Design of a polarization-insensitive subwavelength-thick metalenses

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Metalenses have emerged as one of miniaturized optical components. In this paper, we analyze the phase modulation principle, and demonstrate a highly efficient, micron-thick and reconfigurable polarization-insensitive metalenses at 1550nm based on the transmission phase. Through finite time domain difference (FDTD) simulation, the light field distribution is obtained as it is propagated through the metalenses after the incident plane wave. The focusing imaging of the device is thereby confirmed, achieving diffraction-limited focusing to an ≈6μm spot size at a working distance of around 100μm.

Introduction

Metasurfaces are emerging as leading platforms for the development of integrated optics in compact and planar configurations. In 1948, Winston E. Kock's proposal employed subwavelength elements, specifically metallic lens antennas, to decrease the phase velocity of electromagnetic waves. [1] Since then, the metasurface field has seen significant developments, showcasing various optical components like lenses[2], holograms[3] and gratings[4]. A key aspect of these advancements lies in the realm of ultra-thin optical metasurfaces, which are composed of nanostructures. These metasurfaces rely on subwavelength-scale optical devices to exert precise control over the polarization, phase, amplitude, and dispersion of light[5].An intriguing application is the metalenses, which alters the direction of beam emission or reflection, facilitating beam convergence.

Compared to traditional lenses, which control the wavefront and beam deflection through the phase accumulated as light propagates in the media, metalenses use subwavelength structures of varying height to induce a phase change of 2π. This manipulation allows the conversion of an incident planar wave into a focused spectral wave and facilitates changes in the polarization, phase, and amplitude of the light wave. Consequently, metalenses enhance beam utilization within the photosensitive area of photodetectors and achieve electromagnetic modulation at a sub-wavelength scale, which is crucial for the miniaturization and integration of optical systems.

In this paper, the design and numerical simulation of a polarization-insensitive metalenses with subwavelength-thick features, specifically tailored for optical-communication wavelengths with a radius of 40 μm are presented. To address the challenges of long simulation times and complex boundary conditions, we propose a two-stage design method based on finite-difference time-domain (FDTD) software. Utilizing this approach, we systematically obtain the complete metalenses structure by sweeping through the parameters and demonstrate transmissive polarization-insensitive metalenses operating at 1550 nm. These metalenses have numerical apertures (NA) of 0.37 and exhibit focusing efficiencies up to 83%.

Principle of the mMetalenses design

The metalenses achieves focusing by adjusting the wavefront phase at the incident surface, effectively resolving variations in phase across different spatial positions. This study adopts a transmission phase-type design. In current research, there are two main types of transmission phase-type metalenses: the metal-type metalenses based on the theory of plasmonic waveguides [8], and the dielectric-type metalenses based on the theory of equivalent refractive index[9].

The metalenses consists of symmetric silicon pillars of variable diameter, ith focusing efficiency that remains independent of incident light polarization[10]. The fundamental components of the metalenses are Si nanopillars on a SiO2 substrate (see Figure 1). In transmission mode, the metalenses focuses collimated incident light into a spot. To achieve this, each nanopillar at position (x,y) must impart the required phase as given by

$$\phi(x,y) = \frac{2\pi}{\lambda}(f - \sqrt{x^2 + y^2 + f^2}) \tag{1}$$

where λ is the design wavelength and f is the focal length, representing the distance from the center nanopillar to the focal point[11]. Figure 1 shows a 3-D schematic diagram of the metalenses and nanopillar structure. To ensure high efficiency, additional parameters such as nanopillar height (H), Si nanopillar radius (R), and unit cell size (U) in Figure 1 are optimized at the design wavelength λ. Each nanopillar's height should be sufficient to ensure a phase change covering the range of 2π.

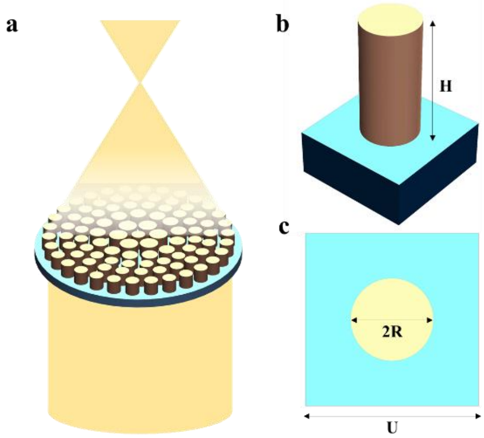

Figure 1(a) Schematic of a metalenses operating in transmission mode; (b) Side-view of the unit cell; (c) Top-view of the unit cell.

