Lens Numerical Aperture Control with Phase-Change Metasurfaces

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ABSTRACT

The control of lens numerical aperture has many applications, including photography, imaging, and laser processing. Here we introduce active control of numerical aperture via a focusing phase-change meta-mirror. This can potentially operate at high speed in a low cost, light and compact format. We demonstrate designs for both infrared (3000 nm) and visible (632.8 nm) wavelengths.

Key words: active lenses, active metasurfaces, phase-change metasurfaces

1. INTRODUCTION

The numerical aperture (NA) of a focusing optical system sets the size of the focal spot, the depth of focus, and the intensity reaching the focal plane. It is therefore critical in many optical fields, including photography, imaging, and laser processing [1,2]: the dynamic control of NA, especially if it could be done with no moving parts, would find widespread application in such fields. An active metasurface offers the potential to realise such dynamic NA control. Metasurfaces are thin materials comprising arrays of sub-wavelength resonant structures (meta-atoms) whose geometry can be optimised to modulate the phase and amplitude of incident light, allowing the output wavefront to be tailored according to a particular requirement. Active metasurfaces have been achieved in recent times by the inclusion of materials whose refractive index can be modified predictably by an external stimulus, such as liquid crystals and phase-change materials (PCMs). Previous work on PCM-based metasurface lenses has mainly been limited to binary switching of the focal position. In this work, we present a design for multi-step dynamic control of the NA with a fixed focal length, using PCMs to adjust the effective aperture of a focusing meta-mirror.

2. EXPERIMENTAL

To control the NA, we effectively divide the surface into two regions of reconfigurable size. The inner, circular region has a parabolic phase profile to focus incident light; the outer, annular region switches between this and a flat phase profile that specularly reflects the light. The effect is that of closing an aperture, as illustrated in figure 1(a), and the resulting change in the output beam is illustrated in figure 1(b).

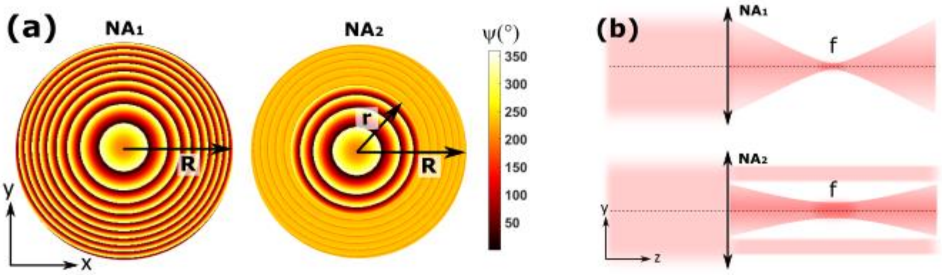

Figure 1. (a) Optical phase profiles (Ψ) of a larger NA state on left and smaller NA state on the right, achieved via generating an effective semi-aperture of *r* with respect to *R*. (b) Effect of switching between two NAs on the focused beam (shown here in transmission for clarity).

We implement these optical phase profiles with meta-atoms comprising cylindrical dielectric resonators with PCM layers on a metallic back plane [3]. We designed devices for operation at 3000 nm and at 632.8 nm. The meta-atom for the former uses the PCM $Ge_2Sb_2Se_4Te_1$ (GSST) and is illustrated in figure 2(a), and the meta-atom for the latter, using Sb_2S_3, is shown in figure 2(b). In one PCM phase, variation of cylinder diameter gives near-2π phase coverage, but the other PCM phase has nearly flat dependence, so enabling the mimicking of the closing of a physical aperture.

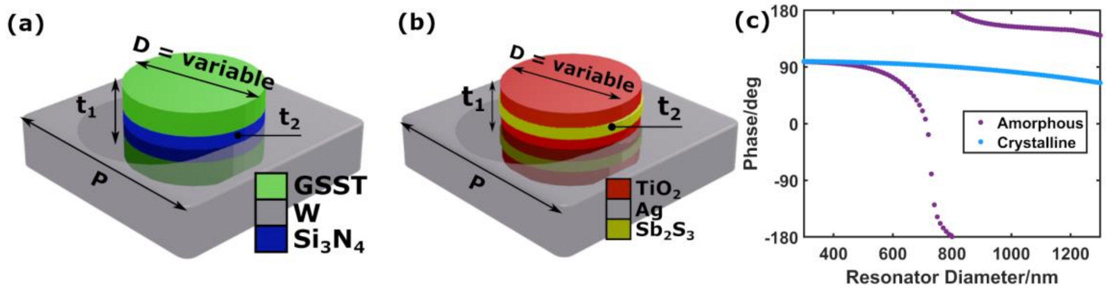

Figure 2. (a) Meta-atom design for use at 3000 nm. t_1=179 nm, t_2=8 nm, P=1400 nm. (b) Meta-atom design for use at 632.8 nm. t_1=74 nm, t_2=32 nm, P=370 nm. (c) Optical phase dependence on resonator size at 3000 nm.

3. RESULTS & DISCUSSION

We simulated focusing meta-mirrors of fixed radius R = 0.5 cm and tunable semi-aperture *r*. Example focal plane intensity profiles as *r* is varied are shown in figures 3(a) and (b) for the 3000 nm and 632.8 nm designs repectively. As *r* decreases, the focal spot broadens, confirming that we have achieved NA control. We can control NA in the range 0.029–0.050 in the IR and 0.026–0.050 in the visible. We have also demonstrated control in the range 0.27–0.45 in the IR by using a shorter focal length, and further focal lengths are also possible.

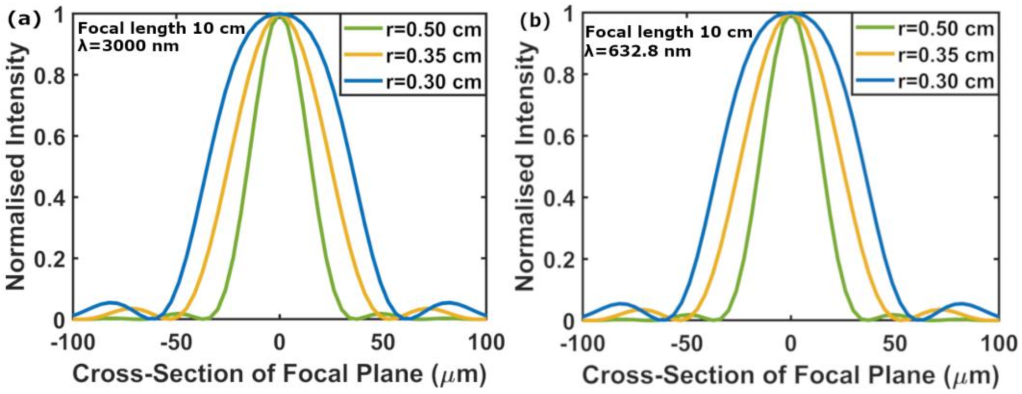

Figure 3. Simulated intensity profiles for 0.5 cm radius lens, and when switched to radii of 0.35 cm and 0.30 cm, operating (a) at 3000 nm and (b) at 632.8 nm with a focal length of 10 cm.

4. CONCLUSIONS

We have successfully designed compact PCM metasurface devices for dynamic and fast control of NA. We have demonstrated that our concept can work for a wide variety of NA regimes and in two different wavelength regimes.

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