# Atom Trapping with Metasurface Optics

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**Abstract:** We present results on trapping ensembles of cold atoms with metasurface optics for portable atomic clock application, and progress towards single atom trapping and detection in high-NA optical tweezers with dielectric metalenses.

In recent years metasurface have sparked great interest in the photonics community due to their versatility in wavefront modification, sub-wavelength planar geometry, and simple integration with on-chip photonics [1, 3]. Metasurfaces modify the wavefront through the surface nanostructures that provides a unique way to manipulate amplitude, phase and polarization of light with sub-wavelength spacial resolution [4].

Recently, the idea of combining miniature atomic devices with diffractive optics has been explored in chip-scale atomic devices [5, 6]. However, the full potential of trapping atom in conservative potentials generated by metasurfaces has not been realized. We are investigating two types of optical potentials for atom trapping using metasurfaces specifically designed for $^{87}$Rb atoms. The first is an optical lattice formed by focusing trapping light through a low-NA metalens. Such traps will find utility in trapping of large atom ensembles for atomic clocks and sensors. Second, we investigate precision optical tweezer traps that can capture and probe single neutral atoms [2, 7] for quantum computing and simulation applications. For this second application, we use a metasurface inside UHV, currently with a NA of 0.55 [Fig. 1(a)], that is polarization-multiplexed for operation at both the atomic transition at 780 nm and far-off-resonance trapping light at 850 nm.

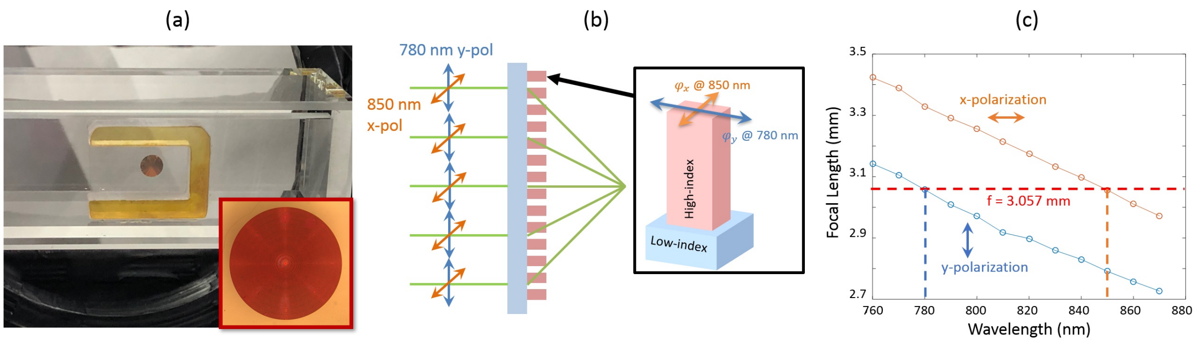


Fig. 1: (a) An image of a 0.55 NA polarization-multiplexed metalens mounted in UHV glass cell. The metalens has focal length $f = 3$ mm and diameter of 4 mm. Inset is an image of a typical high-NA (0.8) metalens of a similar design. (b) Illustration of the design of the polarization-multiplexed achromatic scheme. (c) Measured focal length of the 0.55 NA polarization-multiplexed singlet in x and y polarization. At 780 nm and 850 nm, the focal point of the two polarization coincide at $f = 3.057$ mm

To create an optical lattice for trapping large ensemble of atoms for miniature atomic clocks and sensors, a metalens designed to operate at 850 nm with $f = 150$ mm and NA of 0.01 is fabricated [inset of Fig. 2(a)]. The lens consists of silicon nano-pillars in square-lattice arrangement with the dimension of the nano-pillar optimized to give the desire phase shift at each location that follows the quadratic profile described by equation 1 [1].

$$\phi(x,y) = -\frac{2\pi}{\lambda}\left(\sqrt{x^2+y^2+f^2}-f\right) \tag{1}$$

Where $\lambda$ is the design wavelength, $f$ is the focal length and $x, y$ are the coordinates of the nano-pillars reference to the lens center.