In this design, the height (H) of each nanopillar remains constant. The size of the SiO_2 substrate unit, U, determines the sampling accuracy of metalenses. In accordance with the Nyquist sampling theorem[12]:

$$U < \frac{\lambda}{n_{SiO_2}} \tag{2}$$

where λ is incident wavelength, n_{SiO_2} is set to 1.45. In terms of research methods, the model is simulated using the finite-difference time-domain method. In this simulation, the perfectly matched layer (PML) boundary condition is employed to terminate the propagation of the electromagnetic field around the model.

Structure design and discussion

Simulating the metalenses with FDTD based on the design principle described above allows us to acquire the propagating light field of the plane wave after passing through the metalenses. Figure 2 shows the phase and transmission efficiency of the unit cell of different nanopillar height and different nanopillar radius. To achieve a balance between high transmission and covering a continuous 2π phase, we designed a nanopillar height (H) of 1 μm. In addition, the height of different nanopillars should be the same in the actual fabrication process.

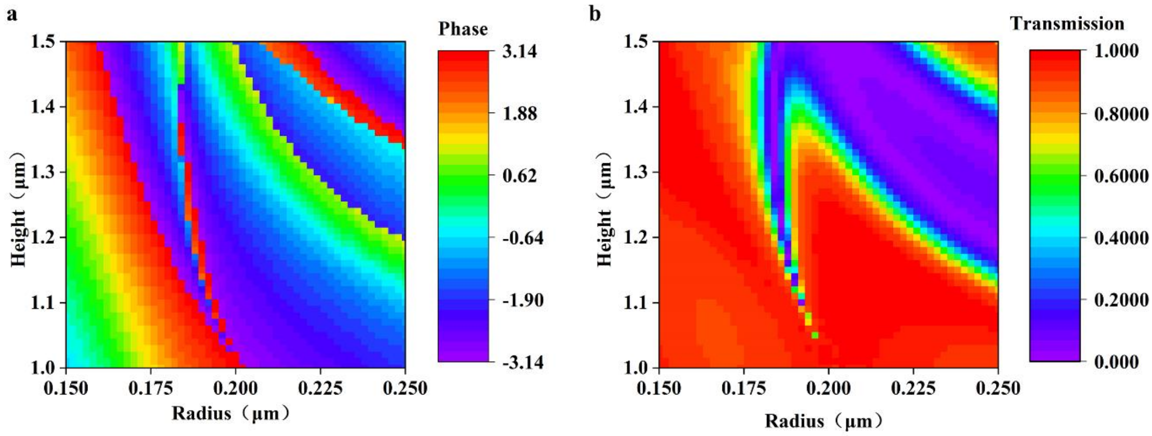

Figure 2 (a) 2D map of the phase; (b) 2D map of the transmission.

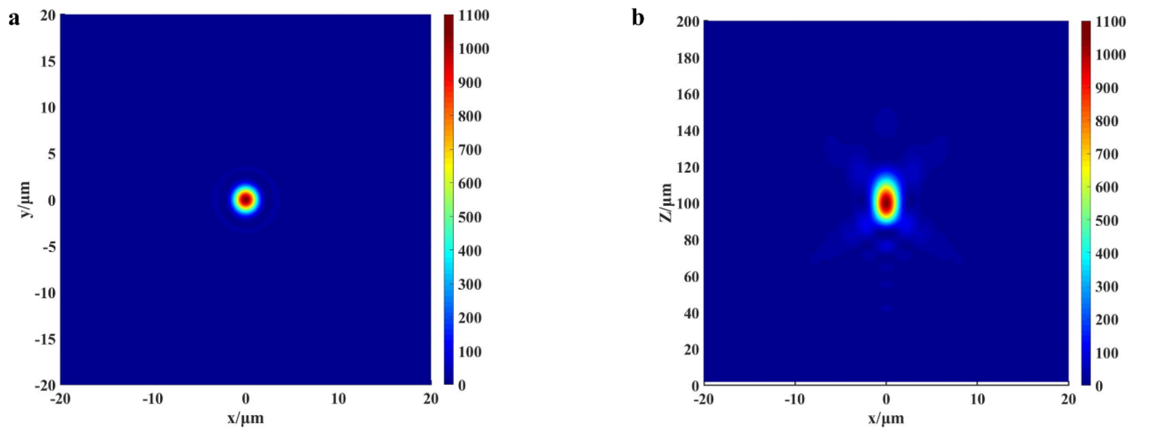

Figure 3 (a) Simulated focal spot (x-y plane);(b) Simulated intensity profiles (x−z plane) in the focal region.

Figure 3 shows the normalized light intensity (NLI) of the plane wave propagating in both the x-y and x-z planes after passing through the metalenses. Clearly visible in the results, the incident plane wave converges to a point on the central axis, forming a focused light field near the designed focal length. This observation validates the convergence effect of the designed metalenses and the line diagram is shown in Figure 4(a). The maximum light intensity point after the light converges through the metalenses is located at z = 100 μm. Thus the actual focal length f = 100 μm is consistent with the designed focal length.

