Subwavelength Gratings for Polarization Control

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Abstract. We investigated components of microoptics with nanostructured surface for polarization control. These components include transmitting or reflecting subwavelength diffractive gratings, which have locally varying direction and filling factor of relief, but have approximately equal period and depth of the relief. We investigated four-sector diffractive polarizers, which transform linear polarization in radial or azimuthal polarization of laser light in detail.

1. Introduction
Diffractive optical elements that control the amplitude and phase of light have been known in optics for a long time. However, only recently researchers have taken an interest in studying elements that converts the polarization of light. Well-suited for this purpose are diffractive gratings with space variant grooves and subwavelength period, which are called subwavelength gratings (SWG) [1]. As light propagates through SWG, due to different effective refractive indices [2] the TE- and TM-waves acquire different phase shifts, making the output polarization vector rotate by some angle. If the phase shift equals to a quarter of wavelength, the grating operates as a quarter-wave plate, performing the linear to circular polarization conversion [3-4]. With a half-wavelength phase shift between the TE- and TM-components, the grating operates as a half-wave plate [5-6].

In this paper the components of microoptics with nanostructured surface for polarization control are investigated. These components include transmitting or reflecting subwavelength diffractive gratings, which have locally varying direction and filling factor of relief, but have approximately equal period and depth of the relief. Four-sector diffractive polarizers, which transform linear polarization in radial or azimuthal polarization of laser light are investigated in detail.
2. Use of subwavelength gratings for light polarization conversion

2.1. Numerical simulation

The simplest way to perform the polarization conversion is through the use of subwavelength gratings. Such gratings have different refractive indices of the TE- and TM-components of the wave [2]:

\[ n_{\text{TE}} = \sqrt{dn_r^2 + (1 - d)n_m^2} \]

\[ n_{\text{TM}} = \frac{1}{\sqrt{\left(\frac{d}{n_r^2} + \frac{1 - d}{n_m^2}\right)}} \]

where \(d\) is the fill factor of the grating (the ratio of the step width to the grating period), \(n_r\) is the refractive index of the step material, and \(n_m\) is the refractive index of the environment.

Figure 1 shows the dependence of the intensity of reflected light on the angle of inclination of the grating grooves and the polarization angle \(\theta\) versus the angle \(\alpha\). With the angle between the grating's grooves and the incident electric vector changing by \(\alpha\) degrees, the respective angle between the incident electric vector and the reflected electric vector changes by \(\theta\) degrees.

In our research we propose SWG based polarization converter consisted of four sectors: in the two sectors the microrelief features have make angles 70° and -70° with the y-axis (vertical), whereas in the other sectors make with the y-axis angles 40° and -40°.

The performance of the micro-polarizer was simulated as follows: first, the FDTD-aided simulation of the complex amplitude of the field reflected at the polarizer was implemented using the FullWAVE software. A linearly polarized plane wave of wavelength 532 nm was assumed to hit the polarizer normally. The mesh of the FDTD method had a \(\lambda/30\) step. The refractive index of the grating grooves and the substrate was \(n = 0.312 + 3.17i\) (gold). The grating feature height was put to be 110 nm, with the substrate thickness being 150 nm.

The field distribution at a significant distance from the polarizer was calculated using the Rayleigh-Sommerfeld integral, with the FDTD-aided complex amplitude calculated 200-nm away from the
surface taken as an initial field guess. Figure 2 depicts the intensity patterns calculated at distances of 5 µm, 300 µm, and 500 µm from the element, the arrows marking the polarization directions.

2.2. Manufacturing of the polarizers

We fabricated two reflective polarizers: the first one was used to produce radially polarized light (Fig. 3a). It had a period of 0.4 µm in all four sectors. The second polarizer was used to produce azimuthally polarized light (Fig. 3b): in the two sectors on the right, the microrelief features have a 0.46-µm period and make angles 70° and -70° with the y-axis (vertical), whereas in the sectors on the left, the features have a 0.4-µm period and make with the y-axis angles 40° and -40°. Both micropolarizers have a size of 100×100 µm and the microrelief height of 110 nm.

![Figure 3. SEM images of micropolarizers for (a) radial [6] and (b) azimuthal [7] polarization.](image)

When the linearly polarized white light is reflected at the micropolarizer under study (Fig. 3a) just two of the four sections of the polarizer appear as bright (or dark) in the image plane (Fig. 4) if observed through the polarizer rotated by +45 or -45 degrees about the incident light polarization plane. From Fig. 4, the light reflected at each micropolarizer sector is seen to be devoid of circular symmetry, whereas the average intensities across two diagonal squares are seen to be different.

