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Design of a sector-variant high-numerical-aperture micrometalens

A.G. Nalimov[a,b,*], V.V. Kotlyar[a,b]

[a] Image Processing Systems Institute—Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of the Russian Academy of Sciences, 151 Molodogvardeyskaya St., Samara 443001, Russia
[b] Samara National Research University, 34 Moskovskoye Shosse, Samara 443086, Russia

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ABSTRACT

Based on the finite-difference solution of Maxwell's equation, we study a unit-NA binary microlens fabricated in a thin-film amorphous silicon as an array of subwavelength diffraction gratings that operate as half-wave zone plates, numerically showing it to focus a linearly polarized plane incident beam into a near-surface circular focal spot. Focusing is shown to be performed with near-same quality for a varying number of polarization-rotation diffraction gratings, ranging from 3 to 16. The subwavelength focal spot is shown to measure, in terms of full-width at half-maximum (FWHM) intensity, FWHMx = 0.435λ and FWHMy = 0.457λ for 16-sector diffraction gratings, and FWHMx = 0.428λ and FWHMy = 0.460λ for 4-sector diffraction gratings, where λ stands for the incident wavelength.

1. Introduction

These days, metasurface photonic components have been actively studied. Their advantages include the possibility of simultaneously controlling the polarization and phase of laser light, while the microrelief height of dozens of nanometers for the visible and IR spectrum make them easy to fabricate. A review of metasurface photonic components can be found in Ref. [1]. The metasurface components may find applications for generating optical vortices [2]; in sawtooth gratings capable of reflecting 80 percent of the incident light into a desired angle for a wide range of near-IR wavelengths [3]; focusing light into a doughnut intensity distribution [4] or a transverse line [5]. Of special interest is the use of the metasurface components as ultra-thin microlenses [5–8].

In a number of earlier published works, the present authors also studied some metasurface components [9–11]. In particular, microoptic components (micropolarizers and microlenses) to perform the linear-to-radial and linear-to-azimuthal polarization conversion and subwavelength focusing of the incident light beam have been considered. Such microoptic components are peculiar to the surface space-variant subwavelength diffraction gratings. Similarly to a half-wave plate, each grating can rotate the polarization plane by a definite angle. In total, four different space-variant gratings have been analyzed [9–11], which were able to rotate the polarization angle by four different angles. This was found to be sufficient to perform an approximate conversion of linearly polarized light into radial or azimuthal polarization.

* Corresponding author at: Image Processing Systems Institute—Branch of the Federal Scientific Research Centre "Crystallography and Photonics" of the Russian Academy of Sciences, 151 Molodogvardeyskaya St., Samara 443001, Russia.
E-mail address: anton@smr.ru (A.G. Nalimov).

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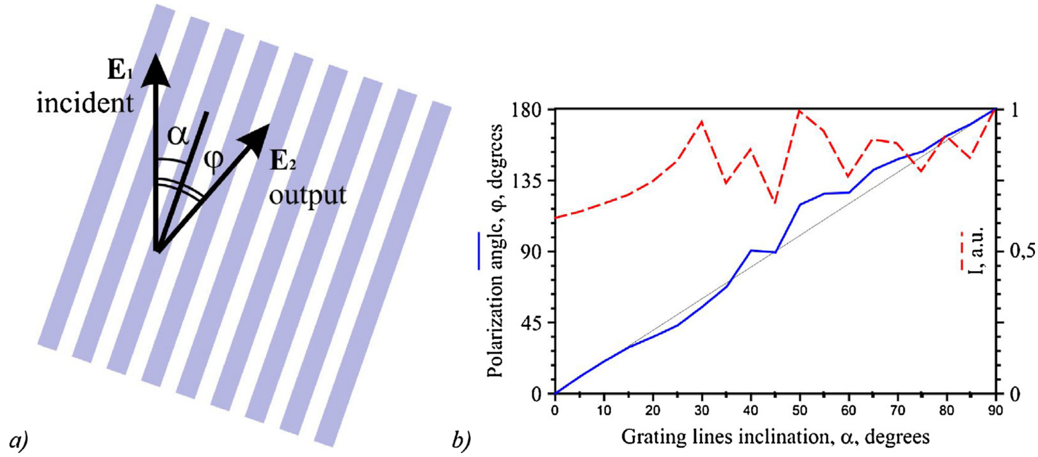

Fig. 1. (a) Vectors of the incident and transmitted electric field intensity, $\boldsymbol{E}_1$ and $\boldsymbol{E}_2$; (b) the angle φ as a function of the transmitted electric field intensity $\boldsymbol{E}_2$(solid line) and the relative intensity I as a function of the grating groove tilt α (dashed line).

