Wide-Acceptance-Angle Circular Polarizers (DIV)

12-11-2012

Shin-Tson Wu
University of Central Florida

Qi Hong
University of Central Florida

Ruibo Lu
University of Central Florida

Xinzhang Wu
University of Central Florida

Xinyu Zhu
University of Central Florida

Find similar works at: https://stars.library.ucf.edu/patents

University of Central Florida Libraries http://library.ucf.edu

Recommended Citation

Wu, Shin-Tson; Hong, Qi; Lu, Ruibo; Wu, Xinzhang; and Zhu, Xinyu, "Wide-Acceptance-Angle Circular Polarizers (DIV)" (2012). UCF Patents. 656.
https://stars.library.ucf.edu/patents/656

This Patent is brought to you for free and open access by the Technology Transfer at STARS. It has been accepted for inclusion in UCF Patents by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
A circular polarizer comprising a single linear polarizer producing a linear state of polarization and at least one phase retardation film layered with the single linear polarizer. In a first embodiment, the at least one phase retardation film includes at least one uniaxial A-plate phase retardation film and at least one uniaxial C-plate phase retardation film. In a second embodiment of the invention, the circular polarizer includes a linear polarizer and at least one biaxial phase retardation film layered with the linear polarizer. In another example of the circular polarizer of the second embodiment, at least one uniaxial A-plate phase retardation film and/or at least one uniaxial C-plate phase retardation film is also layered with the linear polarizer and the biaxial phase retardation film.

2 Claims, 11 Drawing Sheets
FIG. 1 PRIOR ART

$S_3 = -0.829$

FIG. 2
FIG. 3

$S_3 \leq -0.952$

FIG. 4(a)
FIG. 4(b)

FIG. 5
$S_3 \leq -0.991$

FIG. 6(a)

$S_3 \geq 0.991$

FIG. 6(b)
FIG. 7

FIG. 8(a)
FIG. 8(b)
FIG. 10(a)

FIG. 10(b)
BACKGROUND AND PRIOR ART

Circular polarizers are an important optical component in many applications, such as fiber optics, imaging lenses, and liquid crystal displays, especially in the applications when the state of polarization is desired to be independent of the azimuthal angle of the incident light, or to be independent of the azimuthal angle of the slow axis of anisotropic media. Circular polarizer can be used in the studies of the properties of thin films, as described in U.S. Pat. No. 6,219,130 issued to Lesnai on Apr. 17, 2001. Circular polarizers are also used in Liquid crystal displays (LCDs), as described in U.S. Pat. No. 6,549,335 B1 issued to Trapani et al. on Apr. 15, 2003, U.S. Pat. No. 6,583,833 B1 issued to Kashima on Jun. 24, 2003, U.S. Pat. No. 5,796,454 issued to Ma on Aug. 18, 1998, and U.S. Pat. No. 6,628,369 B2 issued to Kamagai on September, 2003.

Circularly polarized light is a polarized plane light with equal magnitude in its orthogonal components and the phase difference between the orthogonal components is \( \pi / 2 \). Circularly polarized light can be generated by cholesteric liquid crystal, according to U.S. Pat. No. 5,796,454, or can be converted from linearly polarized light with a linear polarizer and a quarter-wave plate, of which the principal optical axes is 45 degrees with respect to the transmission axis of the linear polarizer, according to U.S. Pat. No. 6,788,462 B2 issued to Lesnai on Sep. 7, 2004. According to U.S. Pat. No. 2004/0109114 A1 issued on Jun. 10, 2004, a circularly polarized light can also be converted from a linearly polarized light with a substrate having a longitudinal direction and the combination of a half-wave plate and a quarter-wave plate, where the principal optical axes of the half-wave plate and the quarter-wave plate are +30 and -30 degrees with respect to the longitudinal direction of the substrate, respectively. A quarter-wave plate is an optical anisotropic element which induces \( \pi / 2 \) phase difference between the orthogonal components of the light passing through. A half-wave plate is an optical anisotropic element which induces \( \pi \) phase difference between the orthogonal components of the light passing through.