![Figure 4. The image of a golden substrate comprising nine micropolarizer prototypes was obtained in linearly polarized white light and observed through a polarizer rotated by 45º. Each dark square measures 50×50-µm.](image)

2.3. Experiment

The performance of the fabricated micropolarizers (Fig. 3) was experimentally tested using a linearly polarized beam of 1-mm width from a 633-nm laser for radial polarizer and 532-nm laser for azimuthal polarizer. The beam was focused with a 10x lens O₁ onto the substrate containing the grating micropolarizer (Fig. 4). The size of the spot focused on the micropolarizer was controlled by varying the distance from the lens O₁ to the micropolarizer surface. Although in this case, the micropolarizer was not found in the beam waist and the incident wave was spherical, the experimental results we discuss below corroborate that the micropolarizer still operated in a proper way. This may be explained by the fact that while changing from a plane to a spherical wavefront the beam polarization does not acquire an azimuthal component, only acquiring a longitudinal component along the propagation axis, meaning that the angle between the polarization direction in the polarizer plane and the microrelief grooves remains unchanged. The image of the four-sector grating polarizer was displayed in a CCD-camera using a lens L₁ (f ≈ 1.5 cm, NA = 0.01). The polarization of the input beam was determined using a polarizer/analyzer P₂.
3. Metalens

SWG-based elements could be combined with classical diffractive optical elements to design elements that simultaneously control polarization, phase and amplitude of the incident light. In our research we combined Fresnel zone plate with four sector radial polarizer.
The metalens (Fig. 8) was fabricated using electron beam lithography. A 130-nm thick amorphous silicon (a-Si) film deposited on a transparent pyrex substrate (with refractive index $n=1.7$) was coated with a 320-nm thick PMMA resist, which was fixed at a temperature of 180°C. The resist thickness of 320 nm was chosen to be optimal. To prevent an electric charge from forming, the surface was sputtered with a 15-nm thick golden layer. A binary template was transferred onto the resist surface using a 30-kV electron beam. The specimen was developed in the water blended with isopropanol in the ratio 3:7. As a result, gold was completely washed out from the PMMA surface.

![Figure 8](image_url)

**Figure 8.** (a) An electronic microscope image of a 30-µm metalens in an aSi and (b) its magnified 3µm ×2 µm central fragment. [8]

The focusing properties of the metalens were experimentally studied by means of scanning near field optical microscopy (SNOM). An experimental optical arrangement is shown in Fig. 9.

![Figure 9](image_url)

**Figure 9.** Experimental optical arrangement. $M_1$, $M_2$– mirrors, $O_1$– a 100× objective, $C$– a probe, $S$– a spectrometer, and CCD– a CCD-camera.

In the experiment, a light beam from a He-Ne laser (wavelength 633 nm, power 50 mW) was fed via an optical fiber to the metalens under study, generating a subwavelength focal spot. The full width of the incident beam was 30 µm. The intensity in the focal spot was measured using a hollow metallized pyramid-shaped tip C having a 100-nm pinhole in the vertex. Having passed through the pinhole the light was collected by a 100x objective $O_1$, before travelling through the spectrometer $S$ (Solar TII, Nanofinder 30) to the CCD-camera (Andor, DV401-BV).

The experimentally measured focal length of the metalens was $z = 0.6$ µm. Figure 10 depicts the focal intensity pattern experimentally measured by SNOM. Figure 11 shows the intensity profiles in the focal spot (Fig. 10) along the $x$- and $y$-axes. The maximal intensity in the focus was found to be 11 times that of the incident beam.

![Figure 10](image_url)

**Figure 10.** Intensity pattern at distance $z=0.6$ µm from the metalens (Fig.8).
Figure 11. Measured intensity profiles of the focal spot (Fig. 10). Red crosses mark experimental values and black curve presents a polynomial-based approximation.

Experimentally measured size of the focal spot was FWHMx=0.55λ and FWHMy=0.49λ. These values are just 8% different from those obtained via simulation (FWHMx=0.52λ, FWHMy=0.46λ) taking into account the metalens fabrication errors, also being 15% different from a focal spot generated by a perfect metalens (FWHMx=0.434λ, FWHMy=0.432λ), which has a regular microrelief of feature height 70 nm.

4. Conclusions
The components of microoptics with nanostructured surface for polarization control are investigated. These components include transmitting or reflecting subwavelength diffractive gratings, which have locally varying direction and filling factor of relief, but have approximately equal period and depth of the relief. The single elements of the relief can be tens and hundreds of nanometers for the visible wavelength range. Sectoral diffractive polarizers with small number of sectors, which transform linear polarization in radial or azimuthal polarization of laser light are investigated in detail.

5. References
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