The high-NA (0.55) optical tweezer metalens [Fig. 1(a)] shares the similar silicon nano-pillar and phase profile construction with the low-NA optical lattice lens. However, for this lens an achromatic design is required because the metalens serves two purposes. First, it creates the optical tweezer trapping potential by focusing the incoming

850 nm trapping light. In addition, it images fluorescence of a single trapped $^{87}$Rb atom at 780 nm onto a sensitive camera. To achieve achromaticity with a singlet metalens, we incorporate polarization-multiplexing. By changing the aspect ratio of the nano-pillars, illustrated in Fig. 1(b). The lens is designed to focus 850 nm light in x-polarization and 780 nm light in y-polarization onto the same focal point as shown in Fig. 1(c).

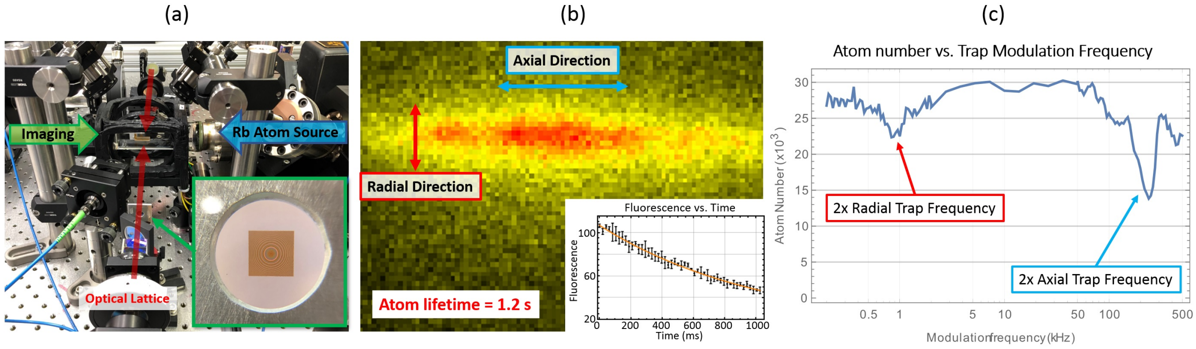


Fig. 2: (a) Image of the atomic platform for testing metalens trapping. The setup consists of a $^{87}$Rb 2D source MOT and a 3D science MOT with an imaging system. The inset is an image of the optical lattice metalens. (b) An image of the atoms trapped in metalens-generated optical lattice. The inset shows the trapped atom lifetime measurement with fitted $\tau = 1.25$ sec. (c) Atom number versus trap modulation frequency shows two distinct dips indicates both radial and axial trap frequency consistent with the presence of optical lattice.

A versatile atomic test platform is constructed for testing various metalenses [Fig. 2(a)]. The metalens for the optical lattice is outside of the UHV cell [inset of Fig. 2(a)]. To create the optical lattice we launch a collimated light into the metalens and re-collimate the focused light with a conventional optic with $f = 150$ mm to retro-reflect the light and create a standing wave. To characterize the optical lattice, the following preliminary measurements have been carried out: trapped atom lifetime and radial and axial trap frequencies. We find the atom lifetime is near 1 second [Fig. 2(b)], which is sufficient for many applications of trapped atoms. Generally significantly longer lifetimes are possible in UHV environments and stable traps, but in these initial measurements, we note an optical lattice created using normal optics has a similar lifetime, indicating we can not yet ascribe any deleterious effects to the metalens optic. More stringent tests would require careful measurements of atom heating rates.

To measure the radial and axial trap frequency, we use parametric heating, which reveals presence of two very different trap resonant frequencies [Fig. 2(c)] consistent with an optical lattice. Note, this first lattice metalens sample we have tested has a large 0th-order leakage light ($\sim 30\%$). In the current setup the 0th-other leakage has negligible effect on the lattice trapping potential due to the large beam size difference (30:1) of the leakage and focused light. However, in cases where the ratio of the focused and 0th order intensity is smaller, for example in a miniature atomic system, additional interference paths are a concern and will be a subject of future study.

Ongoing experiments focus on steps required to trap single atoms using high-NA metalenses. Thus far we have successfully demonstrated the incorporation of sample substrates in UHV environments, and imaged ensembles of atoms through the lens, but have not yet trapped single atoms. For these experiments, requirements on the lens are more stringent, in particular in focusing efficiency. To efficiently trap and detection of single atom a high-NA metalens with efficiency $> 80\%$ is ideal, which has been reported by Arbabi *et al.* with amorphous silicon nano-pillar at 850 nm [1]. Lastly, future metalens designs will look more carefully at doublet metalens where there are prospects for larger field of view at high NA ($> 0.8$) and achromaticity without polarization multiplexing.

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