However, when cholesteric liquid crystal is used, the induced circularly polarized light sustains blue shift at oblique incident angle. Furthermore, the fabrication of cholesteric liquid crystal cell is difficult. When the combination of a linear polarizer and a quarter-wave plate or using the combination of special substrates having a longitudinal direction and a half-wave plate together with a quarter-wave plate, the quarter-wave plate or half-wave plate only induces \( \pi / 2 \) or \( \pi \) phase change at normal incident angle. At oblique incident angles, the phase change is varied with both incident angle and the azimuth of incident plane, which results in elliptically polarized light instead of the desired circularly polarized light.

SUMMARY OF THE INVENTION

A primary objective of this invention is to provide a new method, system, apparatus and device for a circular polarizer capable of inducing left-hand or right-hand circularly polarized light over wide ranges of incident angle and over all azimuths of incident plane.

A secondary objective of this invention is to provide a new method, system, apparatus and device for a wide-acceptance-angle circular polarizer that inducing left-hand or right-hand circularly polarized light either on the output surface of the circular polarizer or inside arbitrary media including air.

A third objective of this invention is to provide a new method, system, apparatus and device for a wide-acceptance-angle circular polarizer with achromatic behavior.

A fourth objective of this invention is to provide a new method, system, apparatus and device for a wide-acceptance-angle circular polarizer with a large error tolerance in the phase retardation of the phase retardation films.

A fifth objective of this invention is to provide a new method, system, apparatus and device for a wide-acceptance-angle circular polarizer with a large error tolerance in the angles between the absorption axis of the linear polarizer and the slow axes of the phase retardation films.

A sixth objective of this invention is to provide a wide-acceptance-angle circular polarizer at a low cost.

A first preferred embodiment of the invention is to provide a structure of a wide-acceptance angle left-hand or right-hand circular polarizer comprising a single linear polarizer producing a linear state of polarization and at least one phase retardation film layered with the single linear polarizer. In a first embodiment, the at least one phase retardation film includes at least one uniaxial A-plate phase retardation film and at least one uniaxial C-plate phase retardation film.

In a second embodiment of the invention, the left-hand or right-hand circular polarizer includes a linear polarizer and at least one biaxial phase retardation film layer with the linear polarizer. In another example of the circular polarize of the second embodiment, at least one phase retardation is layer with the linear polarizer and the biaxial phase retardation film.
Further objectives, features, and advantages of this invention will be apparent from the following detailed descriptions of the presently preferred embodiments that are illustrated schematically in the accompanying drawings.

**BRIEF DESCRIPTION OF THE FIGURES**

**FIG. 1** is a schematic diagram showing an example of conventional prior art circular polarizer.

**FIG. 2** is a schematic diagram showing the state of polarization emerging from the circular polarizer illustrated in **FIG. 1**.

**FIG. 3** shows an example of the circular polarizer structure according to a first embodiment of the present invention.

**FIG. 4a** shows the state of polarization emerging from the right-handed circular polarizer illustrated in **FIG. 3**.

**FIG. 4b** shows the state of polarization emerging from the left-handed circular polarizer illustrated in **FIG. 3**.

**FIG. 5** shows another example of the circular polarizer structure according to the first embodiment of the present invention.

**FIG. 6a** shows the state of polarization emerging from the right-handed circular polarizer illustrated in **FIG. 5**.

**FIG. 6b** shows the state of polarization emerging from the left-handed circular polarizer illustrated in **FIG. 5**.

**FIG. 7** shows another example of the circular polarizer structure according to the first embodiment of the present invention.

**FIG. 8a** shows the state of polarization emerging from the right-handed circular polarizer illustrated in **FIG. 7**.

**FIG. 8b** shows the state of polarization emerging from the left-handed circular polarizer illustrated in **FIG. 7**.

**FIG. 9** shows another example of the circular polarizer structure according to the first embodiment of the present invention.

**FIG. 10a** shows the state of polarization emerging from the right-handed circular polarizer illustrated in **FIG. 9**.

**FIG. 10b** shows the state of polarization emerging from the left-handed circular polarizer illustrated in **FIG. 9**.

**FIG. 11** shows an example of the circular polarizer structure according to a second embodiment of the present invention.

**FIG. 12** shows another example of the circular polarizer structure of the second embodiment of the present invention.

**FIG. 13** shows another example of the circular polarizer structure of the second embodiment of the present invention.

**FIG. 14** shows another example of the circular polarizer structure of the second embodiment of the present invention.

**FIG. 15** shows another example of the circular polarizer structure of the second embodiment of the present invention.

**FIG. 16** shows yet another example of the circular polarizer structure of the second embodiment of the present invention.

