# Application Notes for the Polarization Converter (Radial Polarizer)

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## LINEARLY POLARIZED LIGHT WITH AXIAL SYMMETRY (RADIAL OR AZIMUTHAL POLARIZATION DISTRIBUTION)

The Arcoptix Polarization converter is capable to transform a linear polarized beam (monochromatic or polychromatic light) in all kinds of axial symmetric polarization distribution. The most used are of course the radial and azimuthal polarization distribution but with additional elements other distribution are also possible as it will be explained further in this section.
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 $\phi$ depends only on the azimuthal angle $\theta$ and can be expressed as

$$\phi(\theta) = p \cdot \theta + \phi_0 \quad (1)$$

$\phi_0$ represents a bias polarization orientation for $\theta = 0$. Examples of vector fields with P = -1, 1 and 2 are illustrated in Figure 1.

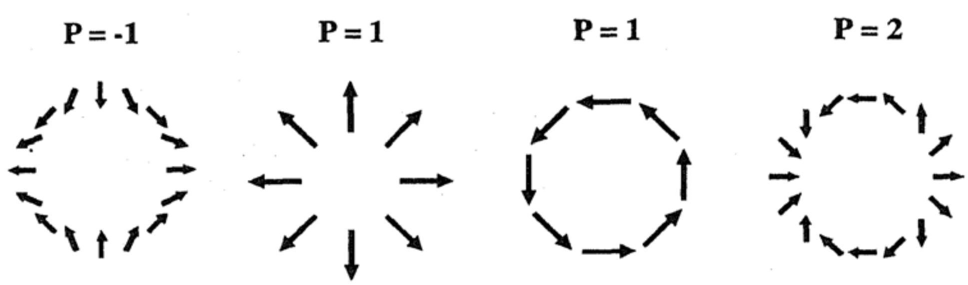


*FIGURE 1 Linearly polarized light with axial symmetry with P = -1, 1 representing radially and azimuthally polarized light and P = 2.*

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 (the heart of the polarization converter)**

The heart of the Arcoptix polarization converter is constituted by the θ-cell (which can be ordered on its own). This fundamental cell is composed of one unidirectional and one circularly rubbed alignment layer (deposed on square glass or fused silica substrates) as illustrated in Fig. 2 (left). The θ-cell is filled with a special blend of nematic LC's. Some of the optical properties of this cell have been described by Yarnaguchi et al.'. 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 q-cell is that of a twisted cell, with a twist angle given by the local alignment layers. The twist angles are always smaller than ~2 and 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. On bothe sides of this disclination lines corresponds to a pi phase step which can be compensated with the phase compensator which is (optionally) included in the system.
The diameter of the center area with undefined LC orientation is typically about 20 μm in our fabricated devices. This central point creates a sort of phase and polarization singularity in the center of the pattern.

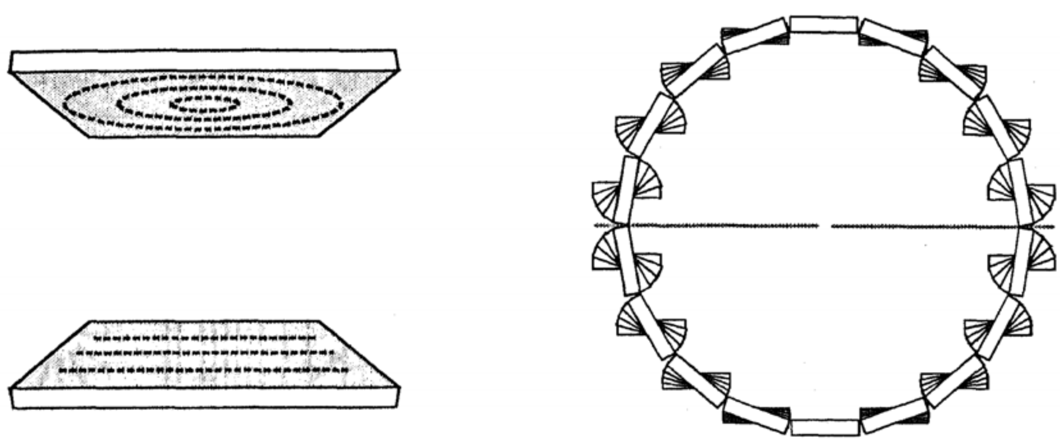

*FIGURE 2 Alignment layers of the θ-cell and the orientation of the LC molecules in the θ-cell seen from above the cell.*

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. 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. 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 (or perpendicular) to the cell axis will emerge as linearly polarized light oriented parallel (or 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.
Notice that the θ-cell has a defect line that dived the usable aperture into two parts which are pi phase shifted with respect of each other. This is illustrated in figure 2 (right hand side) where the LC molecules in the upper part rotate left and in lower part rotate right. This creates a pi shift between the two pars for every wavelength. For this reason Arcoptix proposes polarization converter systems including a phase compensator that compensate this pi phase step and which is tunable for every wavelength.

**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 or directly with polarized laser beam. Such polarizers convert unpolarized light into azimuthally or radially polarized light. The generation of azimuthally and radially polarized light as defined by Eq. 1 is illustrated in Fig. 3.

