Reconfigurable All Dielectric Metasurfaces based on Optical Phase Change Materials: Design Approaches

Mikhail Y. Shalaginov
Dept. of Materials Science & Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
mys@mit.edu

Sensong An
Dept. of Electrical & Computer Engineering
Univ. of Massachusetts Lowell
Lowell, MA, USA
sensong_an@student.uml.edu

Yifei Zhang
Dept. of Materials Science & Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
yzhang94@mit.edu

Fan Yang
Dept. of Materials Science & Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
yangf@mit.edu

Clayton Fowler
Dept. of Electrical & Computer Engineering
Univ. of Massachusetts Lowell
Lowell, MA, USA
clayton_fowler@uml.edu

Hualiang Zhang
Dept. of Electrical & Computer Engineering
Univ. of Massachusetts Lowell
Lowell, MA, USA
hualiang_zhang@uml.edu

Juejun Hu
Dept. of Materials Science & Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
hujuejun@mit.edu

Tian Gu
Dept. of Materials Science & Engineering
Massachusetts Institute of Technology
Cambridge, MA, USA
gutian@mit.edu

***Abstract*—Optical metasurface is a recently emerged paradigm for controlling light propagation, which enables implementation of ultra-compact optical devices with extended functionalities. Nowadays the main challenge in the field is to realize active metasurfaces with high quality, high efficiency, and large tuning range. Here we present a design approach for constructing a two-state reconfigurable metalens made of low-loss optical phase-change material (O-PCM). The metalens design is capable to produce diffraction limited focusing, large change in focal length (from 1.5 mm to 2mm), and decent focusing efficiency of about 20% in both states. The proposed design methodology is generic and can be easily extended towards constructing metasurfaces, which can switch between two or more arbitrary phase maps.**

Keywords—GSST, metasurface, metalens, PCM, phase change materials, reconfigurable optics.

I. INTRODUCTION

Planar periodic arrays of subwavelength antennas, also termed as metasurfaces, open up new functionalities for light manipulation as well as lead to optical components with substantially reduced SWAP-C characteristics. Due to the small volumes of used material, metasurfaces are also a suitable platform for constructing optical devices which characteristics can be modulated or tuned after fabrication. Numerous approaches have been proposed to realize metasurface switching [1]. However, demonstated methods, especially non-mechanical ones, either suffer from low efficiency or have a tiny tuning range.

Recently we developed a new class of chalcogenide glasses, Ge-Sb-Se-Te (GSST) [2]. This material is a low-loss optical phase change material (O-PCM), which can switch between amorphous and crystalline states. In mid infrared the material transition causes drastic change in refractive index ($\Delta n > 1$) while still maintains low losses ($k \sim 0.02$) in both states.

II. DESIGN OF A VARIFOCAL METALENS

The proposed metalens is composed of a patterned 1-μm thick GSST film on top of a low-index CaF_2 substrate [3]. Fig. 1 depicts the concept of the metalens operation. When meta-atoms are in amorphous state, collectively they focus the transmitted optical power to a focal spot $f_1 = 1.5$ mm. After GSST was transitioned to crystalline state, the primary focal spot moves to position $f_2 = 2$mm.

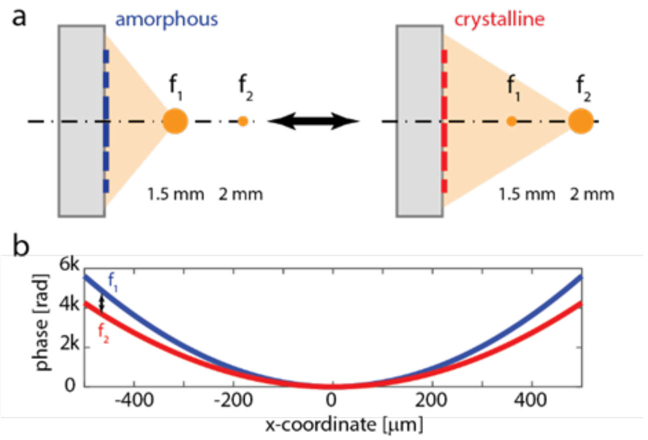

Fig. 1. (a) Operation principle of a reconfigurable bifocal metalens: in amorphous light is primarily focused at a distance $f_1 = 1.5$ mm, and in crystalline state – $f_2 = 1.5$ mm. (b) Modulation of focal spot position is driven by the change in the metasurface phase-profile shape: blue and red curves correspond to amorphous and crystalline states, respectively.

Metasurface focusing capability is dictated by the phase map pattern. For a standard metalens, spatial phase profile is a hyperbolic function. By modulating refractive index of the meta-

---

DARPA Extreme Optics and Imaging (EXTREME) program under contract number HR00111720029.