**DESCRIPTION OF THE PREFERRED EMBODIMENTS**

Before explaining the disclosed embodiments of the present invention in detail it is to be understood that the invention is not limited in its application to the details of the particular arrangements shown since the invention is capable of other arrangements. Also, the terminology used herein is for the purpose of description and not of limitation.

The method, system apparatus and device of the present invention provides a new device structure for producing left-hand or right-hand circular state of polarization over wide-range of incident angle and azimuth of incident plane using the combinations of linear polarizer and multi-layer phase retardation films.

The state of polarization can be represented by Stokes parameters and plotted on Poincare sphere. FIG. 2 is a plot showing the state of polarization emerging from the circular polarizer illustrated in FIG. 1. The incident angle is 0°–85° and the azimuth of incident plane is 0°–360° with respect to the transmission axis of polarizer. Stokes parameters S1, S2, S3 are defined as:

\[ S_1 = (E_p^2 - E_s^2) / (E_p^2 + E_s^2), \]
\[ S_2 = (2E_pE_s^2 + E_p^2) / (E_p^2 + E_s^2), \]
\[ S_3 = (2E_pE_s^2 - E_s^2) / (E_p^2 + E_s^2), \]

where \( E_p \) and \( E_s \) are the parallel and perpendicular components of the incident electrical field, respectively. \( \phi \) is given by: \( \phi = \angle E_p - \angle E_s \), where \( \angle E_p \) and \( \angle E_s \) are the phases of the parallel and perpendicular components of the incident electrical field, respectively.

The circular polarizer of the present invention includes a linear polarizer and at least one phase retardation film layer with the linear polarizer for achieving a state of polarization.
that is closer to a left-hand ($S_1$, approximately equal to 1) or right-hand circular state of polarization ($S_2$, approximately equal to $-1$) than that of a convention prior art circular polarizer.

First Embodiment

FIG. 3 shows the structure of wide-acceptance-angle circular polarizer consisting of one uniaxial A-plate phase retardation film and one uniaxial C-plate phase retardation film according to the first preferred embodiment. A uniaxial A-plate phase retardation film is an optical component that is made of uniaxial anisotropic media with its optical axis parallel to the polarizer-retarder surface and a uniaxial C-plate phase retardation film is an optical component that is made of uniaxial anisotropic media with its optical axis perpendicular to the polarizer-retarder surface.

In an example of the first embodiment shown in FIG. 3, the structure comprises optical components along the propagation direction of the incident light, beginning with a polarizing film $301$ producing linear state of polarization, followed by the combination of one uniaxial A-plate phase retardation film $302$ and one uniaxial C-plate phase retardation film $303$.

The displacements of the uniaxial A-plate phase retardation film $301$ and the uniaxial C-plate phase retardation film $302$ can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation film $302$, the slow axis is approximately $\pm (30°-60°)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n = \pm (0.2\lambda-3.5\lambda)$, where $\lambda$ is the incident light wavelength. For the uniaxial C-plate phase retardation film $303$, the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda-3.5\lambda)$. In the normal incident case, the phase retardation of the uniaxial C-plate phase retardation film is zero.

The emerging state of polarization depends on the phase retardation of the uniaxial A-plate phase retardation film and the angle between the slow axis of the uniaxial A-plate phase retardation film and the transmission axis of polarizer. In the oblique incident case, the phase retardation of the uniaxial C-plate phase retardation film is nonzero, which reduces the difference between the expected circular state of polarization and the state of polarization emerging from the uniaxial A-plate phase retardation film.

