence [5, 11]. Therefore, although the produced polarization is relatively close to the circular polarization, the light leakage of the crossed circular polarizers is still large at wide viewing angles [2-4].

To preserve circular polarization over a wide range of incident angle, we laminate two biaxial retardation films to the linear polarizer as shown in Fig. 1. Since all of the three Stokes parameters are modified inside a biaxial film, the azimuthal angles and the \(d(n_x - n_y)\) as well as the NZ factors of both biaxial films are the key design parameters. Here the azimuthal angle of biaxial film is the angle between the \(n_x\) axis of the biaxial film and the absorption direction of the polarizer as Fig. 2 shows.

We use genetic algorithm [5, 16] to optimize the polarizer design. For a given combination of the above parameters, we first solve the orthogonal components of the electric field using the 4-by-4 matrix method. Then we find the produced polarization and apply it into the following cost function

\[
\cos t = \max \left\{ \frac{1}{2} \left| S_{3,1}(2B) + 1 \right| \left( \theta_{in} = 0° \sim 85°, \phi_{in} = 0° \sim 360° \right) \right\},
\]

where \(S_{3,1}(2B)\) is the \(S_3\) of the produced state of polarization \(P_{2B}\). By minimizing the cost function shown in Eq. (2), we could obtain the optimal design parameters for the biaxial films.

For the two biaxial films, their azimuthal angles are: \(\phi_1 = 0.68°\) and \(\phi_2 = 46.37°\); the \(d(n_x - n_y)\) values are: \(d(n_x - n_y)_1 = 264.08\) nm and \(d(n_x - n_y)_2 = 134.13\) nm; and the NZ factors are: \(NZ_1 = 0.75\) and \(NZ_2 = 0.53\).

Figure 2 illustrates the polarization states inside this circular polarizer using Poincaré sphere representation. As Fig. 2 depicts, the first biaxial film serves as a wide-view half-wave plate so that the light entering the second biaxial film is almost linearly polarized and vibrating at ~45° with respect to the \(n_x\) axis of the second biaxial film. Meanwhile, the second biaxial film performs as a wide-view quarter-wave plate. Therefore, although the polarizations across each biaxial film vary with the incident angle, they compensate each other so that the final polarization remains circular over a wide viewing cone.
As demonstrated in Fig. 3, for the proposed right-handed circular polarizer \( S_3 \) only increases to \(-0.997\) when the viewing angle increases to \(85^\circ\). This is equivalent to having the polarization difference \( \Delta P(\text{OB})-(\text{RC}) \) less than 0.078 over the \(\pm85^\circ\) viewing cone. The produced \( S_3 \) remains at \(-1\) at normal angle as in the conventional right-handed circular polarizer. For a left-handed circular polarizer using above configuration, the NZ factors and \( d(n_x - n_y) \) of both biaxial films are not changed but the azimuthal angles of the biaxial films are the negative of their counterparts in the right-handed circular polarizer.

Since the produced polarization approaches ideal circular polarization, the light leakage from crossed circular polarizers can be significantly reduced. Figure 4 sketches the configuration of the crossed circular polarizers. The top linear polarizer and the first two biaxial films compose a wide-view right-handed circular polarizer. The bottom analyzer and the last two biaxial films form a second circular polarizer crossed to the first one. The absorption axis of the analyzer and the azimuthal angles of the last two biaxial films are perpendicular to their counterparts in the first circular polarizer.
The circular polarization emerging from the first circular polarizer is converted into linear polarization after it passes through the two biaxial films attached to the analyzer. Due to the symmetric configuration of the crossed circular polarizers, this linearly polarized light vibrates along the analyzer's absorption direction. Therefore, the light leakage of the crossed circular polarizers is less than $8.23 \times 10^{-5}$ over the ±85° viewing cone as Fig. 5(a) demonstrates.

Besides the light leakage of crossed polarizers, for wide-view LCD applications we also need to know the angular-dependent transmittance when the polarizers are open. Results are plotted in Fig. 5(b). The maximum transmittance which occurs at normal incidence is 37.8%. The major optical loss is from the absorption of the dichroic linear polarizers. The iso-transmittance contour shown in Fig. 5(b) is relatively symmetric. At ±85° viewing cone, the transmittance remains greater than 31.1%. Thus, from Figs. 5(a) and 5(b), the calculated extinction ratio (at $\lambda = 550$ nm) of the circular polarizer remains ~4000:1 at the ±85° viewing cone.