We define the efficiency as the ratio of the optical power in the focal spot area (circle of radius 3× FWMH spanning the center of the focal spot) to the incident optical power.

An efficiency as high as 83% is achieved for a metalenses designed at wavelengths of 1550 nm.

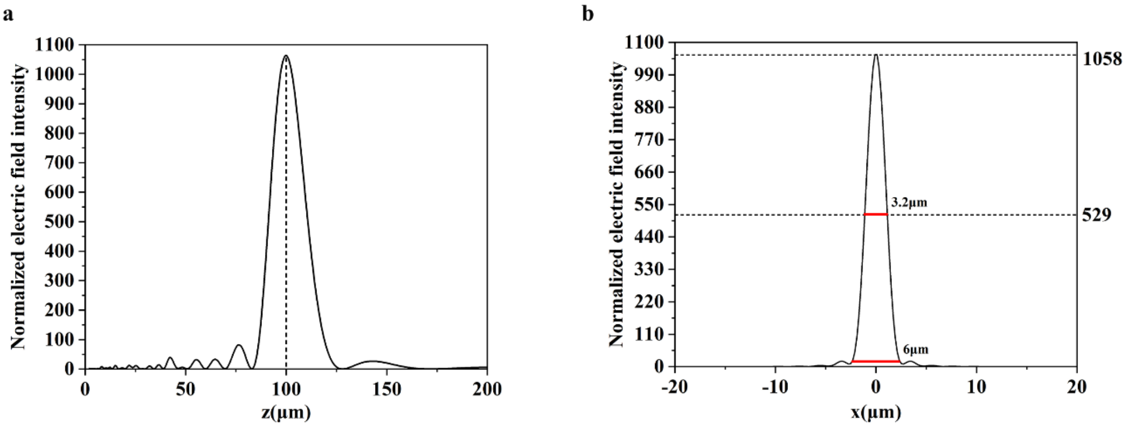

Figure 4 (a) The normalized electric field intensity of the z direction, x = 0 and y = 0;(b)Corresponding horizontal cuts of focal spot in Figure3(a).

Conclusions

In this paper, we have numerically demonstrated the designed subwavelength-thick, polarization-insensitive metalenses using Si nanopillars at 1550nm, and shown the focused light field profile of a plane wave through the metalenses by FDTD simulation. The metalenses demonstrates diffraction limited focusing at the working distance 100 μm, producing a focal spot with 6μm spot size. The metalenses has the compact features and can play a role in achieving miniaturized optical systems. The metalenses provides a solution for versatile applications ranging from detection, spectroscopy, and laser fabrication to wearable optics.

References

[1] Kock W E. Metallic delay lenses. Bell System Technical Journal, 1948, 27(1): 58-82.

[2] Khorasaninejad M, Aieta F, Kanhaiya P, et al. Achromatic metasurface lens at telecommunication wavelengths. Nano letters, 2015, 15(8): 5358-5362.

[3] Ni X, Kildishev A V, Shalaev V M. Metasurface holograms for visible light. Nature communications, 2013, 4(1): 2807.

[4] Khorasaninejad, M.; Capasso, F. Nano Lett. 2015, 15, 6709−6715.

[5] Wang, Wei, et al. "Ultra-thin, planar, broadband, dual-polarity plasmonic metalens." *Photonics Research* 3.3 (2015): 68-71.

[6] Khorasaninejad, Mohammadreza, et al. "Metalenses at visible wavelengths: Diffraction-limited focusing and subwavelength resolution imaging." *Science* 352.6290 (2016): 1190-1194.

[7] Arbabi, Ehsan, et al. "Full-Stokes imaging polarimetry using dielectric metasurfaces." *Acs Photonics* 5.8 (2018): 3132-3140.

[8] Luo X, Pu M, Ma X, et al. Taming the electromagnetic boundaries via metasurfaces: from theory and fabrication to functional devices. *International Journal of Antennas and Propagation*, 2015.

[9] Khorasaninejad, Mohammadreza, et al. "Super-dispersive off-axis meta-lenses for compact high resolution spectroscopy." *Nano letters* 16.6 (2016): 3732-3737.

[10] Arbabi, Amir, et al. "Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmitarrays." *Nature communications* 6.1 (2015): 7069.

[11] Bi, Amir, et al. "Subwavelength-thick lenses with high numerical apertures and large efficiency based on high-contrast transmitarrays." Nature communications 6.1 (2015): 7069.

[12] D. E. Aspnes and J. B. Theeten 1980 *J. Electrochem. Soc.* 127 1359