Broadband optical beam steering over a wide field of view with a silicon quadratic metalens

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Metasurfaces are a potential candidate to substitute bulk lenses in optical beam steering devices. However, off-axis and chromatic aberrations often limit their applicability. Here, we report on a single-layer, silicon metalens simultaneously providing a large field of view and broadband achromatic behaviour at optical communication wavelengths. The metalens features a quadratic phase profile, a numerical aperture of 0.83, and allows beam collimation and steering over a field of view of 86° and a bandwidth of 140 nm.
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INTRODUCTION

Photonic technologies such as light detection and ranging (lidar) and free-space optical communications have attracted a surging interest in the last few years, both from the academic and industrial point of view. This has ignited an intense research on compact solutions capable of generating, shaping, and steering optical laser beams. Integrated optical phased arrays are among the most vastly exploited devices that allow achieving these functionalities. By controlling the relative phase of the light emitted by an array of integrated antennas, it is possible to generate beams with divergence smaller than 0.1° and steer them over a field of view of a few tens of degrees [1,2]. However, phased arrays requires either the use of a laser with the emission wavelength tuneable over hundreds of nanometers or alternatively a very large number of integrated phase shifters.

A different approach to achieve beam steering relies on an array of antennas placed at the focal plane of a lens (focal plane array). Turning on one antenna at the time allows changing the position at which light arrives at the lens and hence the direction of the outgoing collimated beam [3,4]. A promising way to improve the compactness of such a system is to substitute the lens with a flat metasurface (metalens), i.e., a two-dimensional arrangement of subwavelength scattering elements [5]. While high optical performances have been demonstrated [6], metalenses often suffer from off-axis and chromatic aberrations. Simultaneously ensuring broadband operation and a wide field of view remains challenging [7], limiting the applicability of metalenses in the context of beam steering.

Here, we present the design and experimental demonstration of a silicon metalens at optical communication wavelengths overcoming this limitation. The use of a quadratic phase profile and a high numerical aperture of 0.83 allowed experimentally demonstrating a wide field of view of 86°, limited by our experimental setup. Additionally, this phase profile made the metalens inherently tolerant to chromatic aberrations, enabling an operational bandwidth of 140 nm.

RESULTS

Figure 1a schematically shows how beam steering can be achieved using a metalens and an array of antennas placed at its focal plane. If the antenna is aligned with the central axis of the lens, the emitted diverging beam propagating in the z direction is collimated and does not change direction upon crossing the metalens. When the antenna illuminates instead the metalens from an off-center position, for example with a displacement along the x axis, the collimated beam will be directed at a different angle in the far field, achieving beam steering. Reciprocally, when a plane wave illuminates the metalens at different incident angles, light is focused at different positions along x.

In order to achieve this behavior, we designed a metalens with a quadratic phase profile

$$\varphi(r) = -\omega r^2/(2cf), \tag{1}$$

where ω is the frequency of the light, c is the speed of light, f is the focal distance of the metalens, and r is the radial distance from the central axis. The lens was designed to focus light in air. The choice of this phase profile was dictated by its particular characteristics. Compared to diffraction-limited metalenses, the use of a quadratic phase profile introduces spherical aberration which limits the resolution and gives the lens a rather long depth of focus