In order to reduce the interference of the air-polarizer surface reflection, an ideal anti-reflection (AR) film is assumed during simulations. The ten-layer anti-reflection film is coated on the air interface of both polarizers. This AR film is designed using genetic algorithm and the gradient refractive indices profile is illustrated in Fig. 6(a) [5, 16]. The origin represents...
the air-AR interface. The transmittance of this ten-layer AR film is greater than 0.99 over the 
±85° incident cone within the 450 nm ~ 650 nm spectrum as Fig. 6(b) depicts.

3. Spectral bandwidth

For some applications such as direct-view LCDs, broad bandwidth is as important as wide 
viewing angle [1-11]. Although the proposed wide-view circular polarizer is designed at a 
single wavelength $\lambda = 550$ nm, however, at normal incidence the retardation of the first biaxial 
film is almost equal to one half of the designed wavelength, i.e., $d(n_x - n_y) = 264.08$ nm ≈ 
550 nm/2 = $\lambda/2$, and the retardation of the second biaxial film is close to a quarter of the 
designed wavelength, $d(n_x - n_y) = 134.13$ nm ≈ 550 nm/4 = $\lambda/4$. At the same time, the 
azimuthal angles of the two biaxial films satisfy the following relationship:

$$2\phi_1 - 4\phi_2 = 2 \times (360 + 46.37) - 4 \times (180 + 0.68)$$

$$= 90.02°$$

which describes the relationship between the azimuthal angles of the half-wave plate and the 
quarter-wave plate inside a broadband circular polarizer [17]. Therefore, at normal incidence 
the proposed circular polarizer performs as a broadband circular polarizer so that the light 
leakage of the crossed circular polarizers is less than $1.64 \times 10^{-6}$ over the 450–650 nm spectral 
range, as shown in Fig. 7. Within the ±60° viewing cone, the light leakage is maintained less 
than $1.90 \times 10^{-3}$ over the specified visible spectral range. At ±85° viewing cone, the maximum 
light leakage reaches 3.92 $\times 10^{-3}$ at $\lambda = 450$ nm and 1.39 $\times 10^{-3}$ at $\lambda = 650$ nm. For display 
an applications, the light leakage at blue is more forgiven than green and red because human 
visual system is less sensitive to blue. Moreover, the blue spectral content is the weakest 
among the three primary colors.

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4. Discussion

Design tolerance is an important concern from manufacturing viewpoint. For the proposed design of a wide-view circular polarizer, we calculate the maximum light leakage of the crossed circular polarizers over the ±85° viewing cone if the film parameters of the biaxial films deviate from the optimal values by ±5%. The simulation results are plotted in Fig. 8. First we evaluate the influence of film thickness. The blue line in Fig. 8 indicates that a ±5% deviation in the first biaxial film thickness boosts the light leakage to 4.1×10^{-4}. By contrast, the light leakage is quite inert to the errors of the second biaxial film thickness (dashed blue lines). Next, we study how the NZ factor affects the light leakage. As shown by the black solid line in Fig. 8, the NZ factor of the first biaxial film plays a significant role. A ±5% deviation causes ~7.0×10^{-4} light leakage. On the other hand, a +5% error in the NZ factor of the second biaxial film boosts the light leakage to 4.5×10^{-4} (black dashed line). The solid and dashed red lines in Fig. 8 almost overlap with the blue dashed lines implying the light leakage is almost invariant when the orientations of both biaxial films vary by ±5%. Thus, from this tolerance analysis we find that the accuracy of the first biaxial film parameters is more critical than that of the second biaxial film and the NZ factors of both biaxial films require a higher accuracy.

5. Conclusion

We propose a new wide-view circular polarizer consisting of a linear polarizer and two biaxial films. We use phase compensation techniques to constrain the resultant polarization state to the desired circular polarization over a wide range of viewing angle. The phase retardation film parameters are designed using genetic algorithm. The light leakage from the crossed circular polarizers using the proposed circular polarizer is less than 8.23×10^{-5} over the ±85° viewing cone at the designed wavelength λ = 550 nm. Within the 450~650 nm spectral range, the light leakage of the crossed circular polarizers is kept below 3.92 ×10^{-3} over the entire ±85° viewing cone. This simple circular polarizer will find useful application for enhancing the transmittance of the multi-domain vertically-aligned liquid crystal displays.

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