Radially Polarized Beams Forming Using Phase-Compensated Sectorial Dichroic Plates

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Abstract. We propose to create radially polarized beam using 8-sectorial polarizer. The manufacturing technology of such elements is based on axially symmetric discretization of the required polarization and phase distributions. This representation leads to optical elements in the form of sector plates. Simulation is provided with Comsol multiphysics software. We show that the plate can create the radially polarized beam with the vortex phase.

1. Introduction

Cylindrical vector beams of different orders [1] are of practical interest in such fields as multiplexed optical data transmission [2], amplitude-polarization modulation of focal distributions [3], laser micromanipulation [4, 5], and improvement of exoplanet images [6, 7]. Some applications can be based on the phenomenon of the so-called reverse flow [8], which occurs in the focused high-order radially polarized beams. In this case, the integral reverse energy flow increases with the topological order of the radially polarized beam. Thus, the formation of high-order cylindrical beams is a relevant task.

A significant number of works have been devoted to the study of methods for producing cylindrical vector beams, including high orders, in recent years. The main approaches can be called the polarization transformations of the initial beam using spatial light modulators (SLM) [9], based on the superposition of vector beams [10], using subwavelength gratings [11-13], and also using crystalline [14-16] and film [14, 17] sector plates.

Principally, the interference polarizer [18, 19] is a continuous analog of sector plates. All methods have their pros and cons. SLMs convert the polarization of only part of the transmitted light, thereby reducing the polarization instinction ratio. For a converter based on subwavelength gratings, the efficiency and, therefore, the polarization contrast change depending on the angle of rotation of the plane of polarization.

Note that the obstacle of subwavelength polarization gratings, which consists in the unevenness of Fresnel reflections, can be compensated by combining the polarization and focusing elements [20, 21]. It should also be noted that for the infrared range that the technology of manufacturing subwavelength gratings is simpler due to the longer wavelength.

The main advantage of various types of sector converters is the lowest cost per unit area and ease of use. The main factors that worsen the quality of the formed beams and, accordingly, complicate the
manufacturing technology, are the joints of the sectors. In addition, for transducers in which circular polarization is used as the initial one [14, 17-19], a vortex phase presents in the formed beam.

The so-called vortex radial polarization is obtained, and to obtain the classical radial polarization, an additional phase transformation like phase plates is required [7]. However, this also has a positive effect, since the number of degrees of freedom for the formation of various polarizations of high orders increases by simply changing the mutual angular position of the sector polarizing and phase plates.

Technologically, this is easily feasible, since the sectors of the polarizing film and phase plates (phaseshifter) are made in the form of separate plates. In this paper, several options for such transformations are proposed and simulated.

2. Radial polarization formation with polarizer

Various types of high-order cylindrical polarizations are considered [22-28], which can be combined with the formula [22]:

\[
\begin{pmatrix}
    c_x(\phi) \\
    c_y(\phi)
\end{pmatrix} = \begin{pmatrix}
    \cos(p\phi + \phi_0) \\
    \sin(p\phi + \phi_0)
\end{pmatrix}.
\]

(1)

Working of ideal polarizers can be describes with the following equation:

\[
\begin{pmatrix}
    c_{x}(\theta) \\
    c_{y}(\theta)
\end{pmatrix} = \begin{bmatrix}
    \cos^2 \theta & \cos \theta \sin \theta \\
    \cos \theta \sin \theta & \sin^2 \theta
\end{bmatrix}\begin{pmatrix}
    c_{0x} \\
    c_{0y}
\end{pmatrix},
\]

(2)

here \( c_0 = (c_{0x}, c_{0y})^T \) and \( c_\theta = (c_{x}(\theta), c_{y}(\theta))^T \) are vectors of transverse electric components of the initial and transformed fields, respectively. \( \theta \) – is inclination angle of the polarization vector to the axis \( x \).

For a field with initial circular polarization \( c_0 = e^{i\phi_0} = (\sqrt{2})^{-1} (1, i)^T \) the expression (2) can be rewritten as follows:

\[
e^{i\phi_0}(\theta) = \frac{1}{\sqrt{2}} \begin{pmatrix}
    \cos^2 \theta + i \cos \theta \sin \theta \\
    \cos \theta \sin \theta + i \sin^2 \theta
\end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix}
    \cos \theta \\
    \sin \theta
\end{pmatrix} \exp(i\theta) = \frac{1}{\sqrt{2}} c^{\text{circ}} \exp(i\theta),
\]

(3)

here \( c^{\text{circ}} = (\cos \theta, \sin \theta)^T \) corresponds to classical radial polarization.

Thus, if the sectorial films are arranged along radial lines, then we obtain the first-order radial polarization with the first-order phase vortex, as it follows from expression (3).

3. Dichroic sectorial polarizer

Here we propose to create radially polarized beam with 8-sectorial polarizer which is illustrated in Figure 1a. The transmissive axis is radially oriented from the center to the periphery of the element. All other waves are absorbed. The plate can be tailored from cheap dichroic film and glued on a glass substrate.

In the simplest case, this material can be described as follows. If it is required that a polarizer passes polarization along the \( x \) axis, then the dielectric tensor of the material should have the form:

\[
\varepsilon = \begin{pmatrix}
    2.7556 & 0 & 0 \\
    0 & 2.7556+j16 & 0 \\
    0 & 0 & 2.7556
\end{pmatrix}.
\]

(4)
In the matrix (1) at position (2.2), the term has an imaginary part, which indicates that the component of the electric vector along the \( y \) axis attenuates in the material. In order for a beam to be formed with radial polarization at the output, each sector must be oriented in such a way as to pass a polarization oriented along the radius. Thus, in each of the eight sectors, the dielectric constant tensor (1) must be rotated by an angle corresponding to the transmission of a wave polarized along the radius. If there are 8 sectors, then the rotation angle should be equal.

\[
\varphi = \frac{2\pi}{8} l = \frac{\pi}{4} l ,
\]

here \( l \) is the number of the sector.

Thus, the dielectric constant tensor of the sector with the number \( l \) has the following form:

\[
\varepsilon_r = \begin{pmatrix}
2.7556 + j16\sin^2\left(\frac{\pi l}{4}\right) & -j16\sin\left(\frac{\pi l}{4}\right)\cos\left(\frac{\pi l}{4}\right) & 0 \\
-j16\sin\left(\frac{\pi l}{4}\right)\cos\left(\frac{\pi l}{4}\right) & 2.7556 + j16\cos^2\left(\frac{\pi l}{4}\right) & 0 \\
0 & 0 & 2.7556
\end{pmatrix}.
\]

There are the results of simulation of the element working in Figure 1. Circularly polarized beam passes through the element and loses one of the John’s vector components due to the dichroic absorption. Simulation is provided with Comsol Multiphysics software.

![Figure 1](image)

**Figure 1(a, b, c, d).** (a) General view of dichroic sectorial plate; (b) Electric field amplitude after that the circular polarized beam passes through the element; (c) Horizontal component of the electric field; (d) Vertical component of the electric field; black arrows show the polarization

4. Conclusions

In this work, we propose the 8-sectorial dichroic plate for radially polarized beam creation. The plate is much cheaper and easier to manufacture than classical methods. The tensor of dielectric permittivity is derived. An operation of 8-sectorial plate is numerically simulated. We show that the plate can create the radially polarized beam with the vortex phase.

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