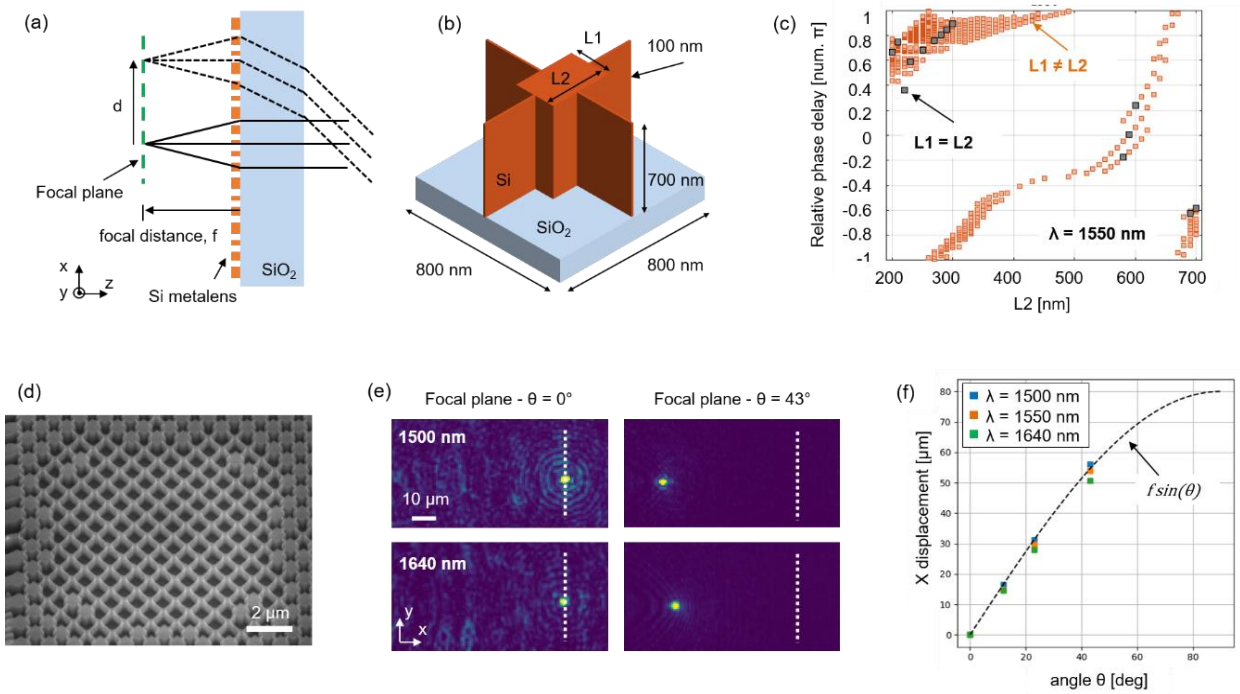

Fig. 1. (a) Sketch representing the metalens operation. Light incident at an angle is focused on the image plane at a distance d from the axis, virtually free of spherical aberrations. (b) Structure of the meta-atom used to realize the fishnet metalens. The dimensions L1 and L2 of the pillar are the design parameters. (c) Relative phase delay imparted by the meta-atom as a function of L2 for different values of L1 (orange marks) for λ=1550 nm. If L1 = L2, the range [-π, π] cannot be properly sampled (black marks). (d) Scanning electron microscope (SEM) image of the center of the realized metalens. (e) Focal spot at the image plane with λ=1500 nm and λ=1640 nm for normal (ϑ=0°) and tilted incidence (ϑ=43°) in the x-z plane, as defined in (a). In the latter case, the focal spot remains undistorted and shifts along the x axis. (f) Focal spot displacement as a function of the incident angle ϑ for λ=1500 nm, λ=1550 nm, and λ=1640 nm. The dashed black line represents the expected displacement calculated using the metalens focal distance f = 80 µm.

[8]. At the same time, however, the lens properly focuses light also under tilted illumination. The focal spot remains undistorted and simply shifts in the focal plane by a quantity $d = f\,sin(\theta)$, being θ the incident angle. The phase profile (1) hence represents an interesting choice for beam steering applications and allows achieving the behavior described in Fig. 1a. While limited resolution could be problematic for imaging applications, in the case of beam steering this is not necessarily a limiting factor since the optimal spot size would ultimately be determined by the size of the antenna. On the contrary, when used in combination with a focal plane array, a quadratic metalens would allow beam steering over an arbitrarily large field of view [9].

