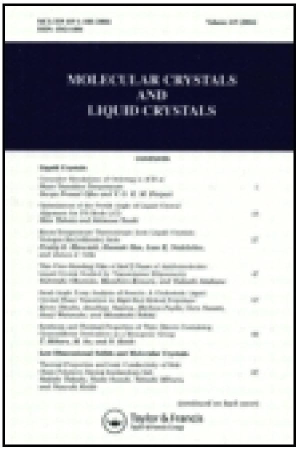

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Polarization Converters Based on Liquid Crystal Devices

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POLARIZATION CONVERTERS BASED ON LIQUID CRYSTAL DEVICES

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Abstract Liquid crystal (LC) devices are presented which convert linearly polarized light into linearly polarized light with axial symmetry. Their symmetry axis is determined by the propagation axis of the light beam. Such light fields can be characterized by an integer P, which we call the polarization order number. Our LC devices are shown to generate P = -2, -1, 1 and 2 fields. Devices that generate P = 1 fields act as azimuthal (A) or radial (R) polarizers or analyzers. Our circularly symmetric polarizers can be used as polarization axis finders or, when two of them are combined, as versatile tools for investigating birefringent, dichroic or optically active materials.

INTRODUCTION

Most of today's LC devices contain alignment layers, which are necessary to fix the orientation of the LC at the LC-substrate interface and which are unidirectionally structured. In this work LC devices are investigated that are based on at least one non-unidirectionally structured alignment layer. Their remarkable optical properties to generate azimuthally, radially or even more complex axial symmetric linearly polarized light, will be described. In this article, optical components that convert linearly polarized light into purely linearly polarized light with axial symmetry will be called polarization converters, thus no elliptically polarized light is involved.

LINEARLY POLARIZED LIGHT WITH AXIAL SYMMETRY

The polarization fields with axial symmetry considered here are described by an integer P, the polarization order number. P is the number of complete polarization rotations per full azimuthal rotation. The orientation of the considered linearly polarized light Φ depends only on the azimuthal angle θ and can be expressed as

$$\phi(\theta) = P \cdot \theta + \phi_0 . \tag{1}$$

ϕ_0 represents a bias polarization orientation for $\theta = 0$. Examples of vector fields with P = -1, 1 and 2 are illustrated in Figure 1.

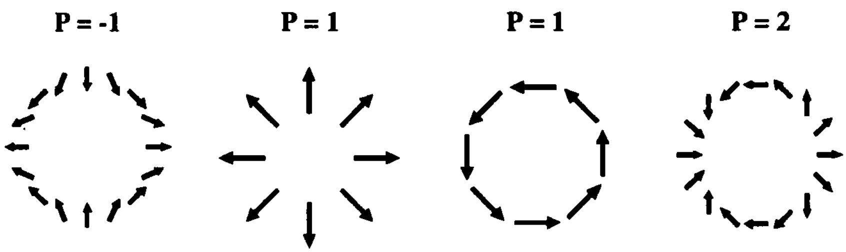

FIGURE 1 Linearly polarized light with axial symmetry with P = -1, 1 representing radially and azimuthally polarized light and P = 2.

P = 1 polarization fields, namely $\phi(\theta) = \theta$ and $\phi(\theta) = \theta + \pi/2$ represent radially and azimuthally polarized light as shown in Fig. 1.

THE θ-CELL

First, a liquid crystal device is described which is able to generate P = 1 light fields. This fundamental cell is composed of one unidirectional and one circularly rubbed alignment layer as illustrated in Fig. 2 (left). The θ-cell is filled with a nematic LC. Some of the optical properties of this cell have been described by Yamaguchi et al.[1]. The unidirectional alignment layer defines a direction parallel to the substrate, the cell axis. We call this LC cell θ-cell, because of its combined linear and circular symmetry. The local orientation of the LC in the θ-cell is that of a twisted cell, with a twist angle given by the local alignment layers. The twist angles are always smaller than $\pm\pi/2$ and minimize the elastic twist energy. The orientation of the LC molecules in a θ-cell seen from above the cell is illustrated in Fig. 2 (right). Two thin radial disclination lines are observed in the θ-cell, separating areas of opposite twist within the cell as indicated in Fig. 2. The disclination lines are parallel to the cell axis, starting close to the center of symmetry and together they form a straight line. The diameter of the center area with undefined LC orientation is typically about 20μm in our fabricated devices.