Submitted On: September 21, 2020
Accepted On: September 23, 2020

https://doi.org/10.47037/2020.ACES.J.351191

1054-4887 © ACES

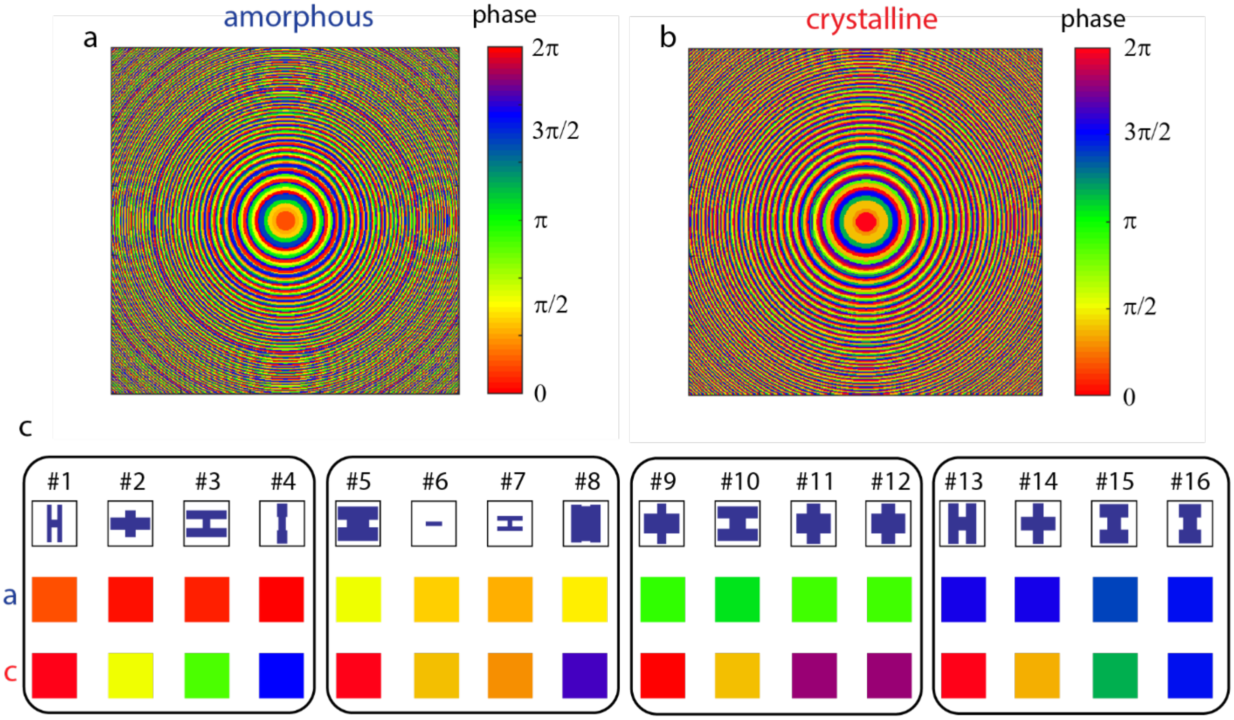

Fig. 2. 2D phase maps of the metalens in amorphous and crystalline states. Change of the focal length is associated with pixel-to-pixel phase pattern transformation. Each of the 16 meta-atoms serves as a phase-pixel switch. The geometry of meta-atoms was selected to enable the phase transitions between the 4 groups of colors: red, yellow, green, and blue, which correspond to the approximate phase-shift values of 0°, 90°, 180°, and 270°.

atoms, we can change the shape of phase profile, hence switch the focal distance (Fig. 1 (b), blue and red curves).

The final 2D phase maps corresponding to amorphous and crystalline states are shown in Figs. 2 (a) and (b), respectively. Initially we generated ideal (continuous) phase maps by employing Kirchhoff diffraction integral method, then the continuous phase maps were discretized into four phase-levels of 0°, 90°, 180°, and 270°. For achieving “pixel-by-pixel” transitioning between the two discretized phase maps, we searched for a group of 16 meta-atoms with specified responses in the two states. In a more general case, one would have to utilize a library of mn meta-atoms, where m is a phase-map discretization level and n is the number of metasurface states, in our example, m = 4 and n = 2. To identify the proper library of meta-atoms, we ran numerous FDTD simulations (CST Microwave Studio) with various shapes (“H”, “I”, “+”) and geometrical parameters, and retrieved their phase/amplitude responses. Film thicknesses and permittivities of the GSST material in both states were measured in an experiment and used as a fixed parameter in the simulations. The best meta-atom candidates were selected from the database by maximizing a figure-of-merit (FOM), which encompasses meta-atom transmittance and its phase error (phase deviation from the desirable phase value). The final set of 16 meta-atoms is presented in Fig. 2 (c). The root-mean-square (RMS) phase errors are approximately 0.1 π. By considering these errors, the metalens in both states is expected to produce diffraction-limited focal spot with a Strehl ratio of > 0.96 and decent focusing efficiency exceeding 35%. The metasurface design can be further improved by increasing phase discretization level as well as by finding better geometries of meta-atoms. For instance, here we used a brute-force method to search for suitable meta-atom designs, however, with the help of neural network machinery it is possible to generate a vast library of unintuitive geometries with better performance metrics [3].

REFERENCES

[1] L. Kang, R. P. Jenkins, and D. H. Werner, “Recent progress in active optical metasurfaces,” Adv. Opt. Mater., vol. 7, no. 14, pp. 1-26, 2019.

[2] Y. Zhang, et al., “Broadband transparent optical phase change materials for high-performance nonvolatile photonics,” Nat. Commun., vol. 10, no. 1, pp. 1-9, 2019.

[3] M. Y. Shalaginov, et al, “Reconfigurable all-dielectric metalens with diffraction limited performance,” arXiv: 1911.12970 7014, 2019.

[4] S. An, et al., “A deep learning approach for objective-driven all-dielectric metasurface design,” ACS Photonics, p. acsphotonics.9b00966, Nov. 2019.