The described metalens was realized using a fishnet structure composed of the meta-atoms schematically represented in Fig. 1b. Silicon pillars have a height of 700 nm and are fabricated on top of a SiO_2 substrate. The lattice period is fixed at 800 nm. The width of the cross fins is fixed at 100 nm while L1 and L2 are varied between 200 nm and 700 nm. For each combination of L1 and L2 we computed the phase delay and amplitude modulation imparted by the meta-atom to an incident wavefront at λ = 1550 nm. We disregarded all meta-atoms with transmission lower than 0.5 in order to minimize losses. For the remaining set of pillars, the relative phase delay as a function of L2 is reported in Fig. 1c for different values of L1 with orange dots. As can be seen, the pillars produce a phase shift from –π to π depending on the values of L1 and L2. It is worth noticing that this is not the case if the geometry of the pillars is constrained to L1 = L2 (square pillars, black dots in Fig. 1c).

The obtained library of meta-atoms was used to discretize the phase profile (1) considering a wavelength λ = 1550 nm, a lens diameter of 240 µm, and focal length of 80 µm, corresponding to a lens with numerical aperture NA = 0.83. The resulting structure was fabricated using electron beam lithography and dry etching (Fig. 1d). In order to characterize the behavior of the metalens we did not use it as a beam steering device but we illuminated it with a collimated laser beam and imaged the resulting focal spots in the x-y plane. We considered different illumination angles and also different wavelengths in order to also characterize the broadband performance of the lens.

Figure 1e reports on the results for λ = 1500 nm and λ = 1640 nm and illumination angles θ = 0°, i.e., normal incidence, and θ = 43°. All focal spots are imaged at a fixed distance along the z axis. As can be seen, the well-defined

spot remains almost unchanged in all the four considered cases. Under tilted illumination, its position on the focal plane shifts, as expected, along the x axis. The displacement of the focal spot as a function of the illumination angle is shown in Fig. 1f for sampled wavelengths across the 1500 nm - 1640 nm range. The measured displacements are in very good agreement with theoretical predictions, reported in Fig. 1f with a dashed line for λ = 1550 nm. These results confirm the proper functionality of the metalens across the entire wavelength range and the achievement of a wide field of view of at least ±43°. Due to limitations of our experimental setup, we could not tilt the illuminating laser beyond this limit. It should be noticed, however, that full ±90° field of view has already been demonstrated using quadratic phase profiles [8].

In order to properly characterize the broadband behavior of the metalens, two chromatic aberrations should be considered. Longitudinal chromatic aberration causes the focal distance in the z direction to reduce at longer wavelengths. In the considered 140 nm wavelength range, the shift is limited to 4 µm. This chromatic focal shift is overcome by the large depth of focus of the lens that causes the fixed image plane to fall within the focal tolerance of the lens. This is confirmed by the results in Fig. 1e showing that the focal spot does not significantly enlarge or distort because of the wavelength change. Additionally, under tilted illumination, also the displacement of the focal spot in the x direction changes with wavelength (transverse chromatic aberration), as can be seen in Fig. 1f. For θ = 43°, the differential displacement between λ = 1500 and λ = 1640 nm is 3 µm. This difference is smaller than the full width at half maximum of the focal spot, measured as 3.5 µm independently of the wavelength or illumination angle. The rather large dimension of the focal spot (a diffraction limited spot would have a full width at half maximum of about 1 µm) allows compensating also the effect of transverse chromatic aberration, ensuring the broadband behavior of the metalens.

DISCUSSION

We have proposed and experimentally demonstrated a metalens exploiting a quadratic phase profile to simultaneously achieve a wide field of view and broadband achromatic behavior. The silicon metalens was realized in silicon using a fishnet structure and characterized in the 1500 nm - 1640 nm wavelength range. Under tilted illumination, the metalens remained free of off-axis aberrations up to an angle of ±43°, limited by our experimental setup. Moreover, the relatively large depth of focus of the lens allowed compensating for longitudinal chromatic aberration. The shift of the focal spot due to transverse chromatic aberration under tilted illumination remained smaller than the full width at half maximum of the spot, ensuring a broadband achromatic behavior across the entire 140-nm wavelength range. These results demonstrate that the use of quadratic metalenses has a great potential for applications in optical beam steering.

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