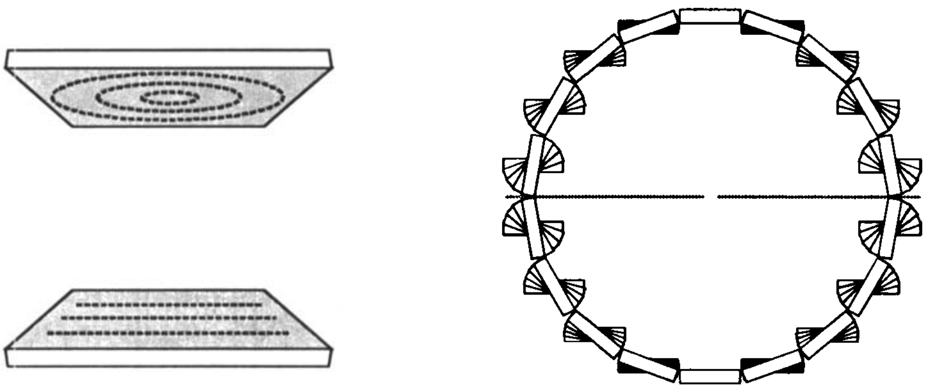

FIGURE 2 Alignment layers of the θ-cell and the orientation of the LC molecules in the θ-cell seen from above the cell.

The θ-cell represents an LC cell with a spatially varying twist angle. For the subsequent discussion it is assumed that the θ-cell fulfills the Mauguin condition [2]. This means that a reorientation of the linearly polarized illumination light occurs under the condition that the incoming polarized light is oriented parallel or perpendicular to the first encountered alignment layer. The reorientation angle is equal to the twist angle given by the local alignment layers [3]. A first optical property of the θ-cell can now be recognized: linearly polarized light, hitting first the unidirectional alignment layer, with the polarization direction oriented parallel [perpendicular] to the cell axis will emerge as linearly polarized light oriented parallel [perpendicular] to the circular alignment layer. The described θ-cell is thus able to convert linearly polarized light into azimuthally or radially polarized light or vice versa.

THE θ-CELL GENERATING P = 1 FIELDS

An azimuthal and radial (A and R) polarizer can be built by combining a θ-cell with a conventional linear polarizer. Such polarizers convert unpolarized light into azimuthally or radially polarized light. The generation of azimuthally and radially polarized light is illustrated in Fig. 3.

