Investigation of the formation of hybrid polarized laser beams using a four-sector polarization converter

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Abstract. The paper presents the manufacturing technology of a four-sector polarization converter for the formation of beams with different hybrid polarizations. A calcite crystal was used as a transducer, two opposite sectors of which were etched to a depth of 1970 nm. The work is demonstrated and experimental patterns of the total intensity distribution, x-components and y-components in the wavelength range of 500-800 nm for the light transmitted through the transducer and also in the focus distribution are shown. The theoretical and experimental dependence of the degree of conversion is described depending on the parameters of manufacturing the sectors of a four-sector converter. For this purpose, a tunable laser was used in the experiment. The operation of the transducer for the vortex field was simulated.

1. Introduction

The use of specially polarized laser beams has several advantages over linearly polarized beams, which makes them relevant for use in areas such as laser microscopy [1], optical communication [2], micromanipulation [3], laser ablation [4–5]. Beams with various hybrid polarizations[6] can serve for the formation of various focal distributions and fibre sensors[7-11]. Beams with a complex polarization state are generated by SLM [12] But are more efficiently generated by sector plates, in which sectors are either half-wave plates [13-15] or film polarizers [15-16].

The former use a linearly polarized illuminating beam, and the latter employ a circularly polarized beam. Polarization converters based on subwavelength diffraction gratings are also known[17-19]. The sectors of the polarization converter can be made in the form of subwavelength reflective gratings and are also known[17-19]. However, the sector-based polarization converters are the easiest to use.

Effective conversion (virtually without energy losses) provides only a variant of a sector converter based on half-wave plates. Obviously, a film converter has an efficiency of 50% at best. In a converter based on subwavelength gratings, the efficiency and, consequently, the polarization contrast, varies depending on the angle of rotation of the polarization plane by the grating. Thus, Stafeev et al.[21] varied the polarization contrast in sectors from 185:1 to 6:1, which, of course, does not meet even the most minimal requirements. It should also be noted that this property of a change in efficiency...
theoretically follows from the very mechanism of the operation of subwavelength gratings and cannot be eliminated by any complication of an already complex technology of their fabrication.

For gratings assembled from half-wave plates and from a polarized film, the main factor that worsens the quality of the formed beams is the presence of sector joints. Gaps and misalignments between the sectors lead to the appearance of parasitic diffraction patterns and additionally violate the axial symmetry of the produced beams. The initial violation of the axial symmetry is determined by the limited number of sectors (usually no more than 8).

In works[13–14], or film polarizers16 the above problems are combated by using low-frequency spatial filtration of the beam obtained by a telescopic system with a point diaphragm in focus. However, this technique leads to significant energy losses.

The effect of sector joints can be significantly reduced by manufacturing a sector plate in the form of a single birefringent crystal, the sectors being formed by a microlief on the crystal surface. In essence, as in[20,21], the converter is implemented using DOE technology, but unlike15,16, the sectors operate as crystal half-wave plates and, consequently, completely eliminate all the imperfections of subwavelength gratings[20-23]. A DOE for polarization conversion, made on a substrate of a birefringent material, was first proposed by Niuet al.[23].

However, this DOE[24] relied on a fundamentally different approach [25-27], based on the interference of a pair of laser modes. The DOE produces, respectively, Hermite-Gaussian modes (0, 1) and (1, 0) in the ordinary and extraordinary rays that are formed at a certain distance. Then, the modes are subjected to an additional phase conversion using a second DOE, after which a radially polarized R-TEM(0.1) mode is obtained. The disadvantages of the method are, first of all, the high technological complexity of manufacturing a multilevel DOE with a maximum relief height of several wavelengths on a quartz substrate. Apparently, for this reason, Niuet al.[24] did not perform a full-scale experiment with the proposed DOE.

Another version of the DOE on a birefringent crystal was proposed in [27,28] to generate radially and azimuthally polarized beams. Such a DOE is a multilevel spiral phase plate, at the full height of the relief the value of the path difference between the ordinary and extraordinary rays being 2λ. Even for a highly anisotropic material used in [25], the height of the relief is about 11 μm.

Thus, the approach in [27-28] suffers from the same drawbacks as that in [18]. In addition, the use of the element 21 involves the employment of an immersion cell with a special gel and the presence of two additional quarter-wave and two half-wave plates in the optical scheme.

Another possible way to create inhomogeneous polarization is the use of interference polarization filters.[29]

However, in this case, the operation of such an element will be limited only to a narrow range of wavelengths for which the interference layers were calculated. It should be noted that there is another mechanism responsible for the formation of inhomogeneous polarizations in anisotropic crystals [30–36], which is not related to the deposition of a microlief on the crystal surface. However, this mechanism works only in conditions of non-paraxial incident beams of a special type, which are also obtained with the help of separate DOEs.

The paper [37] presented the initial results of polarization converter in the far-field zone. In this paper, we propose a new approach to the implementation of a DOE based on an anisotropic crystal for the conversion of the polarization state of beams.

The obtained hybrid polarization states make it possible to form new field distributions in the focal region with high efficiency. In this paper, a four-sector polarization converter is fabricated on a single crystal of calcite. The distribution of the field formed by the manufactured optical element in the near zone and in the focal plane of the lens is experimentally performed.

2. Experimental
Consider the manufacture of a sector plate in the form of a single birefringent crystal with sectors formed on the surface of the microlief.