When the structure in FIG. 3 induces right-handed circular state of polarization, the state of polarization emerging from the structure is shown in FIG. 4a using Poincaré sphere when the linear polarizer is modeled as uniaxial absorptive material, of which the refractive indices $n_r = 1.5+ix3.251\times10^{-3}$ and $n_i = 1.5+ix2.86\times10^{-3}$. The structure in FIG. 3 may also be used to induce a left-handed state of polarization as shown in FIG. 4b. For the left-handed circular polarizer, the slow axis of the uniaxial A-plate films is negative of that of the A-plate films in the right-handed circular polarizer shown in FIG. 3. The incident angle is between $0°-85°$ and the azimuth of incident plane is between approximately $0°$ and approximately $360°$ with respect to the transmission axis of the polarizer. The difference between the $S_3$ of the expected circular state of polarization and the $S_4$ of the state of polarization emerging from the structure is less than $0.008$ over $0°-85°$ incident angle and $0°-360°$ azimuth of incident plane. Compared with the state of polarization emerging from conventional circular polarizer as shown in FIG. 2, the difference between the expected circular state of polarization and the produced state of polarization emerging from the structure shown in FIG. 3 is greatly reduced. Furthermore, the structure has the advantages of simple structure, easy fabrication and low cost.

FIG. 5 shows another example of the structure of the wide-acceptance-angle circular polarizer in which a second uniaxial A-plate retardation is included. In this example, the wide-acceptance-angle circular polarizer includes optical components along the propagation direction of the incident light, beginning with a polarizing film producing linear state of polarization $501$, followed by two uniaxial A-plate phase retardation films $502a$ and $502b$, and one uniaxial C-plate phase retardation film $503$.

The displacements of the uniaxial A-plate phase retardation films and the uniaxial C-plate phase retardation film can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation film $502a$, the slow axis is $\pm (5°-45°)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda-3.5\lambda)$. For the uniaxial C-plate phase retardation film $503$, the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda-3.5\lambda)$. In the normal incident case, the phase retardation of the uniaxial C-plate phase retardation film is zero.

The emerging state of polarization depends on the phase retardations of the uniaxial A-plate phase retardation films and the angles between the slow axes of the uniaxial A-plate phase retardation films and the transmission axis of polarizer. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial C-plate phase retardation film and the two uniaxial A-plate phase retardation films.

The structure in FIG. 5 can induce right-handed circular state of polarization. FIG. 6a shows the state of polarization emerging from the structure using Poincaré sphere when the linear polarizer is modeled as uniaxial absorptive material, of which the refractive indices $n_r = 1.5+ix3.251\times10^{-3}$ and $n_i = 1.5+ix2.86\times10^{-3}$. The structure in FIG. 5 is applicable to left-hand circular polarizer as FIG. 6b shows. For the left-handed circular polarizer, the slow axis of the uniaxial A-plate films is negative of that of the A-plate films in the right-handed circular polarizer in FIG. 5. The incident angle is between approximately $0°$ and approximately $85°$ and the azimuth of incident plane is approximately $0°$ and approximately $360°$ with respect to the transmission axis of polarizer. The difference between the $S_3$ of the expected circular state of polarization and the $S_4$ of the state of polarization emerging from the structure is less than $0.008$ over $0°$ to approximately $85°$ incident angle and $0°$ to approximately $360°$ azimuth of incident plane. Comparing with the proposed wide-incident-angle circular polarizer shown in FIG. 3, the difference between the expected circular state of polarization and the produced state of polarization emerging from the structure shown in FIG. 5 is further reduced.

In another example of the first embodiment shown in FIG. 7, the structure of the wide-acceptance-angle circular polarizer includes a third uniaxial A-plate phase retardation films, and a second uniaxial C-plate phase retardation films. The structure comprises optical components along the propagation direction of the incident light, beginning with a polarizing film $701$ producing linear state of polarization, followed by three uniaxial A-plate phase retardation films $702a$, $702b$ and $702c$, and two uniaxial C-plate phase retardation films $703a$ and $703b$.

The displacements of the uniaxial A-plate phase retardation films and the uniaxial C-plate phase retardation films can be in any order along the propagation direction of the incident
For the uniaxial A-plate phase retardation film 702a, the slow axis is approximately $\pm(0^\circ-85^\circ)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. For the uniaxial C-plate phase retardation film 703a, the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. For the uniaxial A-plate phase retardation film 702b, the slow axis is approximately $\pm(15^\circ-90^\circ)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$.

The emerging state of polarization depends on the phase retardations of the uniaxial A-plate phase retardation films and the angles between the slow axes of the uniaxial A-plate phase retardation films and the transmission axis of the polarizer. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial A-plate phase retardation films.

