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Nanomanufacturing and scattering study of Silicon metasurfaces

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ABSTRACT

We study straylight of metalenses both by systematically adding controlled manufacturing errors as well as numerically. For the experimental realisation, we nanofabricate amorphous silicon (a-Si) nanopillars on a silicon nitride (SiN) membrane via electron beam lithography. For the numerical comparison employ a Finite-Difference in Time-Domain solver.

Keywords: metasurface, flat optics, nanofabrication, straylight

1. INTRODUCTION

Optical nanostructures are promising technologies for space applications. They offer the potential to reduce the size and weight of current space instruments while adding new features to optical systems that would not be possible with conventional materials [1,2]. Since nanostructures are small, they lead to a broad spatial spectrum and, therefore, represent strongly diffractive elements. For that reason, they can be expected to exhibit worse stray light performance than standard lenses and mirrors. This performance degradation could offset any gains in instrument design, as stray light requirements for Earth observation instruments demand resolving up to 6-7 orders of magnitude. Straylight from structures such as gratings has been extensively studied both experimentally and theoretically, as they are a primary source of stray light in spectrometers [3]. The research has primarily focused on the differences between grating ghosts and homogeneous scattering backgrounds. A comparably comprehensive study linking manufacturing tolerances to the straylight performance of metasurfaces and an estimate whether current manufacturing technologies can meet the stringent requirements for Earth observation remains elusive. We aim to address this by designing metalenses with controlled errors and study their straylight both experimentally as well as numerically.

2. LENS DESIGN

We designed and fabricated a transmissive metasurface lens of 7mm diameter based on a-Si nanopillars on SiN membrane. The selection of the materials is driven by a compromise between manufacturability of the metasurfaces and ease of testing at the different facilities. The straylight of the metalenses with induced manufacturing errors were compared with the set of reference samples. For this we first use the a-Si film of SiN membrane, with the same spatial dimensions. Second, a set of nanopillars with constant radii, that does not disturb the phase, but provides a roughness to the surface. Third, the metalens with same focal length, but without introduced errors. The pitch and height remain constant and set to 560nm and 400nm, respectively.

To achieve the focusing effect, the radii of the nanopillars were varied to match the target spherical wavefront $\varphi = \frac{2\pi}{\lambda}\left[f - \sqrt{f^2 + x^2 + y^2}\right]$ and focal length of 1m. The phase shift provided by each nanopillar is simulated in Lumerical using FDTD method [4] to assure the coverage of the phase from 0 to 2π. In every simulation the plane wave propagates through the set of nanopillars with constant radius to the far field, where the phase shift is detected. We use a square lattice for the metalens design, which presents a challenge due to typical algorithms [5] use the radial symmetry to create data-efficient design files. The slight variation of the nanofabricated pillar radius compared to the design is the most common defect, hence a Gaussian noise with known standard deviation is studied. In this work we explore a standard deviation of 10 and 30 percent.

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The formation of the metalens happens on a rectangular lattice and on every step of this grid, the selection of the radius is determined by the interpolation between phase and size of the pillar. In case of Gaussian noise being added, the radius from the interpolation is considered a mean value of the normal distribution with the set by the design standard deviation

The structuring of the gds design file consist of several main steps. First, the creation of the unit cells with the radii in the range of 0 to 2π with step size of 1nm. Second, the 1/8 of the pattern is formed with referencing of the unit cells from the initial layer. To implement the Gaussian noise in the design the additional set of the radii covering all values up to a half period are added to the unit cell set for the further referencing. The metalens with dimensions of 7mm x 7mm consists of more than 200 million nanopillars, hence adding the random noise to the 1/8 of the pattern provides enough contingency to not observe any evidently repeated errors in the experiment. In case the value of radius with noise exceeds the pitch between pillars, a maximum radius is set. The final design for all the metalenses does not exceed 1Gb and accommodates the lattice structure that is comparable with the FDTD simulations.

