Photonic Crystal Slab Metalens on Amorphous Silicon Platform

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Abstract: We report a novel metalens design based on photonic crystal slab (PCS) resonance modes. By implementing the PCS resonance on an amorphous silicon on quartz platform, we experimentally verified with a focusing metalens phase plate.

1. Introduction

Optical metasurfaces have gained much popularity in optical device design and application in recent years. One of the most remarkable discoveries is the light phase modulation on a flat surface, also known as flat optics [1]. To implement a metasurface functionality on a flat material layer, optical structures have featuring size that is equivalent to the operating wavelength. Different structures have been demonstrated to realize such optical phase modulation, such as nanopillar [2], nanorod [3], and deep holy structures [4]. In our previous research [5, 6], we proposed a novel metasurface structure based on a thin photonic crystal slab (PCS) which is more compatible and mechanically reliable for optical interconnect and integration. Here we report the experimental verification of a PCS metalens structure. With a thin layer of amorphous Si (a-Si) on quartz substrate, we designed the metalens devices at working wavelength of 940 nm and fabricated the devices using electron beam lithography (EBL) and reactive ion etching (RIE). Transmission efficiency of 72.8% was observed with focal lengths matching the designs.

2. Theoretical simulation of photonic crystal slab phase plate design

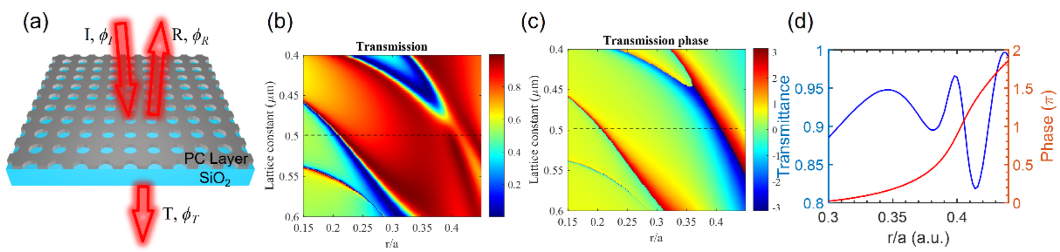

Fig. 1 (a) S4 simulation model for a-Si PCS structure on SiO_2 substrate. (b) A map of transmittance with different lattice constants (y-axis) and different r/a (x-axis). (c) Transmission phase map with different lattice constants (y-axis) and different r/a (x-axis). (d) The transmittance (left y-axis) and phase change in transmission (right y-axis) for different r/a with lattice constant of 0.5μm (the black dash line in (b) and (c)).

We simulate the transmittance and transmission phase through the a-Si/SiO_2 structure, as shown in Fig. 1a, with normal incident light at 940 nm. The simulations were carried out with S4 software [7]. The PCS layer contains circular air holes on a square lattice (lattice constant: a, radius: r). Fig. **1**(b) and (c) show the transmittance and phase change with varying lattice and air filling ratio r/a. The design target is to find the maximal transmission and a full 2π phase change with varying radius. An optimal PCS thickness of h = 160 nm and lattice constant of a = 500 nm are retrieved. With variation of the air hole diameters between 300 nm to 448 nm ($0.3 < r/a < 0.448$), a full 2π phase shift in the transmission can be achieved with higher than 82% transmission, as shown in Fig. **1**(d). We used full structure FDTD to simulate the metalens design and performance on a 200 μm by 200 μm device area[8]. The design numerical aperture (NA) of metalens is 0.2. The focal length is calculated as 0.49 mm with a beam spot diameter of 3.22 μm.

3. Device fabrication and performance characterization

The focal length of a conventional lens can be calculated as [9],

$$S = \frac{1.27 \times M^2 \times \lambda \times f}{d} \tag{1}$$

where M^2 describes the incident beam spot shape quality ($M^2 > 1$), λ is the working wavelength, f is the lens focal distance and d is lens diameter.