For the uniaxial C-plate phase retardation film 703b, the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. For the uniaxial A-plate phase retardation film 702c, the slow axis is approximately $\pm(5^\circ-85^\circ)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. For the uniaxial A-plate phase retardation film 702d, the slow axis is approximately $\pm(15^\circ-90^\circ)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$.

If the structure in FIG. 7 induces right-hand circular state of polarization, FIG. 8a shows the state of polarization emerging from the structure using Poincaré sphere when the linear polarizer is modeled as uniaxial absorptive material, of which the refractive indices $n_1=1.5+i\times3.25\times10^{-3}$ and $n_2=1.5+i\times2.86\times10^{-3}$. The structure in FIG. 7 is also applicable to left-hand circular polarizer as shown in FIG. 8b. The incident angle is between approximately $0^\circ$ and $85^\circ$ and the azimuth of incident plane is between approximately $0^\circ$ and approximately $85^\circ$.

In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardation parallel to the polarizer-retarder surface. The structure comprises optical components along the propagation direction of light, beginning with a polarizing film 901 producing linear state of polarization, followed by five uniaxial A-plate phase retardation films 902a, 902b, 902c, 902d and 902e, and three uniaxial C-plate phase retardation films 903a, 903b and 903c.

In another example, the first embodiment shown in FIG. 9, the structure of the wide-acceptance-angle circular polarizer includes five uniaxial A-plate phase retardation films and three uniaxial C-plate phase retardation films. The structure comprises optical components along the propagation direction of the incident light, beginning with a polarizing film 901 producing linear state of polarization, followed by five uniaxial A-plate phase retardation films 902a, 902b, 902c, 902d and 902e, and three uniaxial C-plate phase retardation films 903a, 903b and 903c.

The displacement of the uniaxial A-plate phase retardation films and the uniaxial C-plate phase retardation films can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation films 902a, 902b, 902c, 902d and 902e, the slow axis is $\pm(0^\circ-85^\circ)$ with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. For the uniaxial C-plate phase retardation films 903a, 903b and 903c, the phase retardation satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. In the normal incident case, the phase retardations of the uniaxial C-plate phase retardation films are zero.

The emerging state of polarization depends on the phase retardations of the uniaxial A-plate phase retardation films and the angles between the slow axes of the uniaxial A-plate phase retardation films and the transmission axis of the polarizer. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial C-plate phase retardation film and those two uniaxial A-plate phase retardation films.

The structure of the wide-acceptance-angle circular polarizer of the second embodiment is shown in FIG. 11 with one biaxial phase retardation film. Biaxial phase retardation film is an optical component that is made of biaxial anisotropic media with its optical axis either parallel to or perpendicular to the polarizer-retarder surface. The structure comprises optical components along the propagation direction of light, beginning with a polarizing film 1101 producing linear state of polarization, followed by one biaxial phase retardation film 1102, of which the slow axis on the plane parallel to the polarizer-retarder surface is $\pm(30^\circ-60^\circ)$ with respect to the transmission direction of the linear polarizer. For the biaxial phase retardation film, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$, and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition $d\Delta n=\pm(0.05\Delta-3.5\Delta)$. In the normal incident case, for the biaxial phase retardation film, the phase retardation perpendicular to the polarizer-retarder surface is zero.

In this example, the emerging state of polarization depends on the phase retardation parallel to the polarizer-retarder surface and the angle between the slow axis of the biaxial phase retardation film and the transmission axis of the polarizer. In this example, the emerging state of polarization is almost circular. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardation of the biaxial phase retardation film.

Therefore, over wide-acceptance angles, the difference between the $S_1$ of the expected circular state of polarization and the $S_0$ of the state of polarization emerging from the structure is much smaller than that of a conventional circular
polarizer. At the same time, the structure shown in FIG. 11 has the advantages of simple structure, easy fabrication and low cost.

FIG. 12 shows another example of the second embodiment, wherein the structure of the wide-acceptance-angle circular polarizer includes more than one biaxial phase retardation film. As shown, the structure includes optical components along the propagation direction of light, beginning with a polarizing film 1201 producing linear state of polarization, followed by two biaxial phase retardation films 1202a and 1202b.

For the biaxial phase retardation film 1202a, the slow axis on the plane parallel to the polarizer-retarder surface is approximately ±(5°−75°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ), and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ). For the biaxial phase retardation film 1202b, the slow axis on the plane parallel to the polarizer-retarder surface is approximately ±(25°−85°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ), and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ). In the normal incident case, for the biaxial phase retardation films, the phase retardations perpendicular to the polarizer-retarder surface are zero.