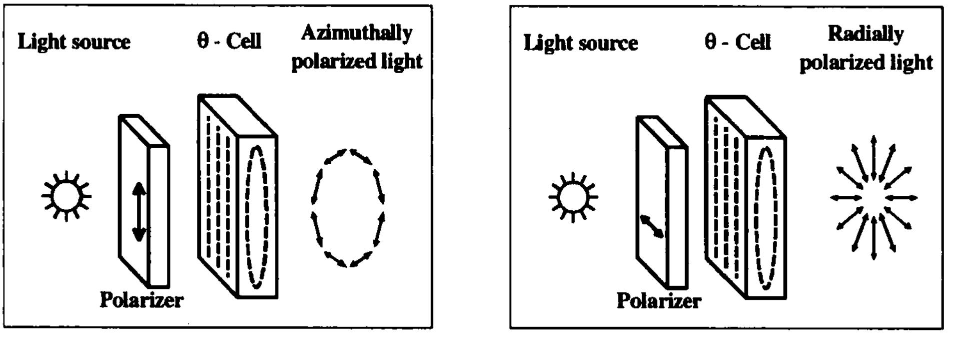

FIGURE 3 Azimuthally and radially polarized light generated by an LC θ-cell

The generated radially and azimuthally polarized light fields are not pure P = 1 light fields as defined by Eq. 1 and illustrated in Fig. 1. There is a relative π-phase shift which occurs between the two cell regions separated by the disclination lines, as one can infer from Fig. 2 (right). Since we are only interested in the geometric optical properties of the described polarization converters in this work, this π-phase shift cannot be detected with the methods described here and will therefore not be considered in more detail. Note that the θ-cell in the described mode of operation acts as an achromatic polarization converter.

POLARIZATION ORDER REVERSAL USING A $\lambda/2$ WAVEPLATE

The effect of a $\lambda/2$ waveplate on linearly polarized light is to reorient the polarization orientation. If the incoming light is characterized by the polarization orientation angle ϕ_{in} and the orientation of the fast axis of the $\lambda/2$ waveplate is given by the angle α, the outgoing polarization orientation will be at

$$\phi_{out} = -\phi_{in} + 2\alpha. \tag{2}$$

The angles are given with respect to some fixed lab coordinates. This reorientation operation corresponds to a reflection of the incoming polarization vector at the fast axis as illustrated in Fig. 5 [4].

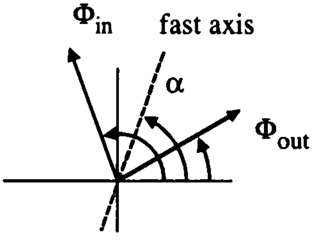

FIGURE 5 Reorientation of linearly polarized light, described by the orientation angle ϕ_{in} with the use of a $\lambda/2$ waveplate, oriented at the angle α. The output polarization orientation is at the angle ϕ_{out}.

Suppose linearly polarized light with axial symmetry described by the vector field $\phi_{in}(\theta)$ illuminates a $\lambda/2$ waveplate. Then the emerging field will be

$$\phi_{out}(\theta) = -\phi_{in}(\theta) + 2\alpha \tag{3}$$

This means that the polarization order of the incoming field experiences a polarization order reversal. Starting with a P = 1 field, for example by using a θ-cell, a P = -1 field can be generated with a $\lambda/2$ waveplate.

CIRCULARLY SYMMETRIC λ/2 WAVEPLATES GENERATING P = 2 FIELDS

Applying the reorientation effect of a λ/2 waveplate again P = 2 fields can be generated. This can be done by illuminating a circularly symmetric λ/2 waveplate (e.g. with the orientation $\alpha = \theta$) with linearly polarized light with an initial orientation of ϕ_{in}. The resulting polarization orientation $\phi_{out}(\theta)$ is, according to Eq. 2, given by

$$\phi_{out}(\theta) = 2\theta - \phi_{in}. \tag{4}$$

This reorientation process is illustrated in Fig. 6.

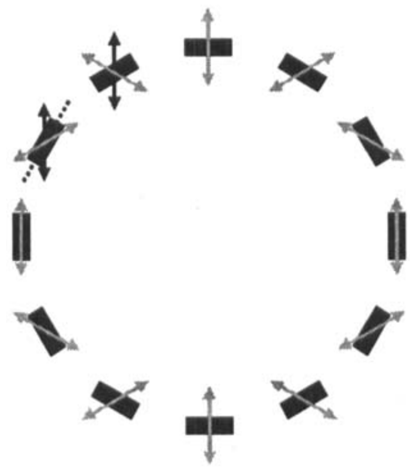

FIGURE 6 The conversion of linearly polarized light (two black arrows) into a P = 2 field (gray arrows) using a circularly symmetric λ/2 waveplate (black boxes).