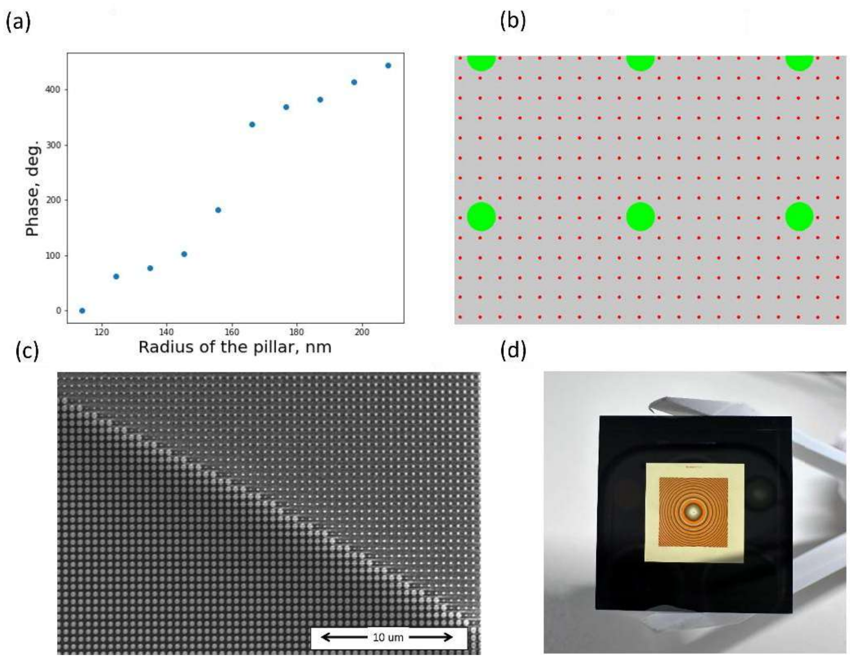

Figure 1: (a) Dependance of induced far field phaseshift for fixed lattice constant on nanopillar radius; (b) Set of nanopillars with radius 10 nm between the ones forming phase profile; (c) Silicon metalens structure manufactured at the Kavli Laboratory in Delft and at SRON; (d) Photo of the metalens after full processing.

3. NANOFABRICATION

The nanostructures under consideration are produced with an a-Si layer deposited on a 4-inch fused silica JGS1 wafer with a SiN thickness of 500±25 μm. The deposition of low-temperature a-Si was carried out using ICPECVD, with a flow of 5 sccm SiH4 and 5 sccm of SiH4 under 1200 W and 5 mtorr at a temperature of 150°C. The choice of low-temperature deposition was made to enhance the adhesion and stability of nanopillars with small radii. The thickness of the layer and the refractive index of a-Si were verified by ellipsometry measurements, showing $n = 3.22$ at a wavelength of 785nm and thickness of 414nm. The measured parameters are used for the simulation of the phase dependence on a pillar radius (fig. 1 a).

The wafer was coated with HMDS and covered with an ARN 7520.17 resist to a thickness of 280nm, providing precision for e-beam writing and preventing overetching during further processing. The pattern was written using an electron beam and developed with the standard MF322 developer. Ultimately, dry reactive ion etching was performed until the aSi/SiN interface. For that matter, SF6/O2 gases with a flow of 13.5/10.5sccm, RF power of 50W, and a bias voltage of -180V were used. To prevent the pillars with smaller radii from falling down due to the difference in etched surface area between pillars and outside of the pattern the final design of metalens confined in the frame with thickness of 560nm to and the array of pillars with radius of 10nm is added in the areas of phase jumps (fig. 1 b). Those pillars are etched away fully during the processing and do not perturb the target phase profile. The residual resist was removed using PRS30 and IPA. After the full processing of the pattern, the backside KOH etching was performed to fabricate the membrane. In fig. 1 c the SEM image of the phase jump zone of the metalens is shown. The structure after the manufacturing consists of a 7x7mm^2 pattern on 10x10mm^2 SiN membrane with thickness of 500nm (fig. 1 d).

4. CONCLUSIONS AND OUTLOOK

In this paper we have given an overview of the nanofabrication procedure of the metalenses for the implemented Gaussian noise for the experimental verification of the straylight signal simulated in Lumerical. We showed that scaling of metalenses can be performed efficiently to accommodate large beamspot size. We plan to also investigate the periodical errors in the nanostructures. We further intend to perform the straylight measurements on the nanofabricated metalenses.

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