A uniaxial birefringent crystal was chosen for the manufacture of the sector plate. The sectors for polarization rotation were made by the method of liquid etching of the substrate material. The depth of
etching in this case should provide paired orthogonal polarization states of the rays passing through them. The manufacturing scheme of such an optical element is shown in Figure 1.

![Figure 1. Scheme of DOE manufacturing process.](image)

As an anisotropic crystal, we chose an x-cut CaCO$_3$. To obtain a four-sector transducer, a microrelief was formed on the surface of this crystal by liquid etching. For the visible wavelength range, the required etching depth of a CaCO$_3$ crystal is about 2 microns. For etching, a solution C$_{10}$H$_{14}$N$_2$Na$_2$O$_8$ was used at a temperature of 60°C.

The etching of the CaCO$_3$ crystal on a given photomask was ensured by the photoresist mask from the FP-2512 resist. The chemical reaction occurs with the formation of a soluble salt:

TrB$_2$-2Na + CaCO$_3$ → TrB-Ca + Na$_2$CO$_3$.

The result of measuring the depth of etching is shown in Figure 2.

![Figure 2. Profilogram of a step on a calcite crystal.](image)

Initially, the wavelength was varied near the calculated wavelength $\lambda_0 = 678$ nm, which should provide the closest wavelength to the calculated one. To select the wavelength, we used a tunable EKSPLA NT-200 laser, which provides the wavelength tuning with a step of 0.1 nm. The experimental setup is shown in figure 3.

![Figure 3. Scheme of experimental setup.](image)

Figure 4 in the first column shows the distribution of the intensity of light transmitted through a converter without a micro-lens and with an analyzer for $\lambda_0 = 678.3$ nm.

One can see from figure 4 that for this wavelength condition is satisfied, which ensures a pairwise orthogonal polarization state in the corresponding sectors. The calculated value of $\Delta \lambda$ for this wavelength is 1.74 nm.

In figure 4, the second row shows the light intensity distribution for $\lambda' = \lambda_0 + (\Delta \lambda / 2) = 678.3$ nm + 0.87 nm = 679.1 nm. As can be seen, dark and light sectors changed places. Then, the wavelength was reduced to 586.4 nm.
Figure 4. Intensity distributions formed by a four-section plate at different wavelengths. The size of the images is $4 \times 3$ mm.

Table 1. Results of an experimental study of a focused beam transmitted through the converter at different wavelengths. The size of the images is $4 \times 3$ mm.

| Wavelength | Intensity distributions in the focal plane of the lens |
|------------|-------------------------------------------------------|
|            | Total intensity | x-component intensity | y-component intensity |
| $\lambda=547$ nm | ![Image](image1.png) | ![Image](image2.png) | ![Image](image3.png) |
| $\lambda=560$ nm | ![Image](image4.png) | ![Image](image5.png) | ![Image](image6.png) |
| $\lambda=580$ nm | ![Image](image7.png) | ![Image](image8.png) | ![Image](image9.png) |
\( \lambda = 586 \text{ nm} \)

\( \lambda = 590 \text{ nm} \)

\( \lambda = 610 \text{ nm} \)

\( \lambda = 679 \text{ nm} \)

**Table 2.** Focusing of a Gaussian beam transmitted through the converter at different wavelengths.

| Wavelength | Intensity distributions in the focal plane of the lens |
|------------|------------------------------------------------------|
|            | Total intensity                              | x-component intensity | y-component intensity |
| \( \lambda = 650 \text{ nm} \) | ![Image](image1) | ![Image](image2) | ![Image](image3) |

As can be seen from figure 4 (third row), condition is also satisfied for this wavelength. The period \( \Delta \lambda \) for this wavelength is 1.16 nm. The first change in the polarization state of the sectors, close to the orthogonal state, occurs at a wavelength of 586.9 nm, as follows from the calculations. However, for this wavelength condition is not satisfied as accurately as for \( \lambda_0 = 678 \text{ nm} \); therefore, as was shown, the resulting polarizations are elliptical, which leads to a decrease in the polarization contrast between the sectors.

**Table 3.** Intensity distributions in the focal plane of the lens for the vortex field \( m=2 \).

| Wavelength | Intensity distributions in the focal plane of the lens |
|------------|-------------------------------------------------------|
|            | Total intensity                              | Total intensity | Total intensity |
| \( \lambda = 532 \text{ nm} \) | ![Image](image4) | ![Image](image5) | ![Image](image6) |

As a result of the polarization change by such a converter, the intensity distributions shown in Table 1 form in the focal plane of the lens. As seen with the change in wavelength, the contribution of
the x-component and the y-component to the overall intensity distribution differs due to different polarization transformations of the original radiation by sectors of the four-sector converter. Table 2 shows the result of modeling the total intensity distribution and the x-components and the y-components for the wavelength $\lambda_0 = 650$ nm.

3. Conclusion
We have considered the work of a DOE in the form of a step on the surface of an anisotropic crystal. We have developed a method for manufacturing sector plates for the conversion of the polarization state of beams. The method based on etching of a calcite crystal has been developed and implemented. The resulting width of the steps on the calcite crystal is 4 times smaller than the width of the joints in a converter assembled from half-wave plates. The results of the experimental study of the manufactured four-sector polarization converter are in good agreement with the results of calculations.

4. References
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