The circularly symmetric λ/2 waveplate can be fabricated with a LC cell using two circularly rubbed alignment layers with two coinciding centers of symmetry. The LC molecules will orient according to these alignment layers and a circularly symmetric waveplate results. By adding transparent electrodes, the retardation can be adjusted to λ/2. The θ-cell acts as a polarization converter only if the linearly polarized light is oriented parallel or perpendicular to the uniaxially rubbed alignment layer. In contrast to this, the circularly symmetric λ/2 waveplate accepts any incoming polarization orientation and converts it into linearly polarized light with axial symmetry. On the other hand, the circularly symmetric $\lambda/2$ waveplate is chromatic due to the chromaticity of the local $\lambda/2$ waveplates.

THE θ-CELL EXPOSED TO AN ELECTRIC FIELD

In another experiment, θ-cells have been fabricated with transparent electrodes, which allow to expose the LC to an electric field. Interesting properties have been observed at an applied electric field of moderate strength and under illumination with a narrow bandwidth light source. If the θ-cell is illuminated with linearly polarized light, hitting first the uniaxially rubbed alignment layer, $P = 2$ fields are observed at the output for any incoming polarization orientation. If the light hits the θ-cell from the other side $P = -2$ fields are generated for any incoming polarization orientation.

From these observations, together with the knowledge of the properties of the $\lambda/2$ waveplate and the circularly symmetric $\lambda/2$ waveplate, we offer the following explanation. The θ-cell can be subdivided into two regions. The first region is defined by the LC molecules adjacent to the uniaxially rubbed alignment layer. These molecules are mainly uniaxially oriented parallel to the cell axis, representing roughly a waveplate, see Fig. 1. The second region is defined by the molecules adjacent to the circularly rubbed alignment layer. Here the molecules are mainly circularly symmetrically oriented, representing roughly a circularly symmetric $\lambda/2$ waveplate. At a certain voltage, the first region represents a $\lambda/2$ waveplate, and the second region represents a circularly symmetric $\lambda/2$ waveplate. If the light is first hitting the uniaxial region, a reorientation of the incoming polarization orientation occurs. The succeeding, circularly symmetric $\lambda/2$ waveplate generates a $P = 2$ field. If the linearly polarized light is first hitting the circular symmetric region, a $P = 2$ field is generated, while the succeeding $\lambda/2$ waveplate inverts the signature of the polarization order. Thus a $P = -2$ field emerges.

The experimentally observed polarized light emerging from a θ-cell exposed to a moderate electric field is slightly elliptically polarized. On average, ellipticities (defined by the tangent of the ratio of the two principal diameter of the polarization ellipse) of about 3.3° have been measured in a typical θ-cell, resulting in a contrast of about 1 : 17.

POLARIZATION AXIS FINDERS

A or R polarizers can also be used as analyzers. Such A or R analyzers are equivalent to linear polarizers with an azimuthal or radial orientation and can be used as polarization axis finders. Darkness is observed at azimuth angles where the polarization direction of the inspected light and the local orientation of the analyzer give an angle of 90°, see Fig. 2. If polarized light is detected with an A (R) analyzer, two black segments are observed which are parallel (perpendicular) to the inspected linearly polarized light orientation. The contrast observed is a measure of the degree of polarization. For purely linearly polarized light, the maximal possible contrast is observed. Purely linearly polarized light analyzed with such circular symmetric analyzers are shown in Fig. 7.

Dichroic materials can also be inspected using A or R analyzers. Using a white light illumination a 4-segment color pattern will be observed indicating the main axis.

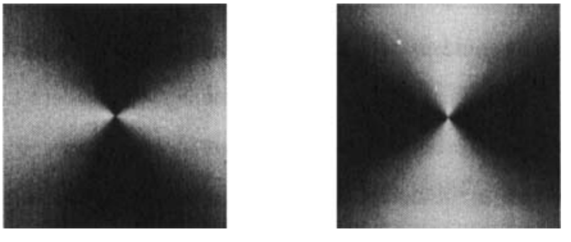

FIGURE 7 East-west polarized light analyzed with an R and A polarizer or expressed differently, observed through an A and R polarization axis finder.