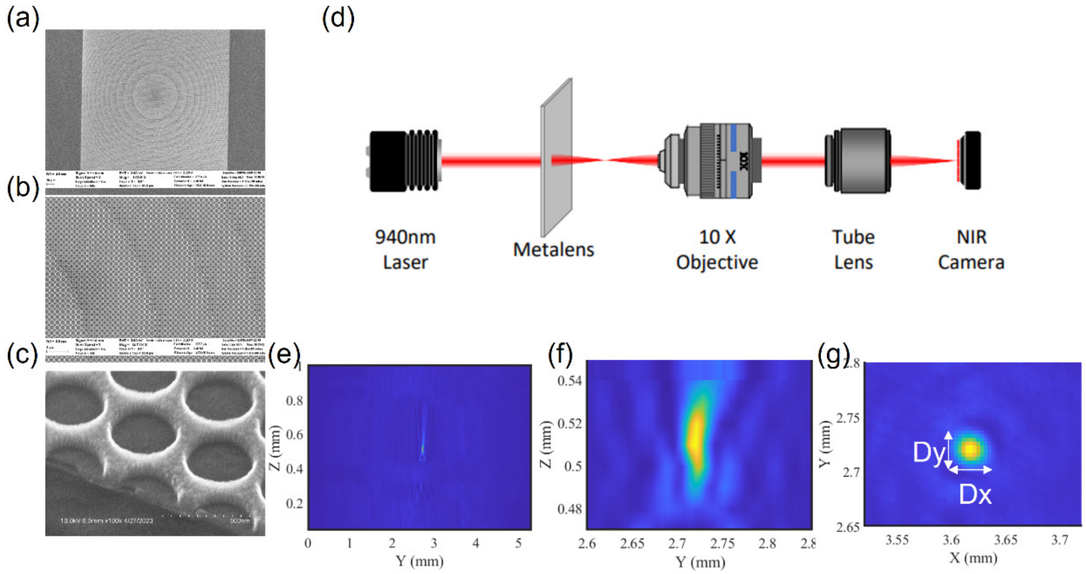

Fig. 2 (a) - (c) Top view of SEM image of a PCS metalens device (NA=0.2) after RIE etching and EBL resist removal. (d) Optical setup to measure beam focusing properties by the metalens. (e) - (f) Measured far-filed intensity distribution. (g) Intensity plots at beam focal plane z = 0.51mm.

To experimentally verify the focusing abilities and performances, we fabricated the metalens devices based on an a-Si on quartz platform with the designed PCS metalens. **Fig. 2** (a) shows the top view SEM image of metalens device with NA = 0.2 in a 200 μm x200 μm area. Fig. 2(b) shows the zoomed-in SEM image of the device. The circular air holes have smooth shapes for regions of different diameters. Fig. 2 (c) shows the side wall of the etched air holes. The field measurement setup of the metalens is shown in Fig. 2 (d). Fig. 2 (e) shows the measured far-filed intensity distribution at different locations (from 0 mm to 1 mm above metalens surface). Fig.2 (f) shows the zoomed-in area of far-filed intensity distribution. This device focus starts around 0.495 mm and end around 0.525 mm, the depth of filed (DOF) is 30 μm where the field intensity decays to 1/e threshold. Due to the fabrication geometry shift, the focal spot location is observed at 0.51 mm, compared to theoretical design of 0.49 mm [9]. **Fig. 2** (g) shows the intensity distribution taken at 0.51 mm with beam spot size of Dx = 3.145 μm and Dy = 3.11 μm, which is determined by the exponential decay of the Gaussian-like beam shape. The measured spot diameter agrees very well with the calculated focusing spot diameter of 3.22 μm [9]. The overall transmission efficiency is 72.8%, which is also close to the simulated transmission efficiency of 82%.

4. Conclusion

In this paper, we reported a thin PCS metalens structure. Such PCS metalens design is implemented on an amorphous Si on quartz substrate. Experimental testing results show an overall transmission efficiency of 72.8%, and focal distance of 0.51 mm. Such compact PCS metalens has potential applications in the optical integration of on chip sensors, display, laser beam collimation, etc.

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5. References

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