Photonic Crystal Slab Metalens

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***Abstract*— We report a highly efficient broadband metalens design based on an amorphous silicon photonic crystal slab structure with a center wavelength of 940 nm. The structure is an ideal candidate for large area phase manipulation with compact, reliable, and low aspect ratio patterning on a thin film. Simulation results show continuous 2π transmission phase control by tuning the air hole filling size near the degenerate band edge, and the metalens structure is achieved with efficiency above 80% and the operation wavelength over 100 nm.**

Keywords— photonic crystal slab, metalens, amorphous silicon, 2π phase transition.

I. Introduction

Nanoscale metamaterial have drawn increasing attention for the last two decades for its broadband, highly efficient capabilities of phase modulation by a flat medium. The research on the flat optics or meta surfaces open new capability for a great variety of applications in beam manipulations such as focusing/imaging [1], formation of vortex beam [2] and patterned spot projection [3]. So far, the common metamaterial are the dielectric pillar structures placed on the applicable substrate with tailored shapes, separation rotation, and placement to bend the transmitted light in the desired way. The mechanism of the localized scattering in these structures often requires the material thickness to be at micrometer scale to provide long enough light paths and to achieve a complete 2π phase transition range. It thus hinders the full adoption of the technology in commercialized product which has higher durability requirements. We propose here an amorphous silicon photonic crystal slab (PCS) metalens structure with full 2π phase modulation, high transmission efficiency and broadband operation centered at 940nm. The design of a focusing PCS Metalens is also verified with COMSOL and 3-dimensional large area finite-difference time-domain (FDTD) method.

II. Theory, Device Design and Applications

Shown in Figure 1(a) is a schematics of a photonic crystal slab (PCS) with lattice constant ***a***, airhole radius ***r***, and its 4-port transportation matrix ***S***. For a PCs on a glass substrate, these parameters can be tuned to achieve continuous 2π transmissive phase control. By construction of in-plane phase distribution according to the phase-radius line in Figure 1(c), highly efficient focusing metalens could be achieved as illustrated in the 3D sketch in Figure 1 (b).

A. *Coupled mode theory and formation of 2π phase continuity*

The PCS guided resonance modes can be quantitively analyzed by the coupled mode theory which establishes the temporal relation of transmittance, reflectance, and the resonant modes that exhibits Fano lineshape in the spectrum [4]. Our previous investigation on the PCS modes has also proposed the condition for reflective 2π phase formation [5]. Similar procedures can be taken to derive conditions for transmissive 2π phase formation. The condition for having a transmissive 2π phase continuity is that the PC transmission coupling strength should be larger than the background transmission. This condition is satisfied for modes that degenerate near the edge of a broad high transmission band.

We investigated the amorphous silicon PCS-on-glass structure and found the degenerate mode at slab thickness $\boldsymbol{t}$ = 160 nm, $\boldsymbol{a}$ = 500 nm and $\boldsymbol{r}/\boldsymbol{a}$ >0.4 for working wavelength at 940 nm. It is then possible to construct a various phase plate by varying the air hole radius (thus r/a ratio) only to achieve the 2π phase line. It was discovered also that further improvements on transmission efficiency can be realized by changing both the air hole radius and the lattice constant. Close to 100% transmission can be achieved for the most part of the designs, as shown in Figure 1(c). More details will be presented in the conference on both theory and design.

B. *Photonic crystal focusing metalens*

To verify the phase modulation capability of our PC-on-glass structure, we constructed a focusing metalens with side length of 21μm×21μm in the FDTD tool Tidy3D [6]. The in-plane phase distribution is in a hyperboloidal profile, increasing from 0 at the center outwards. For an incident planewave with p-polarization, the focusing effect is visualized in Figure 2(a) and (b), for the total

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electric field intensity on the x-z plane (propagation plane) and the x-y plane (focal plane), respectively. For this design, the PCS metalens has a focal length of 14 μm, and a spot size of 0.79μm. This agrees well with the lens focal equation theory. Additionally, the lens can operate in a broadband region, with transmission efficiency of 60% to 80%, over a 100 nm spectral band, as shown in Figure 2(c).