Light from the blue sky is partially linearly polarized and its orientation can easily be detected with an A or an R analyzer. Such an analyzer can thus be used as a sun dial because it indicates the direction to the sun. In contrast to ordinary sun dials, which depend on direct sun light, only a small region of blue sky is needed when using A and R polarizers.

The polarization axis finder can also be a helpful tool when inspecting optically active materials. If linearly polarized white light is used as an illumination source, the angular dispersion of the material can be seen when analyzing the emerging light with an A or R polarizer.

Recently, LC based azimuthal polarizers have also been demonstrated as adequate polarization converters for coupling light into a small-period concentric-circular grating coupler (CGC) for integrated optical applications [5]. In this way, the angular dependence of coupling linearly polarized light into a CGC can be overcome.

ALIGNMENT TOOL USING TWO POLARIZATION CONVERTERS

Two polarizers, either A or two R types, separated by a certain distance, define an optical axis given by the two centers of symmetry. When looking through these two polarizers along the optical axis, the view is undisturbed. When looking at an angle off the optical axis, a dark circle appears, which is indicative of the deviation from the optical axis, see Fig. 8. This instrument can therefore be used as an alignment tool.

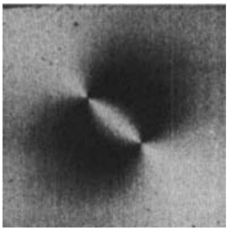

FIGURE 8 Alignment tool with circular polarizers. Shown is the pattern which is seen when looking off-axis through two A or two R polarizers.

The dark circle observed [directions of locally crossed polarizers] passing through the two centers of symmetry is a Thales circle.

INVESTIGATING BIREFRINGENT MATERIALS USING TWO POLARIZATION CONVERTERS

When inspecting birefringent materials the samples are often observed between crossed linear polarizers. In this case the samples have to be rotated with respect to the polarizers to identify potential main axes. In the case of a birefringent plate, characteristic interference colors are observed in the diagonal orientation [6], e.g. where the angle between the main axis of the sample and the polarizers is 45°. Instead of this standard set-up, an A and an R polarizer can be used as a polarizer-analyzer configuration. In this case all polarization orientations are provided, darkness appears in four segments, namely when the main axis of the sample aligns parallel or perpendicular to the polarizers. At 45°, the characteristic interference colors appear. This set-up shows therefore immediately the orientation of the birefringent material, together with the relevant interference or transmission colors, independently of the orientation of the sample with respect to the polarizers. A typical pattern observed for a uniaxial birefringent plate between crossed circular polarizers is shown in Fig. 9.

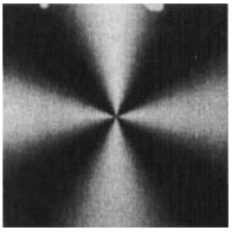

FIGURE 9 Pattern observed for a birefringent plate placed between an A/R polarizer- analyzer system. The optical axis of the plate is held at 45° to west-east.

Azimuthal polarization axis finders based on circularly symmetric sheet polarizer material are commercially available [7]. Radial polarization axis finders are not available and therefore our suggested inspection techniques cannot be applied. The optical quality of our LC based is much higher than the commercial device we have tested and does not include an intrinsic absorption due to a sheet polarizer.

CONCLUSIONS

We have shown that polarization converters can be realized with novel LC configurations. Our polarization converters are able to generate linearly polarized light fields which are difficult, if not impossible, to generate with conventional optical components. The polarization reorientation effect in our devices is due to the twisted nematic effect and due to the reorientation effect of $\lambda/2$ waveplates. The polarization converters can be used as polarization axis finders, for investigating birefringent materials and as alignment instrument.

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