In this work, we conduct the numerical simulation of focusing light with the aid of unit-NA micrometalenses composed of a varying number of local subwavelength diffraction gratings. We show that the linearly polarized light is best focused by an element with 16 local space-variant gratings, generating a near circularly shaped focal spot. For the metalens with 16 different azimuthal angles of the polarization plane, the focal spot size at full-width of half-maximum intensity was found to be FWHMx = 0.435λ and FWHMy = 0.457λ (corresponding to the eccentricity parameter (hereafter termed as ellipticity) of 1.05).

2. Modeling a subwavelength grating polarizer

The metalens under study is synthesized based on the algorithm proposed in Ref. [11], in which the binary lens is composed of a zone plate with desired focal length and numerical aperture (NA). However, rather than considering the microrelief in a transparent substrate resulting in a half-wavelength inter-zone shift, the subwavelength binary microrelief of interest has local space-variant diffraction gratings in each zone. Each space-variant grating is supposed to rotate the polarization plane by a certain angle. Here, questions arise as to whether the angle φ of polarization plane rotation should depend in a linear way on the tilt α of the diffraction grating grooves and whether the light transmittance should be the same for different gratings. The first question can be answered by analyzing the plot for the rotation angle φ of the incident field polarization vector after passing through the subwavelength grating as a function of the angle α between the incident light polarization vector and the grating grooves (Fig. 1a). The plot is shown in Fig. 1b (solid curve), describing the numerically simulated propagation of the linearly polarized light (with the incident plane wave defined by the vertical polarization vector $\mathbf{E_1}$(Fig. 1a)) through a 120-nm high diffraction grating fabricated in an amorphous silicon with the refractive index n = 4.35 + i0.486 [11]. The second question can be clarified from the plot for the transmitted light intensity as a function of the angle α (Fig. 1b, dashed curve). The numerical simulation we conducted employed the FDTD-aided finite-difference solution of Maxwell's equations using the FullWAVE software. The grating under study had a 220-nm period, a 110-nm groove width, a 110-nm ridge width, and a 120-nm relief depth. The incident wavelength was λ = 633 nm.

From Fig. 1b, the output angle φ is seen to depend in a near-linear way on the input angle α for the material used, with the dependence being farthest from linear for the angles α of 40°, 50°, and 70°. However, the dependence does not need to be perfectly linear. Deviations of the curve plotted in Fig. 1 from linearity just need to be accounted for when designing a metalens composed of local space-variant subwavelength gratings. The transmitted intensity I (with the incident one taken to be unit at each point) plotted in Fig. 1b against the grating groove tilt angle α takes the form of a quasi-periodic function ranging in value from 0.7 to 1. Hence, rather than operating as a purely phase element, the metalens modulates the uniform incident intensity, in this way decreasing the efficiency.

3. Metalenses with a varying number of local gratings

In this section, we conduct the numerical simulation of tightly focusing a linearly polarized flat-top laser beam by a binary metalens in amorphous silicon, composed of local diffraction gratings varying in number from 3 to 121. Fig. 2a depicts a metalens composed of 16 space-variant diffraction gratings, which are seen as 16 sectors originating from the common center. The gratings in each sector are arranged so as to produce an azimuthally polarized output beam. Similarly to the radially polarized light [13], the azimuthally polarized light with phase singularity has been known to enable focusing into a circular focal spot of subwavelength size [12]. To realize the phase singularity, we replaced a conventional zone plate with a spiral zone plate with the unit topological charge whose adjacent zones were composed of diffraction gratings with