The emerging state of polarization depends on the phase retardations parallel to the polarizer-retarder surface and the angles between the slow axes of the biaxial phase retardation films and the transmission axis of polarizer. In this example, the emerging state of polarization is almost circular. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the biaxial phase retardation films. Therefore, over wide-incident angles, the difference between the S0 of the expected circular state of polarization and the S0 of the state of polarization emerging from the structure is much smaller than that of a conventional circular polarizer.

FIG. 13 shows another example of the wide-acceptance-angle circular polarizer according to the second embodiment. In this example, the structures of the wide-acceptance-angle circular polarizer consisting of one biaxial phase retardation film and one uniaxial A-plate phase retardation film. The structure shown in FIG. 13 comprises optical components along the propagation direction of light, beginning with a polarizing film 1301 producing linear state of polarization, followed by one uniaxial A-plate phase retardation film 1302 and one biaxial phase retardation film 1303.

The displacements of the uniaxial A-plate phase retardation film and the biaxial phase retardation film can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation film 1302, the slow axis is approximately ±(5°−85°) with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition d·Δn=±(0.05λ−3.5λ). For the biaxial phase retardation film 1303, the slow axis on the plane parallel to the polarizer-retarder surface is approximately ±(5°−85°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ), and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ). In the normal incident case, for the biaxial phase retardation film, the phase retardation perpendicular to the polarizer-retarder surface is zero.

The emerging state of polarization is almost circular. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial A-plate phase retardation film and the biaxial phase retardation film. Therefore, over wide-acceptance angles, the difference between the S0 of the expected circular state of polarization and the S0 of the state of polarization emerging from the structure is much smaller than that of a conventional circular polarizer.

FIG. 14 shows another example of the structures of the wide-acceptance-angle circular polarizer consisting of one biaxial phase retardation film and one uniaxial C-plate phase retardation film. The structure shown in FIG. 14 comprises optical components along the propagation direction of light, beginning with a polarizing film 1401 producing linear state of polarization, followed by one uniaxial C-plate phase retardation film 1402 and one biaxial phase retardation film 1403.

The displacements of the uniaxial C-plate phase retardation film and the biaxial phase retardation film can be in any order along the propagation direction of the incident light. For the uniaxial C-plate phase retardation film 1402, the phase retardation satisfies condition d·Δn=±(0.05λ−3.5λ). For the biaxial phase retardation film 1403, the slow axis on the plane parallel to the polarizer-retarder surface is approximately ±(5°−85°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ), and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition d·Δn=±(0.05λ−3.5λ). In the normal incident case, for the biaxial phase retardation film and the uniaxial C-plate phase retardation film, the phase retardations perpendicular to the polarizer-retarder surface are zero.

The emerging state of polarization in this example is almost circular. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial C-plate phase retardation film and the biaxial phase retardation film. Therefore, over wide-acceptance angles, the difference between the S0 of the expected circular state of polarization and the S0 of the state of polarization emerging from the structure is much smaller than that of a conventional circular polarizer.

FIG. 15 shows the structures of the proposed wide-acceptance-angle circular polarizer includes one biaxial phase retardation film, one uniaxial A-plate phase retardation film and one uniaxial C-plate phase retardation film. The structures shown in FIG. 15 consist of optical components along the propagation direction of light, beginning with a polarizing film 1501 producing linear state of polarization, followed by one uniaxial A-plate phase retardation film 1502, one uniaxial C-plate phase retardation film 1503, and one biaxial phase retardation film 1504.

The displacements of the uniaxial A-plate phase retardation film, the uniaxial C-plate phase retardation film, and the biaxial phase retardation film can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation film 1502, the slow axis is approximately ±(5°−75°) with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition d·Δn=±(0.05λ−3.5λ). For the uniaxial C-plate phase retardation film 1503, the phase retardation satisfies condition d·Δn=±(0.05λ−3.5λ). For the biaxial phase retardation film 1504, the slow axis on the plane parallel to the polarizer-
retarder surface is approximately ±(25°–85°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$, and the phase retardation perpendicular to the polarizer-retarder surface satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$. In the normal incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial A-plate phase retardation films, the uniaxial C-plate phase retardation films, and the biaxial phase retardation films. Therefore, over wide-acceptance angles, the difference between the $S_3$ of the expected circular state of polarization and the $S_3$ of the state of polarization emerging from the structure is much smaller than that of a conventional circular polarizer.