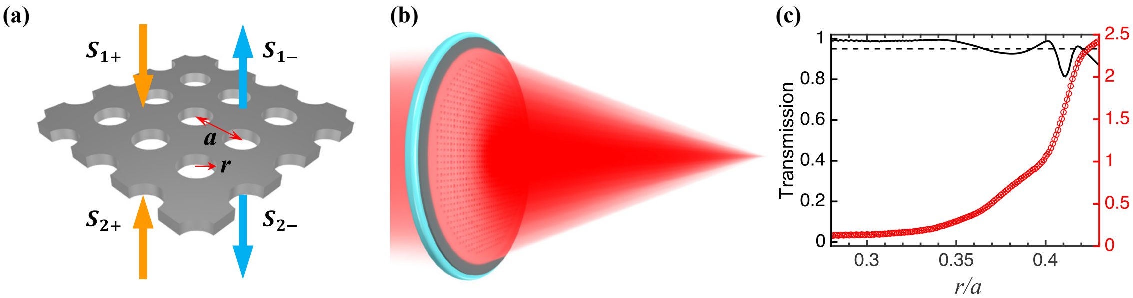

Figure 1. (a) Schematic illustration of a 4-port system in a photonic crystal slab structure with lattice constant ***a***, and airhole radius ***r***; (b) Schematic illustration of the transmissive focusing lens made of photonic crystal slab on glass; and (c) Transmittance and transmissive phase line over r/a ratio range (0.25 to 0.45) by varying both the air hole size and the lattice constant.

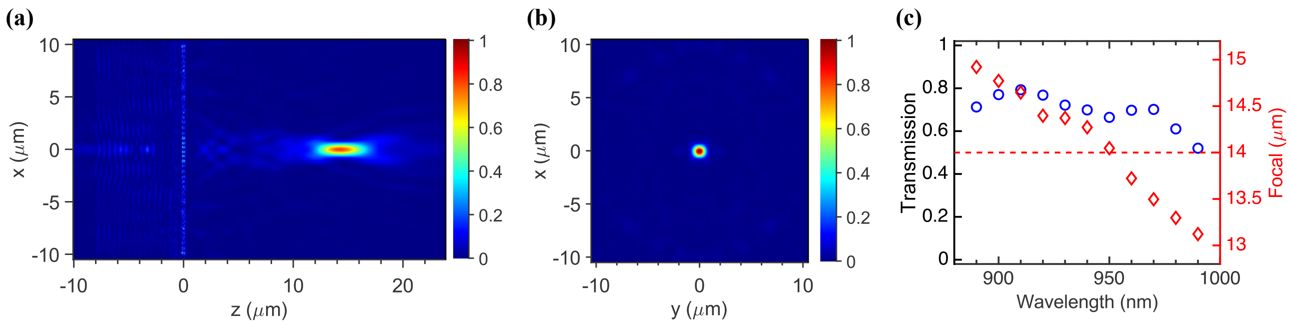

Figure 2. Simulation results for light passing through the focusing lens at 940 nm. (a) and (b) The electrical field intensity distribution contour plots on the x-z plane (propagation plane) and the x-y plane (focal plane) with z = 14μm, respectively; and (c) Simulated transmission efficiencies (blue circles) and the focal lengths (red diamonds) over a broad spectrum band. Note the red dash line is the analytical focal length of 14 μm at 940 nm.

III. Conclusion

We report here a photonic crystal slab based metalens design, verified by FDTD and COMSOL simulations. Transmission 2π phase control can be achieved by the air hole PCS structures. The proposed PCS-metalens have transmission efficiency of 60% to 80% over 100 nm spectral bandwidth. The PCS metalens has comparable performances with the traditional meta-atom metalens. The PCS-metalens design is structurally thinner and mechanically more rubust, thanks to the thin film configuration.

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