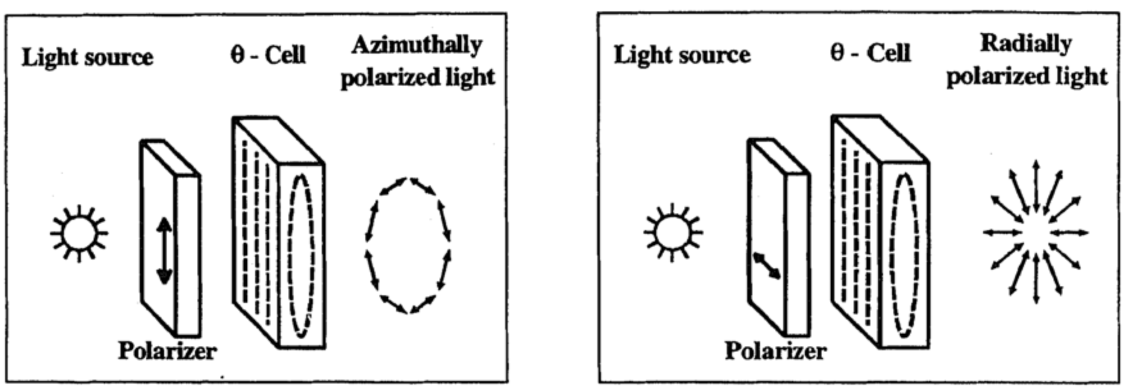


*FIGURE 3 Azimuthally and radially polarized light generated by an LC θ-cell*

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 change the polarization orientation. If the incoming light is characterized by the polarization orientation angle $\phi_{in}$ and the orientation of the fast axis of the $\lambda/2$ waveplate is given by the angle $\alpha$, the outgoing polarization orientation will be at

$$\phi_{out} = -\phi_{in} + 2\alpha \qquad (2)$$

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. 4.

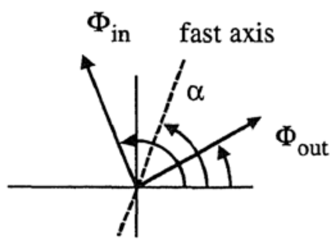


*FIGURE 4 Reorientation of linearly polarized light, described by the orientation angle $\phi_{in}$ with the use of a $\lambda/2$ waveplate oriented at an angle $\alpha$.*
*The output polarization orientation is at the angle $\phi_{out}$.*

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

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

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 $\theta$-cell, a P = -1 field can be generated with the help of an extra $\lambda/2$ waveplate.

**POLARIZATION AXIS FINDERS**

The arcoptix radial (or azimuthal) polarizer (which is a θ-cell) can also be used as analyzers. Such radial (or azimuthal) polarizers 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 a radial polarizer, 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. 5.
Dichroic materials can also be inspected using a radial polarizer. Using a white light illumination a 4-segment color pattern will be observed indicating the main polarization axis.

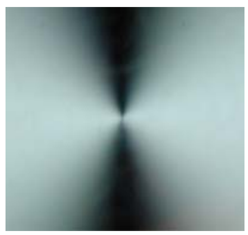

*FIGURE 5 East-west polarized light analyzed with a θ-cell or expressed differently, observed through a radial polarization axis finder.*

Light from the blue sky is partially linearly polarized and its orientation can easily be detected and analyzed with the radial polarizer. Such a polarizer 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 the radial polarizer.
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 analyzed by observing the emerging light with a radial 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. In this way, the angular dependence of coupling linearly polarized light into a CGC can be overcome.

## ALIGNMENT TOOL USING TWO POLARIZATION CONVERTERS

Two θ-cells in between two polarizers, separated by a certain distance (the more they are separated, the more it will be sensible), define an optical axis given by the two centers of symmetry. When looking through these Two θ-cells along the optical axis, the view is undisturbed (no dark circle). When looking at an angle off the optical axis, a dark ellipse appears, which is indicative of the deviation from the optical axis, see Fig. 6. The direction of the ellipse gives also the direction of the deviation. This instrument (including two θ-cells) can therefore be used as an alignment tool.

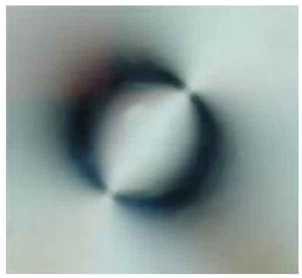

*FIGURE 6 Pattern which is observed when looking off-axis through two θ-cells in between polarizers.*

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***,*** e.g. where the angle between the main axis of the sample and the polarizers is 45°**.** Instead of this standard set-up, an azimuthal and a radial 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. 7.

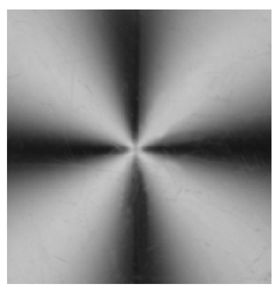

FIGURE 7 *Pattern observed for a birefringent plate placed between an azimuthal-Radial polarizer-analyzer system. The optical axis of the plate is held at 45° to west-east*.

Azimuthal polarization axis finders based on circularly symmetric sheet polarizer material are commercially available**.** Continuous 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.