FIG. 16 shows the structure yet another example of the wide-acceptance-angle circular polarizer according to the second embodiment. In this example, wide-acceptance-angle circular polarizer includes a combination of more than one biaxial phase retardation films, more than one uniaxial A-plate phase retardation films and more than one uniaxial C-plate phase retardation films. The structure shown in FIG. 16 consists of optical components along the propagation direction of light, beginning with a polarizing film 1601 producing linear state of polarization, followed by two uniaxial A-plate phase retardation films 1602a and 1602b, two uniaxial C-plate phase retardation films 1603a and 1603b, and two biaxial phase retardation films 1604a and 1604b.

The displacements of the uniaxial A-plate phase retardation films, the uniaxial C-plate phase retardation films, and the biaxial phase retardation films can be in any order along the propagation direction of the incident light. For the uniaxial A-plate phase retardation film 1602a, the slow axis is ±(0.1°–89.9°) with respect to the transmission direction of the linear polarizer and the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$. For the uniaxial C-plate phase retardation film 1603a, the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$. For the biaxial phase retardation film 1604a, the slow axis on the plane parallel to the polarizer-retarder surface is ±(0.1°–89.9°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$. For the uniaxial C-plate phase retardation film 1603b, the phase retardation satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$. For the biaxial phase retardation film 1604b, the slow axis on the plane parallel to the polarizer-retarder surface is approximately ±(0.1°–89.9°) with respect to the transmission direction of the linear polarizer, the phase retardation on the plane parallel to the polarizer-retarder surface satisfies condition $d\Delta n = \pm (0.05\lambda - 3.5\lambda)$, and the phase retardation perpendicular to the polarizer-retarder surface are zero.

As in the previous example, the emerging state of polarization is almost circular. In the oblique incident case, the difference between the expected circular state of polarization and the state of polarization emerging from the structure is reduced by the phase retardations of the uniaxial A-plate phase retardation film, the uniaxial C-plate phase retardation film, and the biaxial phase retardation film. Therefore, over wide-acceptance angles, the difference between the $S_3$ of the expected circular state of polarization and the $S_3$ of the state of polarization emerging from the structure is much smaller than that of a conventional circular polarizer.

We claim:

1. A circular polarizer consisting of: one single linear polarizer producing a linear state of polarization; and two biaxial phase retardation films adjacent to the one single linear polarizer forming the circular polarizer, the circular polarizer not including a liquid crystal material, wherein said at least one biaxial phase retardation film comprises: a slow axis on the plane parallel to a polarizer-retarder surface of said at least one biaxial phase retardation film between one of approximately +0.1° to approximately +2.1° and approximately −0.1° to approximately −2.1° with respect to the transmission direction of the said linear polarizer; and a phase retardation on the plane perpendicular to the polarizer-retarder surface of approximately $d\Delta n = \pm (0.47\lambda - 0.49\lambda)$; and a phase retardation on the plane perpendicular to the polarizer-retarder surface of approximately $d\Delta n = \pm (0.35\lambda - 0.37\lambda)$ where $\lambda$ is the wave length of incident light.

2. A circular polarizer consisting of: one single linear polarizer producing a linear state of polarization; and two biaxial phase retardation films adjacent to the one single linear polarizer forming the circular polarizer, the circular polarizer not including a liquid crystal material, wherein said at least one biaxial phase retardation film comprises: a slow axis on the plane parallel to a polarizer-retarder surface of said at least one biaxial phase retardation film between one of approximately +45.1° to approximately +47.1° and approximately −45.1° to approximately −47.1° with respect to the transmission direction of the said linear polarizer; and a phase retardation on the plane perpendicular to the polarizer-retarder surface of approximately $d\Delta n = \pm (0.24\lambda - 0.24\lambda)$; and a phase retardation on the plane perpendicular to the polarizer-retarder surface of approximately $d\Delta n = \pm (0.12\lambda - 0.13\lambda)$ where $\lambda$ is the wave length of incident light.